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HYDROGEOLOGICAL ROLE OF LARGE CONDUITS IN KARST DRAINAGE SYSTEM

EXAMPLES FROM THE LJUBLJANICA RIVER CATCHMENT AREA

DISSERTATION

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UNIVERZA V NOVI GORICI
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HIDROGEOLOŠKI POMEN VELIKIH PREVODNIKOV V EPIFREATIČNI CONI KRAŠKEGA VODONOSNIKA

PRIMERI IZ POREČJA KRAŠKE LJUBLJANICE

DOKTORSKO DELO

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Izjavljam da je doktorko delo v celoti moje avtorsko delo.

I declare that this thesis is my author work exclusively.

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Hydrogeological role of large conduits in karst drainage system.
Examples from the Ljubljanica river catchment area.

Abstract:
We have performed regional and local study of groundwater dynamics in the Ljubljanica catchment area by continuous and simultaneous observation of groundwater levels and temperature at selected locations. The local scale study was focused to Postonjska Jama system, the underground Pivka River respectively. Seven data loggers were installed along pathway of the underground Pivka River, to monitor water level and water temperature. Also discharge at the ponor was measured. Purpose of this monitoring was to study hydraulic of underground drainage and flow velocity (transit time of water) in several underground reaches. The importance of different hydraulic restrictions has been demonstrated. Among them the Martel's rock-fall is the most important. At high floods the water level from the ponor to the Martel’s rock-fall is practically uniform. Flow velocities (water transit times) at different flow rates were assessed based on the time lags between diurnal temperature maxima and minima at different locations. Flow velocities locally vary a lot in the underground system. Flow velocities are in average the highest in the most upstream third of the system (between ponor and Otoška Jama), where they can reach at least 70 m/min (at flow rate around 60 m^3/s). Velocities are in average the lowest between Martel's chamber and Pivka Jama, where they do not exceeds 14 m/min. However, flow velocities were not studied in Pivka Jama, where higher than 70 m/min probably occur. Also tracer test was carried out in the system of Postojnska Jama, to compare mass (artificial tracer) and heat (natural tracer) transport. Results show that first appearance of the mass at the measuring stations is equal to transit time of temperature signal.
Aquifer studied on regional scale stretches between Planinsko polje in the south and springs of the Ljubljanica River in the north. Underground water is accessible only in a few caves in the southern part of this aquifer. There we monitored water level and water temperature in caves Vetrovna Jama, Najdena Jama, Gradišnica and Gašpinova Jama. These caves get water mainly from the Planinsko polje, where the Unica sinking River flows. But at least some caves are recharged also by other small sinking streams, which were not monitored. There are two groups of ponors in Planinsko polje and their activity depends on water conditions in the polje. We found

out that regarding to activity of ponors, the Unica River recharges only the Vetrovna Jama through eastern ponors, or Vetrovna Jama, Gradišnica, Gašpinova Jama through eastern ponors, or Najdena Jama, Gradišnica, Gašpinova Jama through northern ponors. Underground connections were tried to explain also by the help of geological structure of the discussed area. The important hydrogeological barrier should appear downstream from four discussed caves, in direction toward springs of the Ljubljanica. Such barrier can explain stage fluctuations in Gradišnica and Gašpinova Jama. Another barrier should appear in direct vicinity of eastern ponors and Vetrovna Jama, with direction S – N. This barrier in large scale prevents underground water to drains also toward north-west; it is forced to drain toward north mainly. Vetrovna Jama is presumably situated on other side (eastern) of this barrier, as other caves (on western side). Consequently, hydraulic characteristics of the Vetrovna Jama are very different as in other three caves.

Key words: karst aquifer, underground drainage, hydraulic restriction, monitoring, transit time, flow velocity, flood pulse, hydrograph, Postojnska Jama, Slovenia.

Hidrogeološki pomen velikih prevodnikov v epifreatični coni kraškega vodonosnika.
Primeri iz porečja kraške Ljubljanice.

Izvleček: Kraški vodonosnik smo preučevali v lokalnem in v regionalnem merilu, in sicer z zveznimi meritvami nivoja in temperature podzemne vode na različnih lokacijah v vodonosniku. Lokalno smo raziskali sistem Postojnske jame, oziroma podzemno Pivko, ki se pretaka skozi ta sistem. Vzdolž njene podzemne poti smo namestili sedem merilcev vodnega nivoja in temperature. Merili smo tudi pretok Pivke pri ponoru. Namen merjenja fizikalnih parametrov je bil preučiti hidravlične procese v podzemlju in določiti hitrost podzemnega pretakanja (oziroma potovalne čase) med sedmimi merilnimi postajami. Ugotovili smo da predstavlja Martelov podor najpomembnejšo hidravlično prepreko v obravnavanem sistemu. Dvig vodne gladine pred podorom je lahko relativno velik, posledično izrazito naraste nivo vode v strugi tudi v gorvodnih delih sistema. Vodni nivo je ob izjemnih poplavah skoraj poravnan med ponorom in Martelovo dvorano. Hitrost pretakanja (oziroma potovalne čase) smo določili na podlagi naravnega sledila (temperature). Vsak dnevni temperaturni vrh (ali sedlo), ki se pojavi pri ponoru, potuje skozi podzemni sitem z neko hitrostjo. Posledično je takšen temperaturni signal na vsaki nadaljnji merilni postaji zabeležen z nekim časovnim zamikom, ki ustreza potovalnemu času tega signala (oziroma vode). Ker so razdalje med merilnimi mesti približno znane, lahko izračunamo tudi hitrosti vodnega toka. Hitrosti se vzdolž podzemne poti zelo spreminjajo. Najvišje so v prvi tretjini sistema (med ponorom in Otoško jamo), kjer dosežejo vsaj 70 m/min (določeno pri pretoku okoli 60 m^3/s). Hitrosti toka so v povprečju najnižje med Martelovo dvorano in Pivko jamo, kjer povprečne ne presegajo 14 m/min. Vendar pa hitrosti toka nismo preučevali v Pivki jami, kjer so domnevno lokalno najvišje, menimo da zlahka presegajo 70 m/min. V Postojnski jami smo opravili tudi sledilni poskus. Namen poskusa je bil primerjati masni transport (umetno sledilo) s toplotnim transportom (temperatura kot naravno sledilo). Rezultati so pokazali, da je prvi pojav sledila na merilnem mestu popolnoma enak potovalnemu času temperaturnega signala.

Vodonosnik, ki smo ga preučevali v regionalnem merilu, se razteza na območju med Planinskim poljem na jugu in izviri Ljubljanice na severu. Vendar je podzemna voda dosegljiva le v maloštevilnih jamah, ki se vse nahajajo na jugu obravnavanega območja. Vodni nivo in temperaturo vode smo merili v štirih izbranih jamah: v Vetrovni jami, v Najdeni jami, v Gradišnici in v Gašpinovi jami. Glavnina vodnega toka priteka v te jame iz Planinskega polja, kjer teče reka ponikalnica z imenom Unica. Nekatere izmed teh jam pa se napajajo tudi z drugih območij, kjer tečejo manjši ponorni potoki, katerih pretokov in temperature nismo spremljali. Na Planinskem polju sta dve skupini ponorov, njuna aktivnost je povezana s hidrološkimi razmerami na polju (pretokom Unice). Ugotovili smo da Unica napaja izključno Vetrovno jamo preko vzhodne skupine požiralnikov, prek istih požiralnikov lahko ob višjem vodostaju poleg Vetrovne jame napaja še Gradišnico in Gašpinovo jamo, ob visokih vodostajih pa poleg že omenjenih še prek severne skupine požiralnikov napaja Najdeno jamo, Gradišnico in Gašpinovo jamo. Podzemne vodne zveze smo poskušali razložiti s pomočjo znane geološke zgradbe obravnavanega območja. Najpomembnejša hidrogeološka bariera se domnevno nahaja nizvodno od vseh štirih obravnavanih jam, v smeri proti izvirom Ljubljanice. Usklajena nihanja podzemne vode v Gradišnici in Gašpinovi jami najlažje razložimo s takšno bariero. Druga pomembna hidrogeološka bariera naj bi se nahajala v neposredni bližini vzhodnih požiralnikov in Vetrovne jame, s smerjo J – S. Ta domnevna bariera v veliki meri preprečuje pretakanje podzemne vode proti severozahodu, zato se podzemna voda večinoma pretaka proti severu. Vetrovna jama se nahaja v neposredni bližini te bariere, oziroma na njeni vzhodni strani, medtem ko ostale tri obravnavane jame ležijo na drugi, zahodni strani bariere. To je eden izmed razlogov, da je hidravlični odziv Vetrovne jame na poplavne sunke precej drugačen kot v ostalih treh jamah.

Ključne besede: kraški vodonosnik, podzemni vodni tok, hidravlična prepreka, zvezno merjenje, potovalni čas, hitrost vodnega toka, poplavni sunek, hidrogram, Postojnska jama, Slovenija.

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1. INTRODUCTION

1.1. A karst aquifer; its definition, importance and characteristics. The problem of underground water dynamics in karst areas.

Karst rocks occupy 15 - 20 % of the Earth's ice-free land surface. About one quarter of the world's population is supplied by karst waters (Ford & Williams, 2007); in Slovenia up to 50 % (Morales et al., 2007). Therefore karst rocks are, beside alluvium, the most important aquifer formations. The protection of karst aquifers, exploitation and maintenance of water quality is essential for sustainable management of water resources in many countries around the world (Kovács, 2003).

As we are dealing with karst underground hydrogeology we should define the term aquifer first:

Aquifer is a rock formation which is capable to retain large quantities of water (White, 1988). It does not only store, but also transmits and especially yields economically significant amounts of water (Ford & Williams, 1989). A characteristic of **karst aquifers** are the solution-generated voids, i.e. a network of large conduits may be formed as a consequence of rock dissolution. Transport of ground water through the conduit system is rapid and often turbulent (White, 2002). A precise definition of a karst aquifer is given by Huntoon (Worthington et al., 2000): “A karst aquifer is an aquifer containing soluble rocks with a permeability structure dominated by interconnected conduits dissolved from the host rock which are organized to facilitate the circulation of water in a down gradient direction wherein the permeability structure evolved as a consequence of dissolution by the water.”

Dynamics of underground water in aquifers with inter-granular porosity (aquifers in unconsolidated sediments) are well known and may be easily described by Darcy's law, due to homogeneity of such aquifers. Darcy's law describes dependence of specific discharge on hydraulic conductivity (considered as constant), and hydraulic gradient. Darcy's law assumes laminar flow. Hydraulic conductivity of mature karst aquifers is usually extremely anisotropic and heterogeneous, due to spatial distribution of the conduit network, which is largely unknown. Therefore the parameterization of such aquifer, where turbulent flow through conduits prevails, is an extremely difficult task. Depending on the development of the karst aquifer, it may be intersected with two or three types of porosity. We tend to describe mature karst aquifer with triple porosity (Bonacci, 1987; White, 1988, 2002, 2003; Ford & Williams, 1989; Brenčič, 1996; Motyka, 1998; Ralston, 2000):

- porous or granular or matrix

Porous permeability is a complex of voids in a small rock fragment. The spaces consist of primary pores (syngenetic voids) and secondary pores (metasomatic and diagenetic). There are not only inter-granular pores, but also micro-fissures and small karst voids.

Porous permeability depends on the age of the rock mass, but pores are generally considered as impermeable (except if they are interconnected). Porous rocks more store water than transmit it.

- fracture or fissure

Fracture or fissure permeability is usually a consequence of solution processes. It affects and enlarges mechanical joints and bedding plane partings (White, 2002; Bonacci et al., 2006).

Fissure permeability is dependent on several parameters: fracture aperture, length, width, turtousity, fracture spacing and wall roughness (Motyka, 1998). Apertures may range from micrometers to at most one centimetre. Their original aperture is in the range 50-500 μm and may be later enlarged by dissolution. Width is quite variable because of the roughness of the fracture walls (Schwartz & Zhang, 2003). Water flow in fractures is laminar, on average it may be considered to follow Darcy's law, or its version Hagen-Poiseulle law (White, 2002).

Rocks with fissured porosity are supposed to be fairly permeable (Gospodarič & Habič, 1976).

- conduit

Conduit permeability of karst aquifers may range from solutionally widened joints and bedding planes of diameter at least 1 cm to pipe like passages many metres in diameter; in extreme conditions more than a hundred metres. Classically they are a few metres wide and kilometres long (Bakalowicz, 2005). Onset of the non Darcian behavior occurs when the aperture of the void exceeds around 1 cm (White, 2002). Flow through such void (conduit) is no more laminar, but turbulent. Distribution of conduits is rare in karst aquifers, they make up only a low percentage of the aquifer cross section, but they transmit 90 % or more underground karst water (White, 1988;

Worthington et al., 2000). Rocks with conduit permeability are therefore considered as very permeable.

Worthington (1999) examined matrix, fissure and conduit porosity in four carbonate aquifers (Silurian dolostone aquifer, Mississippian aquifer, Cretaceous chalk aquifer in Britain and a tropical Cenozoic limestone aquifer). Percentage of matrix porosity is high in all four aquifers, ranging from 2.4 % to 30 %. Fissure and conduit porosity represent a similar percentage. Conduit porosity ranges from 0.003 % to 0.5 % and fissure porosity from 0.01 % to 0.1 % in the four studied aquifers.

Karst aquifer evolves in soluble rocks, which usually results in high heterogeneity and anisotropy. Water dissolves surrounding rocks and increases the diameter of preferred voids. The process of karstification is temporally variable and relatively rapid in comparison with common geological processes. For example, the timescale for evolution of a karst aquifer with integrated karst network is in the range of ten thousand to several hundred thousands of years according to numerical models (Dreybrodt et al., 2005).

Flow and transport in karst aquifer depends on the spatial distribution and geometry of conduit systems. These develop along preferential structures such as fractures (i.e. faults, thrusts, joints) and bedding planes or along other preferential pathways (Bakalowicz, 2005). Groundwater flow will enhance by dissolution particularly those fractures and discontinuities which are sub-parallel to the local hydraulic gradient and which are in the vicinity of the free groundwater table (Kiraly, 2002). Distribution of such prevailing underground pathways is sparse in comparison with volume of the entire karst aquifer. It is not possible to define representative elementary volume, as in other aquifers.

An important characteristic of mature karst is its duality. Interaction of different porosity in karst aquifer reflects in two types of flow: slow and rapid. Slow flow is diffuse and laminar; it occurs through fissures and matrix. Fast and turbulent flow takes place in conduits (Bonacci, 1993). Hydraulic conductivity in karst aquifers spans more than six (up to ten) orders of magnitude (Kiraly, 2002). Duality occurs also in transport and storage capacity. Low permeable fissures and matrix have high storage capacity, in contrast with high permeable conduit network, which has low storativity and high transmissivity (Mohrlok & Sauter, 1999; Peterson & Wicks, 2005).

Matrix and conduits exchange water depending on head gradient. At base flow conditions, the conduits gain water from the surrounding matrix. At flood conditions, head gradient within the conduit becomes greater than the head of surrounding matrix, causing water to flow from the conduits to matrix. Water is then stored in inter-granular porosity and fractures, until the head gradient is reversed again (Martin & Screaton, 2001). Therefore water table is not exactly the same in caves and surrounding matrix. It is changeable in time and space.

Conduits can gain also a significant contribution of water from matrix, especially in some aquifers developed in "young" carbonates (where matrix is extensively fractured and dissolved). Water discharging from certain karst spring can range from nearly all allogenic water to nearly all water derived to conduit from the matrix porosity to feed the spring (Martin & Screaton, 2001).

1.2. Hydrogeological significance of caves

Caves are one of the most characteristic features of mature karst landscape. Ground water flow in caves is localized and under normal gradients flows in a turbulent regime. Such conditions occur when the aperture of conveyer exceeds about 1 cm. Hence, voids with diameter at least 1 cm are considered as conduits. Caves are fragments of conduit network, which are large enough for human explorations (with diameter more than 0.5 m). However, accessible caves usually represent only a minor length of the total conduit network (often even less than 1 %) (White, 2002). Caves can be entered and explored from ponors or springs (Fig. 1). Underground water flow is very rarely accessible along its entire pathway between ponor and spring. Sometimes it may be accessible also through some vertical shafts, collapsed dolines or through artificially widened fissures. Such intermediate water caves are considered as independent caves, until they are physically connected with a neighboring ponor or spring cave.

Caves as a system of connected conduits transmit the great majority of underground water in karst massif. They concentrate and drain the catchment; therefore large amounts of water may drain through caves, with discharges more than 100 m^3/s.

Velocities of such underground flow may be very fast, similar to the velocity of surface flows (rivers).

We treat here water caves which occur in epiphreatic zone of karst aquifer. It is a transitional zone between phreatic zone (permanently saturated zone) and vadose zone (permanently unsaturated zone) (Fig. 1). Hence epiphreatic zone is a zone where saturated and unsaturated conditions change, dependent on water conditions in the aquifer. Water flow in epiphreatic conduit is similar to pipe flow, where both open channel (atmospheric pressure) and full pipe flow (under pressure) occurs (Bakalowicz, 2005). Water levels in epiphreatic zone may fluctuate significantly, even for hundred metres or more, depending on cave hydraulic, recharge characteristics and thickness of the karst massif. Rising and lowering of groundwater level is sudden and rapid. Therefore storage capacity of caves is considered to be low in contrast with their high permeability (Bonacci et al., 2006).

Caves represent suitable measuring points within the aquifer. Karst aquifers have been mainly studied at the springs (Bonacci, 1993; Brenčič, 2002; White, 2002; Kovács, 2003; Toran et al., 2006). Hydro and chemo-graphs obtained at karst springs reflect input and transfer function of karst aquifer. Spring hydrographs provides information about the aquifer geometry and chemo-graphs information about travel times, origin of water, type of flow etc.

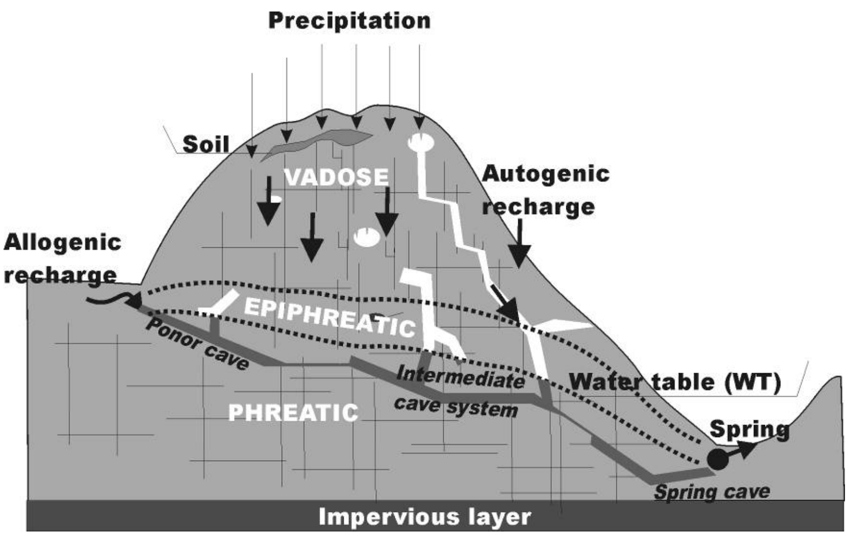

Figure 1: Conceptual model of a karst hydrogeological system with its zonation (adapted from Dreybrodt et al., 2005).

We measured parameters in caves. Physical and chemical parameters can be measured directly in the aquifer, where the majority of the underground drainage takes place. Measured parameters directly reflect the hydrogeological processes within the aquifer (in front and behind the monitored micro-location) and in the drainage basin at the surface (recharge). Bore holes are less representative measuring points, as they rarely penetrate highly permeable structures as conduits (White, 2002; Reinmann et al., 2008).

2. BACKGROUND AND GOALS OF THE THESIS

Hydrology of the caves is relatively poorly known, even in some karst systems where detailed research by combined tracing tests has been performed. In the best case, the epiphreatic zone within karst massif is accessible only at few locations, through often technically difficult cave systems. Autonomous sensors with large storage capacity were either not available or too expensive in near past.

New instruments, which enable continuous monitoring of physical properties (temperature, water level, electrical conductivity) of water flow, have been widely used in water science for a decade. Therefore we decided to use such equipment to measure water temperature and level in caves of Notranjska region (central Slovenia). Data loggers, Divers^{TM}, produced by Van Essen have been used to measure parameters in selected caves (Fig. 2). The temperature accuracy of data loggers is 0.1°C and accuracy of measured water level is ±0.2 % of maximal range (100 or 50 m), according to technical information. Data may be recorded at arbitrary intervals. 10, 15 and 30 minute, sampling intervals were chosen, depending on the system monitored. Intervals should be short enough to detect all important changes in measured parameters.

Moreover, modern caving techniques and intense speleological research have opened some new accesses to the underground flow in Slovenian karst. The number of underground locations (caves), where water flow may be potentially monitored, has increased during the last few years.

Because of these reasons we think that there is a new opportunity to study groundwater flow in karst aquifers.

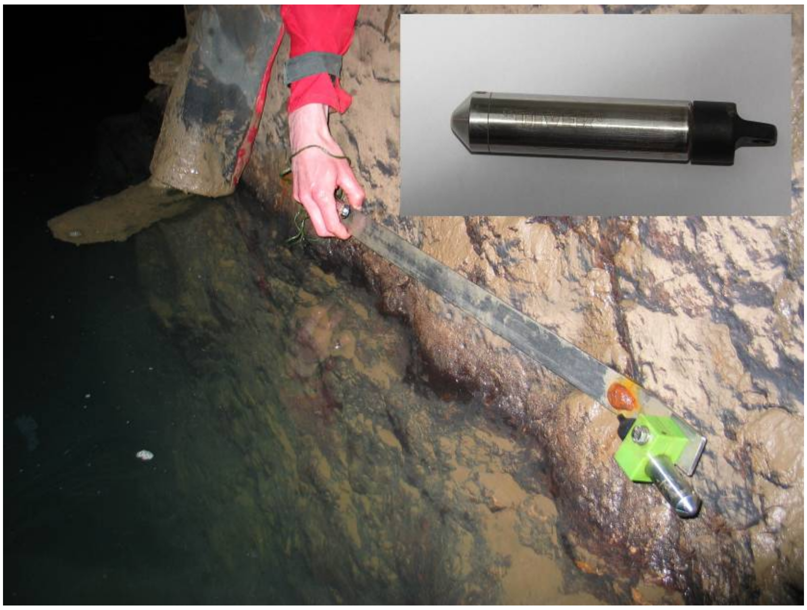

Figure 2: Data logger, which we used to measure level and temperature of underground water in caves (Photo: F. Gabrovšek).

We have two main goals:

1. To improve the knowledge about ground water dynamic within karst aquifer based on the study of flow and transport on local and regional scales.
2. To demonstrate the application of new equipment in karst hydrogeology. Data loggers have been produced to measure parameters of surface waters and underground waters in drilling wells. Their application in water caves (epiphreatic zone of karst aquifer) has been much less demonstrated. They are used for the first time in Slovenia, to monitor karst underground water which recharges Ljubljanica Springs (Notranjski kras, central Slovenia), and the underground Reka River (Karst plateau, SW Slovenia) (Gabrovšek & Peric, 2006).

Due to the heterogeneity of karst aquifer, we decided to study and describe its functioning on both scales, local and regional:

- Monitoring of underground flow through one single conduit system with known geometry has been established on **local scale**. The main idea of such research is to improve the understanding of flow and transport through a continuous and well defined conduit system in the epiphreatic zone of the karst aquifer. Furthermore, basic hydraulical (hydrogeological) processes may be directly observed by measurements. Such processes are propagation of flood pulse through the conduit, media (mass) transport, transport of thermal signal and thermal interaction between water and bedrock. All these processes can be qualitatively and maybe also quantitatively defined within the studied conduit.

- **Regional** hydrodynamic of underground water in mature karst aquifer is difficult to asses. Each karst aquifer has its specific hydrogeologic and hydraulic characteristics, which have to be determined by measurements or numerical modeling. To study a system accurately, an underground flow should be accessible in numerous continuous and spatially distributed caves within the aquifer. But reality in karst is different. Underground water is accessible in a few caves only and their distribution within the aquifer is usually far from regular.

Even though only few locations in the aquifer are possible to monitor, we may try to interpret regional flow due to high frequency measurements in known water caves. Measurements in disposable water caves may be applied to evaluate hydrodynamic and recharge characteristics of the certain aquifer. Studied systems may be evaluated from hydrological and hydrogeological points of view.

At the same time, we would like to verify general hydraulical (hydrogeological) principles in the epiphreatic zone of karst aquifer, obtained by measurements. Such measurements in water caves have not been done before in Slovenian karst. Nor has it been common hydrogeological practice elsewhere in the world. The main question is again the representativity of such measurements, based only on a few locations within the aquifer.

3. A BRIEF OVERVIEW OF APPLIED METHODS

Analytical and field methods applied in this work are described below. Field methods represent a basis for further analytical work. Data may be collected automatically by modern devices or manually. Automatic data loggers are in widespread use today in hydrology and hydrogeology. Field methods to collect hydrogeological data manually are represented only. Analytical methods deal with processing and analysing of data by various statistical and modeling computer programs.

3.1. Methods of data analysis and modeling

3.1.1. Mathematical models

Two different modeling concepts in karst hydrogeology are represented by global and distributive models.

3.1.1.1. Global models

Global methods are based on the analysis of spring discharge and precipitation time series. According to this method, karst system can be considered as transducers that transform input signal (recharge) into output signal (discharge). Output data reflect hydraulic characteristics of bulk underground system, but the spatial heterogeneity and structure of karst underground is neglected, so only qualitative interpretation is possible (Brenčič, 2002; Petrič, 2002; Kovács, 2003; Sauter, 2005).

Detailed analysis of rising and recession limbs on hydrographs

This method belongs to global model approach and is mainly used to interpret spring hydrographs. The method may be roughly used to interpret fluctuations of water level within epiphreatic zone of karst aquifer (in water caves). After a single rainfall event discharge through caves increases, but with some time delay due to storm event. The crest may be roughly divided into three main components: rising limb, flood recession and baseflow recession (Fig. 3.1). The decreasing limb may be further divided into several exponential segments. Some theories assumed that different segments represent parallel reservoirs, which all feed spring discharge (or total discharge through cave in our case). Such reservoirs were interpreted as conduit network, intermediate fissured system and low permeability network of pores. But recession segments (especially base flow recession) do not depend only on the hydraulic properties of the low permeability matrix. They depend also on global configuration of the aquifer, geological and morphological structure of the catchment area (Kovacs, 2003).

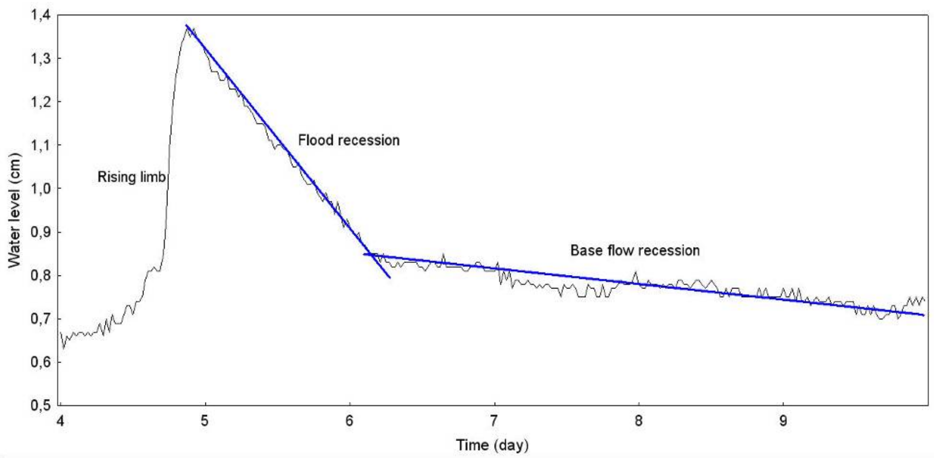

Figure 3.1: Hydrograph can be divided to three basic components: rising limb, flood recession and base flow recession (example is from Najdena jama).

Inflection points on the hydrograph can be caused by a change in characteristics of an underground or surface karst reservoir. Changes may be in the micro-regime flow through the karst aquifer. Such for example is a change from transportation to storage capacity due to the decrease of water table underground (decrease of the underground catchment area) and decrease of effective porosity with depth. Or it could be a sudden change in the active surface area of the aquifer or in catchment area (Bonacci, 1988 and 1993).

Inflection points or segments in the recession curve are linked with variation of recession coefficient, which may be calculated from discharge data. As it is impossible to measure discharge in caves where water stagnates during the floods, we cannot really calculate recession coefficient. But we can observe the slope of different segments of the recession curve and try to explain inflection points and inclination of segments with flow regime through the aquifer or with some hydrogeological, geological or morphological processes. The purpose of hydrograph analysis in the epiphreatic zone of the karst aquifer is to find out some of such hydrogeological characteristics.

3.1.1.2. Distributive models

Quantitative interpretation of spatial and temporal variations of hydrogeological parameters of karst aquifer may be done by distributive method. However, it requires sufficient information about aquifer geometry, hydraulic parameter fields and recharge conditions (Kovács, 2003). The distributive method incorporates two concepts:

- A discrete concept describes flow within networks of fractures or conduits (Sauter 2005). This method assumes different structures of karst aquifer and a simplified geometry of conduits. It can be used to assume the amount of underground water flow or aquifer's response to a certain storm event (Halihan et al., 1998).
- A continuum concept treats heterogeneities in terms of effective model parameters and their spatial distribution (Kovács, 2003).
- A hybrid model is a combination of both concepts (Sauter 2005), where network of discrete fractures and conduits is embedded into a matrix. Hybrids are for example double continuum models and discrete-continuum models.

Storm Water Management Model (SWMM)

As an example of distributive model, we applied Storm Water Management Model (SWMM) to study temporal and spatial variations of hydrological parameters in the epiphreatic zone of aquifer with well developed conduit permeability.

SWMM was designed to simulate flow and solute transport in a sewer system. The program is very versatile; it could be applied to conduit karst system with well known geometry. Pipes may be interpreted as conduits and junctions between them may represent reservoirs and (or) inputs such as sinkholes. Amount of surface water that enters the system (recharge) may be set arbitrarily. Other variable parameters are length and cross-section of pipes (conduits), hydraulic gradient (the slope of the conduit) and Manning's roughness coefficient of the conduit. All these parameters should be at least approximately known for certain underground system, to apply SWMM. Disadvantage of the SWMM is that it does not enable lateral exchange between conduits and matrix (Peterson & Wicks, 2006).

Application of “Storm water management model” (SWMM) computer program is to simulate realistic underground systems with known geometry. Geometry of the cave system is usually very complex, but it may be simplified for model purpose. Also recharge (input) in the system should be known. It may be measured at the ponor, if the system is fed by allogenic recharge and no significant lateral inflows occur underground. Input of flood pulse may induce ponding of water in some parts of the system (reservoirs), due to occurrence of hydraulic restrictions (rock-fall, weir, channel narrowing). Realistic and modeled hydraulic responses are therefore dependent on hydraulic characteristics of the system.

3.1.2. Time series analysis and statistics

Data, with which we correspond, are measured typically at successive times, spaced at uniform time intervals. Such data are called time series. **Time series analysis** comprises methods to identify the nature of the phenomenon represented by the sequence of observations or to forecast of the time series variable (predicting future values). Both approaches require that the pattern of observed time series data is identified and more or less formally described. Once the pattern is established, it can be interpreted and integrated with other data (Hill & Lewicki, 2007).

Time series analyses are univariate (auto-correlation, spectral analyses) and bivariate (cross-correlation and cross-spectral analysis). We applied or at least test the data with following time series analyses:

- **Autocorrelation method** may be used to identify some overall characteristics of a time series, such as cyclic variations. The autocorrelation method compares the time series with itself.
- **Spectral analysis** is a tool for demonstrating periodities within the time series, such as diurnal temperature periodities of surface streams.
- **Smoothing** is based on averaging of data, such that the non-systematic components of individual observations cancel each other out. The most common technique is moving average smoothing which replaces each element of the series by either the simple or weighted average of *n* surrounding elements, where *n* is the width of the smoothing "window" (Hill & Lewicki, 2007). We applied smoothing to correct small disturbances, which may permanently occur during measurement of stage as a proxy of discharge.

We represent all data graphically on two-dimensional line plots, scatterplots and also box plots. We applied mainly **basic statistics** (mean, variance, correlation coefficient, maximal – minimal value etc.) to process and describe the data.
Sratistics StatSoft 6.0 was applied to study relationship between surface stream as main recharge source and underground stream in a nearby aquifer. Hydrogeological parameters (water level and temperature) gained in caves were compared with parameters gained on recharge areas (water level, discharge and temperature). Based on correlations we determined recharge and hydraulic characteristics of caves (at different water conditions).

3.1.3. Tracing test and application of QTRACER2 program

Tracing test with artificial dyes is an important part of this research and was performed in system, which is studied on local scale.
Tracer tests are increasingly used to simulate the transport, fate and attenuation of different types of contaminants in vadose and saturated zone of karst aquifer (Benischke et al., 2007; Morales et al., 2007). Only sophisticated quantitative ground-water tracing study may well define hydraulic processes in the underground. According to quantitative tracing studies, parameters such as tracer mass recovery, mean residence time, mean ground water flow velocities, longitudinal dispersion and maximum volume contact may be determined. Moreover hydraulic processes such as dispersion, divergence, convergence, dilution and storage may be evaluated. Flow channel geometry parameters are estimated by evaluating discharge with respect to mean residence time. Parameters of flow channel geometry are volume of the aquifer, cross-sectional area, flow-channel diameter, flow-channel hydraulic depth, flow-channel surface area and tracer sorption estimation (Field, 2002).
Artificial tracer Sulphorhodamine G was applied. It is a water-soluble tracer, with detection limit 10^{-2} µg/L; it is absent in natural background and safe of human toxicity (Benischke et al., 2007). Tracers in the underground river were detected by means of field fluorometer (Fig. 3.2). The field fluorometers GGUN-FL24 were fixed into the river bank. The fluorometers have quadruple excitation and detection axes, allowing simultaneous use of three tracers and independent turbidity measurement. They were preliminary calibrated for the Amidorhodamine G and turbidity (Schnegg & Bossy, 2001; Gabrovšek et al., 2010).

Fluorescence of manually or automatically (ISCO 6700) sampled waters was measured in laboratory by a luminescence spectrometer LS 30, Perkin Elmer: Amidorhodamine G at E_{ex}=531 nm and E_{em}=552 nm with detection limit of 0.04 ppb. First measurements were carried out immediately after sampling and then also later when possible suspended particles in the samples were decanted. Low, uncertain concentrations were additionally tested several times (Gabrovšek et al., 2010).

The results were quantitatively evaluated by QTRACER2 Program. Program is used to analyse tracer breakthrough curves. Shape of tracer breakthrough curve for hydrological systems depends upon the character of the tracer, prevailing flow conditions and structure of the aquifer. Therefore all previously mentioned parameters can be found out by detail numerical analysis of breakthrough curve.

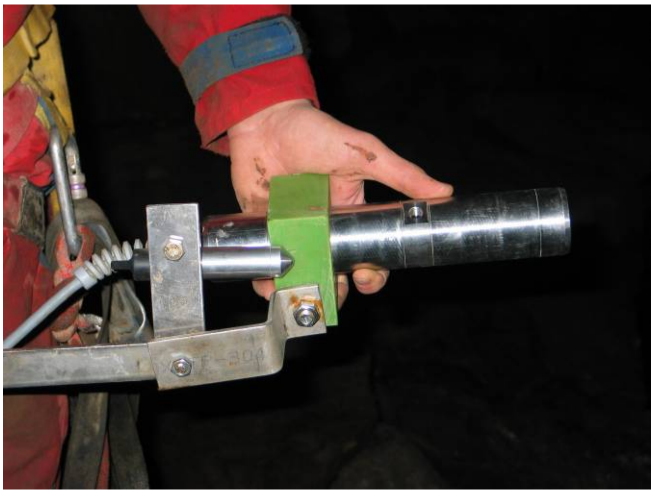

Figure 3.2: Field fluorometer, which was fixed into the bank of underground river (Photo: Janez Turk).

3.1.4. Data mining method

The data mining method is concerned with finding patterns in data, by using different algorithms. Discovered patterns are reliable if they are valid on new data with some degree of certainty and they should lead to some actions that are useful. Data mining include predictive modeling (classification and regression), clustering (grouping similar objects) and summarization (as exemplified by association rule discovery) (Džeroski, 2001).

Data which we use are numerical. We analysed them by a regression for the purpose of predictive modeling. With known recharge, we predicted hydraulic response of the local studied system at each of monitored location.

3.2. Field equipment methods - measuring of discharge

3.2.1. Basic methods to measure discharge of natural streams

Three standard methods are broadly used to measure discharge of streams in natural channels: cross-sectional current metering, dilution method and the use of weirs. Each method is suitable for a different type of channel (Hudson & Fraser, 2002). The choice of method also depends on volume, geometry and accessibility and range of values of the flow to be measured (Groves, 2007).

- Current meters are devices that measure water velocity. The discharge is equal to a flow's mean velocity times its cross-section area (Groves, 2007). Current meters are the most suitable for application in channel subsections with known depth, width and relatively “laminar flow”. Total discharge is calculated from subsection discharges. They represent the product of subsection flow velocity, width and depth of subsection (Capesius et al., 2004). Usage of hand-held flow meter requires a bridge or boat, especially in deep water channels. Hand-held flow meters are totally useless in turbulent conditions.

- On the contrary, the dilution method is much more suitable for discharge measurements of turbulent, torrential streams with steep slopes, steep gradient and rough channels (Hudson & Fraser, 2002; Moore, 2005). Such streams occur especially in mountains and karst (underground) areas. According to Moore (2005), the precision of discharge measurement with dilution method is ± 5 % under suitable conditions.

Technique of tracer dilution is based on the conservation of mass law. A known mass of tracer is injected into stream which distributes downstream uniformly across the channel. The tracer can be added to the channel by continuous or slug injection. Concentrations of the tracer are measured downstream at the gauging

station, until tracer passes it by. According to the tracer concentrations measured at the gauging station, discharge can be calculated (Capesius et al., 2004).
Different substances can be used as a tracer. It is important that they satisfy some criteria, such as fast dissolving in water, harmless to human and water organisms, detectible in low concentrations, absent in natural stream water (Rantz et al., 1982).
The most used and inexpensive tracer is salt (NaCl). Other tracers are radioactive elements (gold 198 and sodium 24) and dye tracers such as rhodamine dye, fluorescent dye, sodium dichromate (Rantz et al., 1982).

- Weirs are artificial regulations in the streams. Discharge can be calculated due to the level of water, which spills over the weir. Discharge is calculated from equations, which are various, depending on the geometry of the weir (Steinman, 1999).

Hand-held current meter and tracer dilution technique are used together with continuous stage measurements, which are nowadays automated. Discharge is measured periodically to develop stage-discharge relation - known as rating curve (Fig. 3.3). When it is done, stage measurements can be directly converted into stream discharge. Hence, such techniques can be time consuming and sometimes difficult (Groves, 2007).
On the other hand, weirs may be used to convert water level directly into discharge, using mathematical formulas, based on the weir properties (Steinmann, 1999). Weirs are usually used to measure low flow volumes.

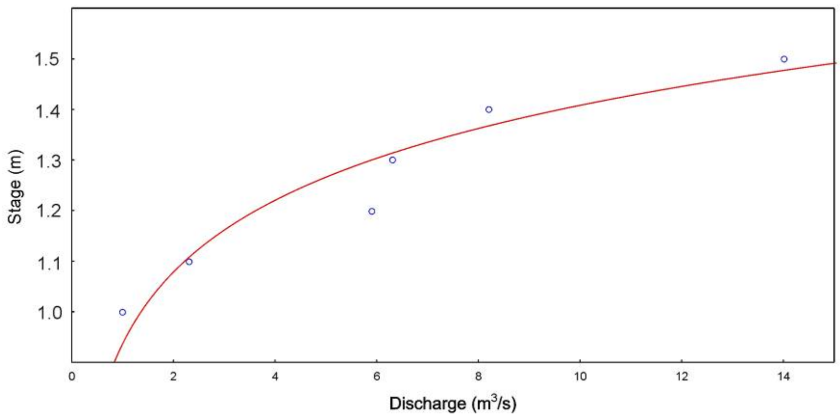

Figure 3.3: Rating curve. Blue dots are actual measurements, fitted by a rating curve (red).

3.2.2. Discharge measurement in karst underground

Discharge measurements of underground streams in caves are generally analogous to the discharge measurements in surface stream channels. Although when conduits become filled it is quite a different situation (Groves, 2007).

Three discussed techniques are usually used to measure flow rate (discharge) of surface and also concentrated underground streams, however their application to measure flows in karst underground is often limited. There are a lot of limitations associated with access to the cave and underground flow respectively. Even if the cave is easily accessible with a tourist footpath leading through it, it is difficult to measure high discharge from practical and safety reasons. Flow rate of underground streams may be high, and water flow may be highly torrential and turbulent. In such a case the dilution method is the most suitable. If salt is used as a tracer, large masses of salt should be carried to the cave.

Because of all these reasons, it is much easier to measure discharge of the stream at the surface, before it sinks underground. But if we are interested in underground discharge through a certain part of the cave which belongs to a large underground system with many underground tributaries, the dilution method would be the best choice. Discharge was measured by this method in a cave system studied on local scale, where underground flow behaves very similarly to torrential flow.

A suitable method to measure discharge of the sinking river at the ponor (as an input) was developed later. SWMM computer program was applied to model stage-discharge relation in combination with calibration based on discharge measurement by the dilution method.

Rating curve for the river (the Unica River), which recharge aquifer was studied on regional scale, was obtained by a Environmental Agency at the Ministry of the Environment and Spatial Planning of Slovenia. Hence we measure stage only, and even that automatically. If we have to measure discharge of this river by ourselves, the most appropriate would be method by current meter, due to the morphology of the riverbed and flow characteristics.

3.2.3. Description of dilution method

Salt is an inexpensive and readily available tracer, so it is the most common used as a tracer in this method. We used it also; hence description of methodology of tracer dilution is therefore based on salt as a tracer.

First the mixture of water and a certain mass of salt was stirred in a barrel to obtain a saturated salt solution, which was injected to the underground stream. Injection may be continuous or slug. We applied slug injection only.

It is important to estimate roughly the discharge, before salt solution is injected into the stream. Different authors advise to use from 0.2 kg to 5 kg of salt for every estimated cubic metre per second (Moore, 2005). According to Kite (1993) not more than one to two kilograms of salt per every cubic metre per second should be used, if we do not want to harm aquatic organisms. If we use too little salt for the solution, results will be less certain and calculated discharge will have possibly a higher error. Too much salt certainly does not diminish accuracy of measurement, on the contrary, but it could harm water organisms or even cause their death (Kite, 1993).

Concentration of the tracer is measured indirectly downstream from injection site. Tracer must be completely mixed across the stream width at measuring station. Instead of salt concentration, electrical conductivity (μS/cm) is measured. However, both parameters are in linear relationship (Hudson & Fraser, 2002). The gauging station should be chosen carefully. If it is too close to the injection place, the tracer would not mix completely throughout the water flow. After injection, the dispersion takes place in all three dimensions within the stream. Mixing distance may vary and it is strongly influenced by discharge (flow velocity) and also water temperature. After the mixing is complete, the concentration of tracer is constant across width and depth of stream channel. If not, the measured discharge would be underestimated where concentration would be too low or overestimated where concentration would be too high (Kite, 1993). Even when mixing is complete, distance between injection and gauging stations should not be too large for practical reasons. Sampling period prolongs with distance, while wave of electrical conductivity extends, due to peak reduction (Fig. 3.4) (Rantz et al., 1982). If we do not have very accurate conductance meter, error may be higher with longer distance.

The optimal mixing length (L) can be estimated (calculated) by following equation (Kite, 1993):

$$L = 260\sqrt{w*d} \qquad [m]$$

where *w* is the average water surface width [m] and *d* [m] is the average stream depth.

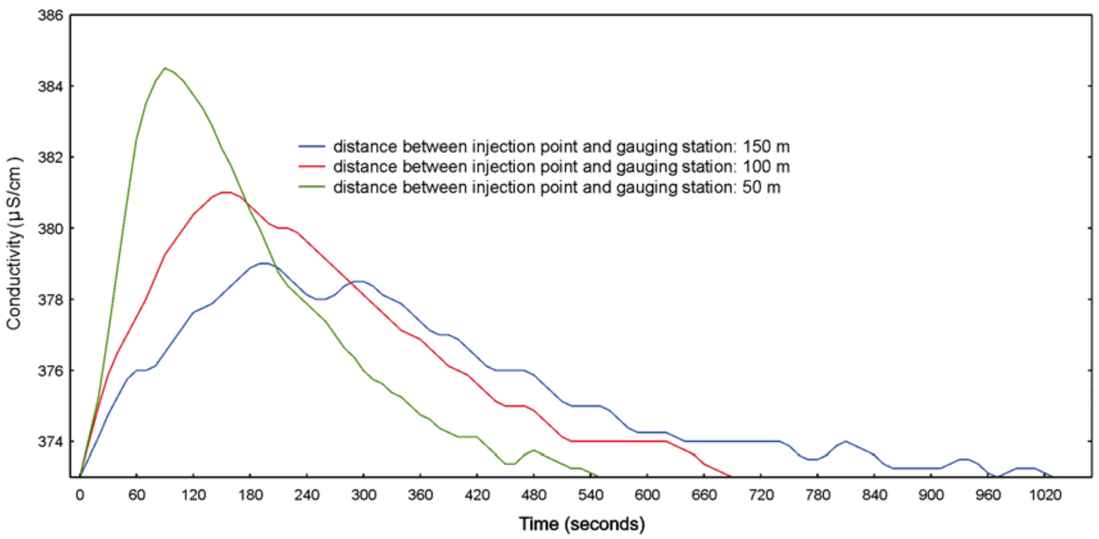

Figure 3.4: Breakthrough curve of salt-dilution method regarding to various injection-gauging distances. As distance between injection and gauging sites increases, breakthrough curve extends. All measurements were performed at the same discharge conditions.

After the transition of all the injected tracer, natural (or background) stream conductivity is reestablished and measurements can cease. The measured conductivities (σ) can be converted to mass concentration C_m by

$$C_m = K*(\sigma - \sigma_{\min})$$

where:

K is the slope $dC/d\sigma$, which is determined in the laboratory, using the stream water.

σ is conductivity of stream water measured at specific time during transition of wave of electrical conductivity [µS/cm],

σ_{min} is natural (background) conductivity of stream water [µS/cm].

To determine K, calibration should be done. Different methods can be used, if the calibration has to be done in the field (Rantz et al., 1982; Kite, 1993; Hudson & Fraser, 2002; Moore, 2005). We used two points calibration in the range of measured conductivity. 0.1 gram of salt was dissolved in 5 litres of stream water to get C_{max} and σ_{max} and non-salted water was used for C_{min} and σ_{min}. Hence,

$$K = \frac{C_{\max} - C_{\min}}{\sigma_{\max} - \sigma_{\min}}$$

Tracer-dilution discharge measurements rely on the conservation of mass law. Hence, the relation between discharge $Q(t)$, mass of used salt M and time dependent mass concentration $C_M(t)$ is given by:

$$M = \int_0^t Q(t)\, C_M(t) dt$$

For steady flow, discharge is calculated as:

$$Q = \frac{M}{\int_0^t C_M(t)\, dt} = \frac{M}{\sum_{i=0}^{i_{\max}} C_{M,i}(t)\, \Delta t_i} \qquad [m^3/s] \qquad (3)$$

where t is the duration of transition of tracer wave and Δt is the sampling interval (both in seconds) (Kellerhals & Church, 1973).

3.2.4. Computation of discharge by applying SWMM and calibration of rating curve with dilution method

We measured discharge, as an input into caves system studied on local scale, directly at the ponor. The most adequate and simple method to evaluate discharge for chosen micro-location is based on stage measurements and application of SWMM computer program.

Cross-section of bottom of the conduit, just behind the ponor, where gauge station is installed, was measured by geodetic equipment (Fig. 3.5). Ceiling is more than 20 m above the bottom of the conduit, left and right banks are vertical, water level does not ever reach ceiling at this section. For these reasons, transect may be considered as a surface channel transect, where water level never spills over the river bank. Transect was transferred into the SWMM, where additionally a roughness coefficient can be set for both left and right banks and the riverbed. Roughness coefficients were estimated from the literature (Rossman, 2004; Peterson & Wicks, 2006).

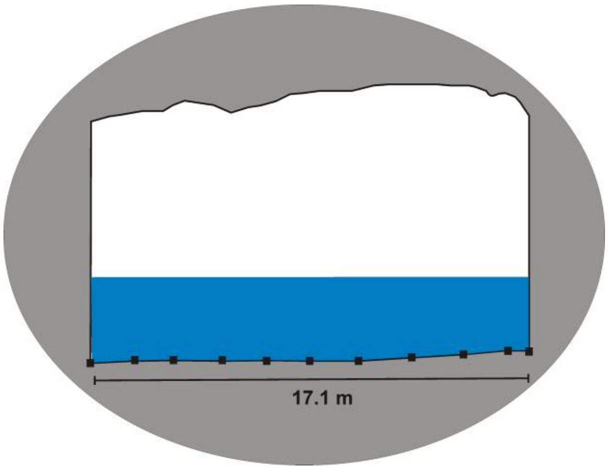

Figure 3.5: Cross-section of the conduit at certain location in Postojnska jama was measured with geodetic equipment. We measured variation of elevation of the conduit bottom at every 1.5 to 2 m.

Some fictive, regularly increasing inflow was routed through the SWMM, to obtain relation between water level and discharge at discussed transect (stage-discharge relation). The diagram was calibrated by data obtained and measured in situ, i.e. discharge was once measured by salt injection method at certain stage (water level). Roughness coefficient of conduit bottom and banks was set to such a value that discharge measured by salt dilution method fits well to stage-discharge curve of the SWMM. Therefore some relatively good stage – discharge relation was obtained (Fig. 3.6).

The rating curve was divided into three segments (Fig. 3.6). Polynomial relation of stage-discharge is given for each of the three segments. Based on these three polynomial equations, stage data from this gauge station can be directly converted into discharge. Data were measured at frequency of 10 or 15 minutes, which is also a resolution of discharge data.

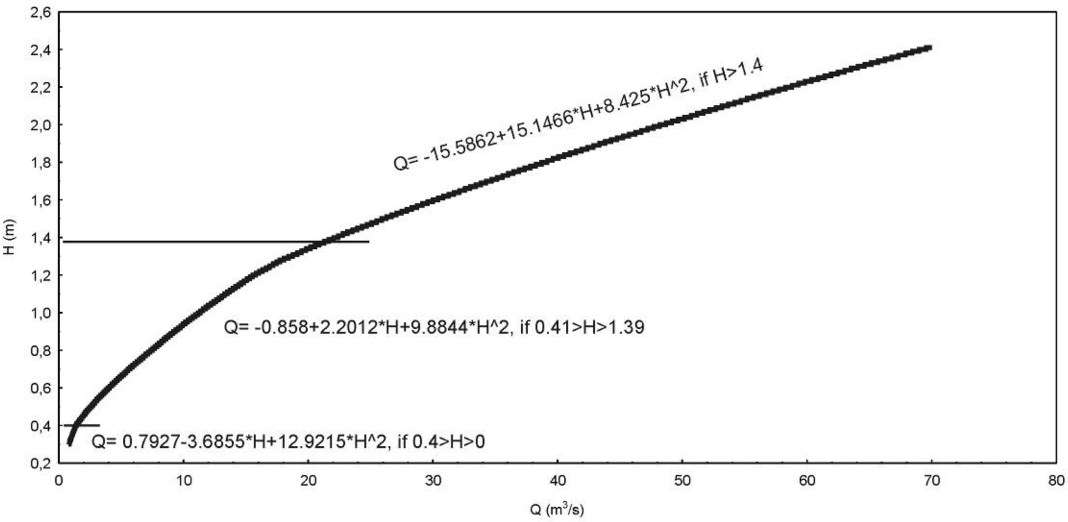

Figure 3.6: Rating curve for the Pivka River, which recharges the system studied on local scale.

4. RESEARCH AREA

4.1. Geographical description

The drainage basin of Ljubljanica River belongs to kras of Notranjska region (central part of Slovenia). Characteristics of Notranjski kras are high Dinaric karst plateaus, low valleys and poljes. Dinaric plateaus are Snežnik (1798 m), Javorniki (1216 m), Nanos (1313 m), Hrušica (1240 m), Trnovski gozd (1495 m) and Krim (1107 m) (Fig. 4.1, Snežnik and Trnovski gozd Mts. are already out of the map).

Valleys are Postojna – Pivka valley, which is considered also as a basin (600 to 500 m a. s. l., surface area 50 km^2) and Rakov Škocjan karst valley (510 – 500 m a. s. l., surface area less than 1 km^2). Poljes are Babno (750 m a. s. l., 4 km^2), Loško (580 m a. s. l., 12 km^2), Bloško (720 m a. s. l., 13 km^2), Cerkniško (550 m a. s. l., 36 km^2), Unško (520 m a. s. l., 3 km^2), Planinsko (450 m a. s. l., 16 km^2) and Logaško (480 m a. s. l., 6 km^2) (Gams, 1974).

Some poljes are periodically flooded (Cerkniško and Planinsko polje) some are flooded very rarely (Loško, Unško and Logaško polje).

The entire catchment of Ljubljanica River spans between the Ljubljansko barje (barje means moor) (where springs occur, 300 m a.s.l.) in the north and Snežnik Mountain (1798 m) in the south. In the west it borders with Trnovski gozd high karst plateau, Vipava and Idrijca valleys; in the east with Želimeljščica valley and Ribnica-Kočevje polje. Studied area belongs to extreme NW part of Dinaric karst which is known also as “Classical karst” (Gospodarič & Habič, 1976).

4.2. Hydrological characteristics of the research area

The Ljubljanica River is 41 km long and it belongs as the Sava affluent to the Danube part of Black Sea water basin. Its total (karstic and non karstic) catchment area is 1780 km^2, with 1792 mm of annual precipitation and annual mean runoff of 31.36 $l/sec/km^2$. Limestone surface represents 48 % of the whole basin, dolomite 27 %, quaternary sediments 18 % and other sediments 7 % (Breznik, 1998).

Ljubljanica emerges in many springs at the border of Jurassic limestone and Quaternary sediments, which fill tectonic basin of Ljubljansko barje moor (Pleničar et al., 1970). Majority of the spring’s catchment area is karstic, calculated as 1109 km^2 (Šušteršič, 2000a).

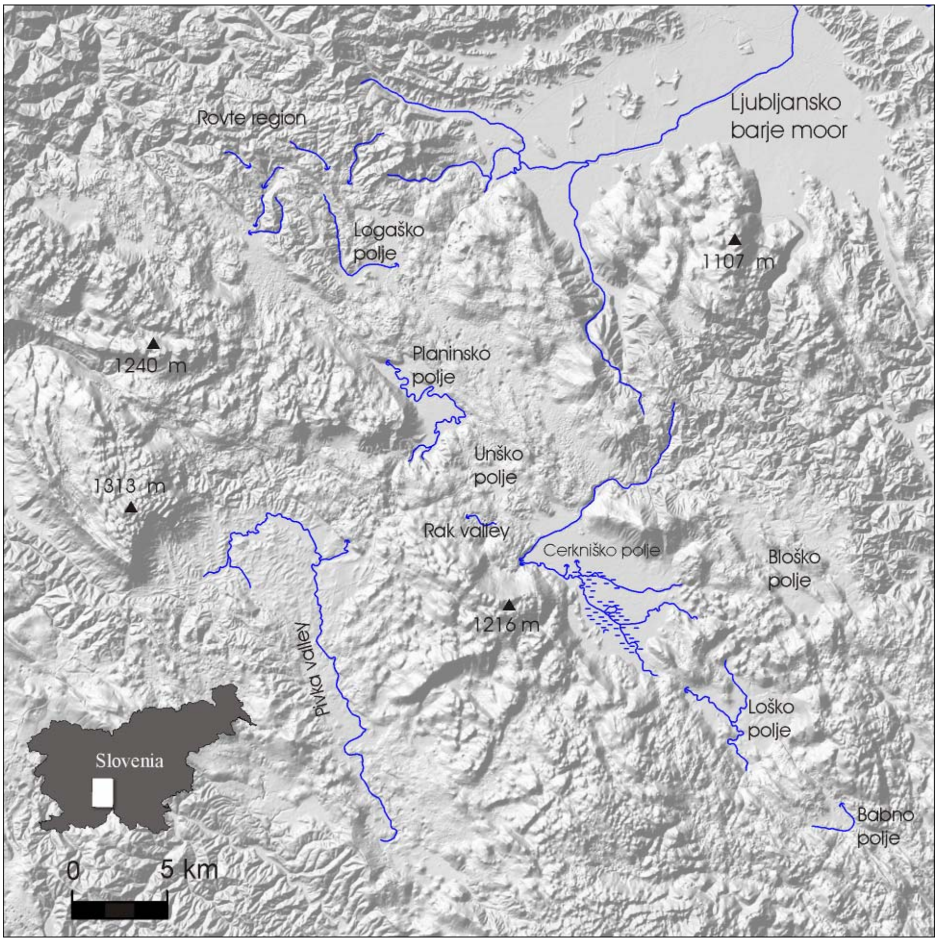

Figure 4.1: Map of Ljubljanica River drainage basin; only the most important surface water flows are shown, given heights represent the highest points of high karst plateaus: 1313 m is Nanos Mt., 1240 m is Hrušica Mt., 1216 m is Javorniki Mts. and 1107 m is Krim Mt.

Catchment area is considered as one of the most complex in Dinaric karst. It cannot be accurately defined because Ljubljanica springs gather waters from regions where bifurcation towards Black and Adriatic Sea occurs (Gams, 1974 and 2004).

The mean annual precipitation at the karst of Notranjska is around 1300 mm at poljes and valleys, while it is up to 3000 mm at the high karst plateaus (Gams, 1974). All precipitation disappears underground as autogenic recharge in high karsts plateaus. These waters may drain directly toward springs (as Ljubljanica springs) or may feed sinking streams.

Surface water flows or sinking streams appear in poljes, which are composed of relatively less permeable rocks (dolomite, flysch) or covered with Quaternary sediments. Poljes are of overflow (Planinsko and Loško polje) or of border (Babno, Cerkniško, Logaško and Bloško poljes) types, Unško polje is dry (Šušteršič, 1996). Also the Postojna – Pivka basin may be treated as border (Gams, 1974) or peripheral polje (Šušteršič, 1996) according to some interpretations.

Sinking streams are Trbuhovica, Obrh (mean annual discharge 3.12 m^3/s), Stržen (m. a. d. 9.2 m^3/s), Rak (m. a. d. 9.85 m^3/s), Pivka (m. a. d. 5 m^3/s) and Unica (m. a. d. 26 m^3/s) (Žibrik & Pičinin, 1976; Breznik, 1988). As soon as surface streams reach karst rocks, they sink underground again. Underground streams finally emerge near Vrhnika and Bistra in the northern margin of Notranjski kras. All springs occur at the contact of karst rocks with Quaternary sediments, which cover the tectonic basin of Ljubljansko barje moor. Waters from springs converge into one non-karstic river of Ljubljanica.

Postojna – Pivka basin with its karstic hinterland represents the most SW part of the Ljubljanica River catchment area. There are two important surface streams: the Pivka River and its affluent the Nanoščica stream. The Pivka River sinks underground into Postojnska Jama. After about 10 km of underground flow, water emerges in Planinska Jama as the Unica River. It continues as a surface flow over Planinsko polje and disappears underground through many ponors disposed along the eastern and northern margin of the polje.

Planinsko polje represents confluence with another important water flow coming from SE. The Trbuhovica sinking stream represents the origin of this water flow. It is also the most remote stream, which feeds Ljubljanica springs. Trbuhovica has its source and ponor in Babno polje. It emerges at Loško polje as the Veliki Obrh stream and the Mali Obrh stream. Obrh sinks into Golobina cave, from where underground water drains to Stržen spring on Cerkniško polje. Also streams from Bloško polje drain underground to Cerkniško polje. Waters from Cerkniško polje drain underground through numerous bottom swallow holes directly to Ljubljanica springs and from marginal ponors (Cerkniščica and Stržen streams) to Rakov Škocjan valley (the Rak River) and further to Planinsko polje (Fig. 4.1).

All waters from Planinsko poje disappears underground through many marginal ponors, which drain water underground directly towards Ljubljanica springs.

Part of the water (coming from non-karstic Logaške Rovte in the NW) is collected in the Logaščica (with mean annual discharge 0.5 m^3/s), which sinks underground in

Jačka ponor at Logaško polje. There are many other small sinking streams in Logaške Rovte, some of them drain water not only toward Ljubljanica springs (Black sea watershed) but also toward the Idrijca River (Adriatic sea watershed).

4.3. Geology of the area

The area which is studied in this work is represented in the Basic geological map of Slovenia (1:100,000) on the Postojna sheet (Fig. 4.2). Lithology and tectonic of Postojna sheet was described by Pleničar et al. (1970). Also Buser et al. (1976) and Čar & Gospodarič (1984) wrote about geology of the area between Postojna, Planina and Cerknica. Tectonic characteristics of SW Slovenia were described by Placer (1981, 2008), of Ljubljanica drainage basin by Gospodarič (1976) and Gospodarič & Habič (1976) and of Pivka basin (Postojna – Pivka valley) by Šebela (2005).

4.3.1. Lithology

Lithology of the studied area consists of Triassic, Jurassic, Cretaceous and Quaternary rocks. Tertiary rocks (flysch) appear in Postojna basin, elsewhere they are very rare. Some Carboniferous and Permian rocks are located in the most NW area of Ljubljanica drainage basin, but this region was not studied in this survey. Most rocks are carbonates (limestone and dolomite). Quaternary sediments cover poljes as Cerkniško, Unško, Planinsko and Logaško. Also Ljubljansko barje which is situated north from studied area is covered with Quaternary sediments.

Upper Triassic beds

Triassic beds are marked with pink color in the Fig. 4.2. Upper Triassic dolomite of Norian and Retian stage (T_3^{2+3}) appears at SW margin of Planinsko polje and in the eastern and southern slopes of Planinska gora Mountain. Dolomite is stretching also from Planinsko polje towards SE over Unško polje, Rakek, Cerkniško polje and Loško polje. Dolomite forms the bottoms of the all these poljes, but it is covered with Quaternary sediments (except at Unško polje). Triassic dolomite is thrusted over Cretaceous and partly Jurassic rocks at the southwestern margin of Planinsko, Unško and Cerkniško poljes.

In the north, upper Triassic dolomite is followed from Hoterdršica to Idrija and from Logatec to Zaplana and Podlipa valley. It mainly forms also the bottom of the Ljubljana moor tectonic basin.

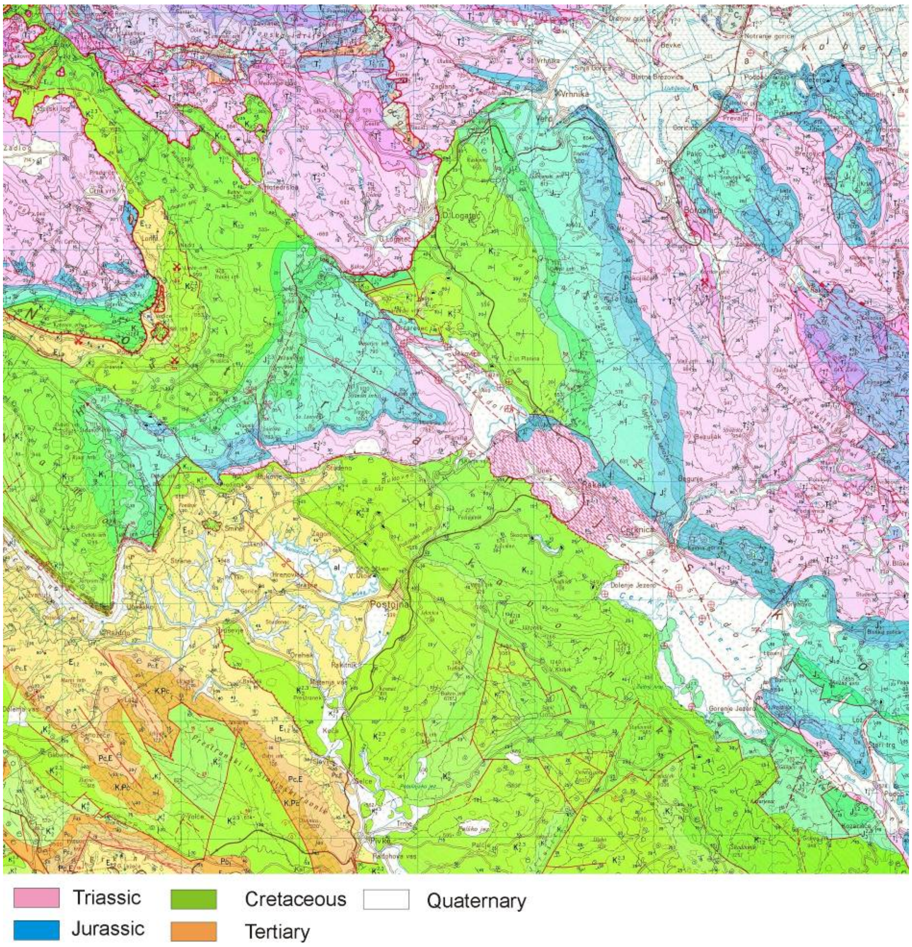

Figure 4.2: Geological map of major part of drainage basin of Ljubljanica springs (situated in the north of the map). Planinsko polje with the Unica River is in the middle of the map, Postojna basin with the Pivka River is in the SW part of the map and Cerkniško polje in the SE part of the map (Reference: Geological survey of Slovenia).

Upper Triassic dolomite is thick bedded (0.5 – 1 metre) and it consists of dark and white microcrystal belts. Near faults it is crushed to milonite breccias. Such crushed zones can be more hundred metres wide and they represent partial barriers for underground water (Pleničar, 1970). However, in comparison with Jurassic and especially Cretaceous limestone, Triassic dolomite is regarded as relatively less permeable and karstified rock (Gospodarič, 1976).

Jurassic beds

Jurassic rocks compose a belt of karst region between Ljubljansko barje in the north and Cerkniško polje in the south (Fig. 4.2, blue colour). These rocks are tilted towards the west (with strike 20° to 40°) and represent the west wing of an anticline with Triassic rocks in the core (east from Jurassic rocks). They are also found west of the Planinska gora Mountain and on the eastern side of Hrušica plateau. Jurassic limestone is six times more frequent than dolomite (Buser et al., 1976).

Lower Liassic beds lie concordantly on Upper Triassic dolomite, western from Planinsko polje. They cover also the area of Krim Mountain and the area north from Cerkniško polje (Pleničar, 1970). Lower Liasic beds are also found in minor extent along Upper Triassic dolomite in the region between Logatec and Vrhnika.

Lower Liassic rocks occur in two lithologycal sequences: the first one is grained dolomite and other represents alternation of bright grey limestone and grained dolomite. Grained dolomite is bituminous and well karstified.

Total thickness of Lower Liassic beds is around 100 to 200 metres and it can vary a lot in horizontal direction (Pleničar, 1970).

Middle Liassic beds contain grey bituminous grained dolomite, grey oolitic limestone and alternation of dolomite and limestone. All beds contain *lithiotis*. Middle Jurassic limestone prevails in the area of Ljubljanica springs, at the northern margin of Planinsko polje and near Cerknica. Total thickness of Middle Liassic beds vary from 100 to 200 metres.

Common thickness of **Upper Liasssic** and **Dogger** beds, which cannot be stratigraphically and lithologically distinguished, is approximately 500 to 750 metres. Sequence is presented by granular and oolitic limestone with inliers of coarse granular bituminous limestone. In these beds the majority of Ljubljanica springs occur (Buser et al., 1976).

Lower Malmian ($J_3^{1,2}$) beds, which are represented by bright gray oolitic limestone, are found in Planinska gora Mountain and in narrow belt alongside Logatec plateau. Limestone beds in Planinska gora contain characteristic horizon with numerous fossils of *Cladocoropsis mirabilis*. Thickness of this horizon is around 40 to 50 metres.

Upper Malmian ($J_3^{2,3}$) rocks lie concordantly on Lower Malmian beds and are found in narrow belt alongside Logatec plateau. Rocks are represented by alternation of white grained dolomite and bright grey limestone. Dolomite is lithologically similar to Lower Liassic dolomite, but it is brighter and not bituminous. Dolomite dominates in the southern part of the discussed area and limestone in the northern part of area. They are both bedded, thickness of entire Upper Malmian sequence is around 200 metres (Pleničar, 1970).

Cretaceous beds

Cretaceous beds lie between Planinsko and Logaško poljes (Fig. 4.2, green colour). These beds overlay concordantly on Jurassic beds, with similar strike. The west wing of this anticline is covered with nappe of Triassic dolomite in the west. Moreover Cretaceous beds are found in Hrušica and Javorniki Mountains and in Postojnski and Pivški ravnik (Pleničar, 1970). Cretaceous rocks are covered by Quaternary sediments in SE parts of Unško and Cerkniško polje (Čar & Gospodarič, 1984).

Lower Cretaceous stage is developed in grey limestone, which contains inliers of grained bituminous dolomite. In those rocks, the principal ponor zones and underground caves are situated along the northern and eastern margin of Planinsko polje. Thickness of Lower Cretaceous rocks is around 1200 metres (Buser et al., 1976).

The **Upper Cretaceous** rocks are represented by organogenic bedded reef limestone, by platy limestone with cherts and by massive rudist limestone in the region between Planinsko and Logaško poljes. These rocks, which belong to Cenomanian and Turonian, are found also north from Postojna. Their thickness is up to 400 metres (Buser et al., 1976).

Eocene rocks

Cretaceous limestone lies in direct contact with Eocene flysch in Postojnski ravnik area. The border between two lithological units can be explained either by tectonic (thrust faults) or by erosional – tectonical discordance (Pleničar, 1970).

Flysch occurs in many erosional remains. It consists of shale, limestone breccias with numulites, carbonate sandstone of Eocenian age and brown – reddish shale (Pleničar, 1970).

Quaternary sediments

Karst poljes as Cerkniško, Unško, Planinsko and Logaško are covered with Pleistocene sediments such as clay, sand and gravel. The thickness of Quaternary sediments on Cerkniško polje is from 5 to 15 metres, on Planinsko polje up to 25 metres, average 4 metres (Ravnik, 1976) and on Ljubljansko barje moor up to 100 metres (Buser et al., 1976). Quaternary sediments are marked with white color in Fig. 4.2.

4.3.2. Tectonic

At least three important **tectonic phases** formed the geologic structure of the studied area of the Ljubljanica River basin (Gospodarič, 1976; Gospodarič & Habič, 1976).

- Erosion discordances were characterized for Middle Triassic.
- The most important tectonic deformations occurred in next phase, in lower Tertiary (Eocene). Rocks were folded and thrust into several geotectonic units with sophisticated stratigrafical and hydrological characteristics. Erosion was significant and karst processes began.
- Significant tectonic movements occurred in upper Tertiary. Faults with NW-SE and NE-SW direction were active. All tectonic units were broken and dislocated by tectonic movements.

The most important is **Idrija fault** with NW – SE direction. Idrija fault composes a wide fault zone with several parallel faults. The wide of this zone is around 0.5 km. Idrija fault stretches from Žaga in Soča valley, to Idrija, Kalce, along NE margin of Planinsko polje, Cerkniško polje, Lož valley and upper Kolpa valley (Gospodarič & Habič, 1976).

Planinsko, Unško, Cerkniško and Loško poljes were formed along tectonic dislocation of Idrija fault. Horizontal movement is supposed to be around 2.5 km. Ponors at Planinsko polje are disposed in crushed zone of Idrija fault (Gospodarič, 1976; Čar, 1982).

Another important fault in the region is **Predjama fault** with NW-SE direction. It stretches from Bela valley to Predjama, Postojna and further towards SE (Gospodarič, 1976).

Tectonic structure of the area

The area of Ljubljanica drainage basin consists of three **tectonic structures**: autochton zone, parautochton zone and high karst or allochton (Pleničar et al., 1970; Gospodarič & Habič, 1976; Placer, 1981; Šebela, 2005).

- **Autochton zone** is represented with Vrhnika – Cerknica block, which includes also Logatec plateau and Bloke plateau. A great part of studied area belongs to this block. It borders to Ljubljansko barje tectonic basin in the north, to Krim Mountain unit in the east and to Rakitna block in the SE. In the NW it borders to Idrija – Žiri block, which already belongs to the drainage basin of the Idrijca River (Adriatic watershed).
- **Parautochton zone** includes Postojna and Pivka basins, Prestranški ravnik and Slavinski ravnik (SW of basin). Only the southern part of basin belongs to parautochton of Komen thrust sheet, while the northern part of the basin belongs to Snežnik thrust sheet (allochton).
- Nanos, Hrušica, Trnovski gozd and Snežnik (with Javorniki) Mountains belong to high karst or **allochton**. High karst is thrusted over the parautochton in the SW. High karst is confined with Idrija fault in NE. Idrija fault therefore represents border between autochton zone (Vrhnika – Cerknica block) in the NE and allochton zone (Snežnik thrust sheet) in the SW.

All structures located NW from Idrija fault belong to inner Dinarides and those located SE from fault belong to External Dinarides.

There are also three small thrust structures or nappes in catchment area of Ljubljanica springs:

Koševnik nappe is formed from Cretaceous rocks and it lies on autochtonous base. It stretches from Idrija towards Logatec. This nappe is very important for underground water drainage. Waters from here drains partly towards the Ljubljanica and partly also towards the Idrijca River.

Čekovnik nappe is composed by upper Triassic dolomite. It is located in the area of Godovič and Hotedršica. Also dolomite of the Zaplana belongs to this nappe. In the NW it is thrusted over Idrija – Žiri block and in the SE over Vrhnika – Cerknica block.

Idrija nappe is found in Rovte region and it consists of different rocks: Carboniferous, Permian to Triassic. Rovtarica, Pikeljščica and Žejski potok sinking streams are found in the area of Idrija nappe.

4.4. Hydrogeological characteristics of the studied area

Three hydrogeological units may be distinguished, according to karst aquifer porosity and permeability (Kranjc, 1997; Krivic et. al., 1976):

- high permeable rocks, with conduit and fissure porosity
- medium permeable rocks with fissure porosity
- alternation of medium permeable and impermeable rocks with granular porosity

Hydrogeologic conditions of Ljubljanica drainage basin were detailed described by Buser et al. (1976) for the purpose of underground water tracing (1972-1975). Different areas may be assigned to certain hydrogeological units:

High permeable rocks

Cretaceous and Jurassic limestone in the areas Postojna – Rakov Škocjan – Planinsko polje and Planinsko polje – Vrhnika are considered as high permeable. Rocks are tectonic broken and well karstified. Conduit flow prevails.

Medium permeable rocks

Already medium permeable rocks in Ljubljanica drainage basin partly behave as barriers for underground water flows. All prevailing underground pathways were developed in neighboring Cretaceous and partly Jurassic rocks which are much more soluble and karstified.

Beds of dolomite or alternation of dolomites and limestones of Mesozoic age (Triassic and partly Jurassic) represent medium permeable rocks. Fissured porosity prevails in such rocks. They are found in a belt between Borovnica and Cerknica in the east, between Planinsko polje and Cerkniško polje, in Planinska gora Mt., and from Logatec towards Idrija (in the NW). Nappe structure in NW part of the area represents only surface barrier. Base of the Triassic dolomite nappe is high permeable Cretaceous limestone, which easily transmits underground water flows.

Alternation of medium permeable and impermeable rocks

Alluvial sediments (clay, silt, gravel), which cover karst poljes can be medium permeable to impermeable. Such are mainly Quaternary sediments in the Planinsko, Cerkniško and Logaško poljes, where surface water flows occur.

Quaternary sediments, which fill tectonic basin of Ljubljansko barje moor, represent a barrier for underground karst water. Therefore it emerges at the contact of Jurassic rocks with Quaternary sediments.

Different Permian and Carboniferous rocks alternate to a minor extent in the NW part of drainage basin. These rocks are impermeable; such are sandstone, marlstone, alternation of limestone and marl, alternation of dolomite and marl.

Not only lithology, but also tectonic structure makes rocks impermeable. Milonitic dolomite along Idrija fault between Rakek and Cerknica represents impermeable hydrologic barrier, which causes bifurcation of waters from the Cerknica Lake. Those sinking underground north of the fault use other underground courses than those sinking south of it.

4.5. Previous surveys of studied area

Classical Dinaric Karst has attracted scientist for centuries. Special interest was given to underground water connections among sinking streams such as Pivka, Rak, Unica and Ljubljanica springs and to seasonal Cerknica Lake. Kircher, Schönleben, Valvasor and Steinberg were some of the early scientists from 17th and 18th century who were interested in karst phenomena of Notranjska region (Gams, 1974).

Modern surveys started in the 20th century, with tracing tests. The first modern tracing test was done in year 1928, when tracers was injected into the Pivka (uranin) and the Rak (saccharomytes) Rivers in front of the ponors. Water was sampled in Pivka Jama and in Planinska Jama (Italo et al., 1928). Many further tracing tests were performed in the Pivka and the Rak Rivers between years fifties and nineties (Hribar, 1955; Avdagić et al., 1976; Čadež 1976; Kogovšek, 1996). One of the most interesting findings was the bifurcation of underground waters in Postojna basin (including the Pivka River) toward Black Sea and Adriatic Sea (Habič, 1989).

A brief review of tracing tests in drainage basin of Ljubljanica springs before year 1972 was made by Čadež (1976). The purpose of all tracing tests before 1972 was to define underground connections between ponors and springs only. Tracers were injected to ponors of the Unica River, the Logaščica Stream, the Rovtarica Stream and the Cerknica Lake. Water at Ljubljanica springs was sampled. But quantitative occurrence of tracers at springs was not calculated and discharges of sinking streams were only roughly estimated. Therefore all hydrogeolocial and hydrodynamical questions were not solved with these tracing tests (Hribar, 1976).

The most important work to illuminate and research underground hydrogeology of Ljubljanica drainage basin was done in years 1972-1975 (Gospodarič & Habič, 1976). Comprehensive underground water tracing tests, which covered almost entirely karstic drainage basin of Ljubljanica River, were done. Tracers were injected in all important ponors and their concentrations were measured at the springs. The connections between some ponors and karst springs had been mainly discovered already with previous tests. But all tracing tests, before the 1972-1975 combined tracing test, gave only qualitative data. The main purpose of the 1972-1975 test was to evaluate system quantitatively, by measurements of tracer recovery at springs. The understanding of hydrogeology of this karstic area would be much less known, without such quantitative evaluation.

Different types of tracers were used to determine underground water connections: fluorescent tracers (such as uranine, eosine, sulphorodamine G, rhodamine FB and tinopal CBS – X), spores (Lycopodium), Potassium Chloride, Lithium Chloride, Cr-51 and hard detergents.

Work included also some investigations of speleohydrology in caves. Water levels were observed in all the there known water caves, but there were no automatic devices for measuring it. Therefore only some basic hydrogeological characteristics were carried out, by periodical direct observation of water levels and occurrence of flood sediments.

On the base of supposed runoff of waters from particular smaller areas and by comparison of discharges, the Ljubljanica drainage basin was divided into eight hydrologic regions (Fig. 4.3).

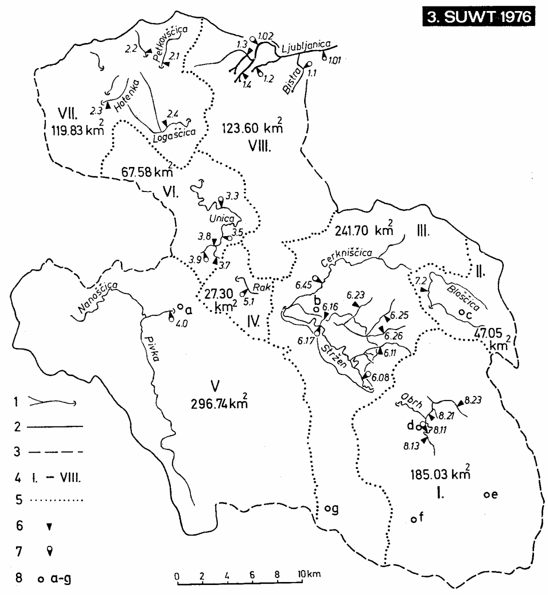

Figure 4.3: Karst Ljubljanica River basin with calculated hydrologic regions. 1 – surface rivers, sinking streams, 2 - surface watershed, 3 – supposed karst watershed, 4 – mark of hydrologic regions, 5 – borders between hydrologic regions, 6 – hydrologic survey stations, 7 – stations with limnographs, 8 – precipitation station. Several hydrologic parameters were determined for each of eight regions. Such parameters were surface of the area, precipitation, runoff, mean discharge, specific runoff, runoff ratio and evapotranspiration (adapted from Gospodarič & Habič, 1976).

Previous water tracing investigations are important because a lot of data were obtained, which helped to interpret the underground systems in the drainage basin of the Ljubljanica River. The underground system was especially well researched during 1972-1975 survey. Above all underground water pathways and water retention times became generally known with past surveys. The 1972-1975 tracing test mainly, and also many other surveys which had been done in the Slovenian classical karst, serve as a base for new, more detailed and profound researches of Slovenian karst. In our work we decided to focus on cave hydrogeology mainly to extend some work of previous surveys. Part of our thesis is based on supplementation of previous surveys, especially 1972-1975 survey (Gospodarič & Habič, 1976). Therefore findings of this and other water tracing tests are of crucial importance for our work.

5. HYDRAULICS OF KARST CHANNELS: A SIMPLE THEORETICAL MODEL OF UNDERGROUND DRAINAGE

5.1. Types of underground water flows

Mature karst aquifers have extreme heterogeneity of hydraulic conductivities, ranging from 10^{-10} m/s to 10^{-1} m/s. The lowest conductivity is due to inter-granular porosity and the highest due to large conduits: caves (Dreybrodt et al., 2005). Hence, all possible types of flow occur in karst aquifers, from laminar flow in connected pores and narrow fissures, to turbulent flow in conduits. Moreover, conduit flow is both open channel and full pipe (Bonacci, 1999).

Conduit flow represents at least 90 % of water migration within karst aquifer, not only because their volume, but also because they present pathways with low resistance for underground flow (White, 2002). Peterson and Wicks (2005) argued that water exchange between conduit and matrix (primary porosity) is negligible in some representative karst carbonate. According to simulations, the fluid maximum penetrates maximally 0.07 m deep in the matrix (usually around 0.003 m deep) and the volume of water transported into and stored in a matrix with a high porosity and high hydraulic conductivity (such as Floridan Aquifer) is less than 0.34 m^3 (but usually around 0.001 m^3 only). They concluded that conduit – matrix exchange is less than 1 % of water moving through the system.

We will focus mainly on conduit flow; viscous flow within rock bulk is less important for our research. We mainly neglect the viscous flow. However we presume that the same situation occurs also in the aquifer treated in this thesis, as results of Peterson and Wicks (2005) show.

5.1.1. Viscous (Darcy) flow in pores

Viscous (Darcy) flow is characteristic for aquifers in unconsolidated sediments as sandstones for example. The water moves through the pores between rocks or grains. Water flow through porous aquifer is characterized by (Steinman, 1999):

- hydraulic conductivity
- transmissivity
- porosity
- effective porosity

- capacity of the aquifer

In porous aquifer, the scale of the pores is very small compared with the scale of the aquifer. Therefore the permeability of porous aquifer is characteristic and water movement is continuous (White, 1988). In such homogeneous, isotropic porous aquifers, with laminar flow, the water flow is controlled by **Darcy's law**, which can be written as (Schwartz & Zhang, 2003):

$$Q = K \times A \times \frac{h_2 - h_1}{L} = K \times A \times i$$

where Q is discharge [m^3/s], K is hydraulic conductivity [m/s], A is cross-section area [m^2], L is length [m], h is hydraulic head [m] and i is hydraulic gradient [-].

5.1.2. Flow in fractures and conduits

Ground water flow in fractures and conduits can be characterized into two flow regimes; laminar and turbulent. Reynolds number is the measure, which tells us whether the flow is laminar or turbulent. Reynolds number is calculated as the relative balance between inertial and viscous forces (Anwar, 2008):

$$\mathrm{Re} = \frac{uL}{v}$$

where u is the average velocity of the fluid (m/s), L (m) is a characteristic length and v is the kinematic viscosity (m^2/s) of the fluid.

5.1.2.1. Laminar flow

Viscous forces are dominant at low flow velocities, when water moves through a smooth pipe in streamlines, with no mixing across streamlines (Fig. 5.1). Such flow is laminar. It is characteristic not only for low flow velocities, but also for very small pipes - fractures (Ford & Cullingford, 1976).

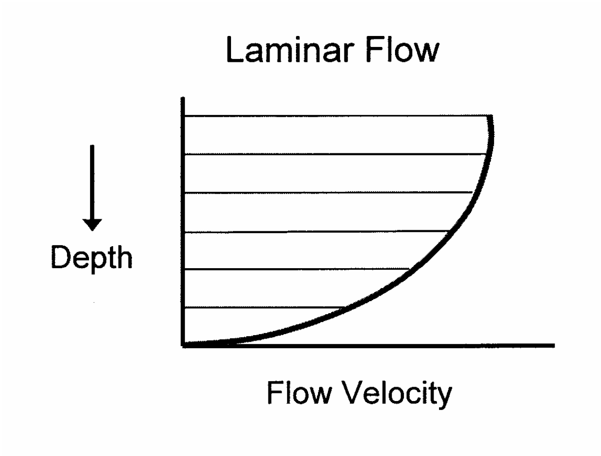

Figure 5.1: Streamlines are parallel with water flow at laminar flow (from http://cronodon.com/files/River_Processes_1.pdf).

Laminar flow does not necessarily take place in fractures only, but at certain conditions even in conduits. Such laminar flow is described by **Hagen-Poiseuille equation**, which is a version of Darcy's law (Birk et al., 2002; White, 2002; Dreybrodt et al., 2005; Kovacs & Sauter 2007; Anwar, 2008):

$$Q = \frac{h}{R} = \frac{iL}{R}$$

where *i* is hydraulic gradient defined as h/L and

$$R = \frac{12\eta}{\rho g}\int_0^L \frac{dx}{a^3(x,t)b(x,t)M(x,t)}$$

M is geometrical factor, which depends on the width – aperture ratio.

5.1.2.2. Turbulent flow

At higher velocities, the streamlines become unstable, because irregularities in the walls of the pipe introduce disturbances (Fig. 5.2). With increasing the velocities, also disturbances increase and the transition from a laminar to turbulent flow regime occurs (White, 1988). Turbulent flow involves transverse mixing and eddying motion superimposed on the main flow direction. Such turbulent flow usually occurs in pipes and conduits greater than about 1 cm in diameter (Ford & Cullingford, 1976; Ralston, 2000). The main difference between laminar and turbulent flow is the role of friction. In turbulent flow friction is responsible for head losses (de Rooij, 2008). Turbulent flow is predominant in cave systems.

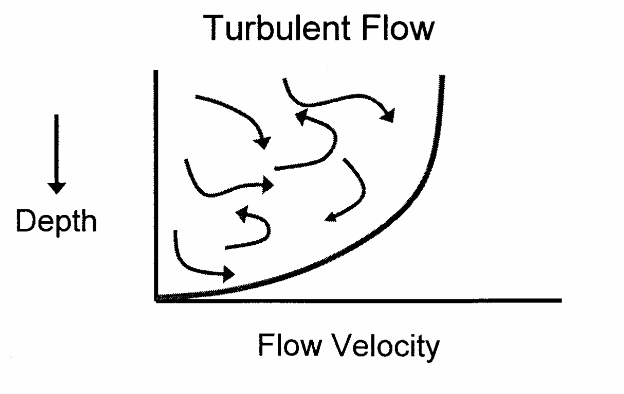

Figure 5.2: Streamlines are unstable at turbulent flow (from http://cronodon.com/files/River_Processes_1.pdf).

The mathematical formulation of turbulent flow in one dimensional conduit is given by the **Darcy – Weisbach friction law** (Kovacs, 2003):

$$Q = K' A_c \sqrt{I}$$

where K' is the turbulent flow effective hydraulic conductivity [m/s], A_c is the cross sectional area [m^2], and I is hydraulic gradient [-].

5.1.2.3. Full pipe and open channel flow

Depending on water conditions in the conduit, we distinguish **full pipe flow** (pipe or conduit is completely filled with water) and **open channel flow** (conduit is only partly filled with water, in the rest of conduit air pressure exists).

- Full pipe flow

Full pipe flow in karst aquifer usually occurs within restrictions, which interrupt large conduits. Such restrictions may be phreatic loops or other narrowings.

Full pipe flow in conduits is sufficiently well described by the **Darcy-Weisbach equation** (Birk et al., 2002; Anwar, 2008; Prelovšek et al., 2008):

$$\Delta h = \lambda \frac{L}{d} \frac{v|v|}{2g}$$

where Δh is head difference along pipe [m], λ is friction factor [-], d is pipe diameter [m] and L is length of pipe [m].

Two types of forces affect flow in closed conduits:
- inertial forces (F_i), which are associated with the momentum of the mass of water in motion.
- viscous forces (F_v), which are generated by the layers of fluid sliding past each other.

As mentioned, likelihood of turbulent flow is estimated by the **Reynolds number** (Re) (White, 1988; Anwar, 2008):

$$\frac{F_i}{F_v} = \frac{\frac{\rho v^2}{R}}{\frac{\eta v}{R^2}} = \frac{\rho v R}{\eta} = \mathrm{Re}$$

where R is hydraulic radius [m], η is viscosity of fluid [m^2/s], ρ is density of fluid [kg s^2/m^4] and v is the average velocity of the water flow [m/s].

For smooth pipes, it can be said that when (Steinman, 1999):
Re < 2300, flow regime is laminar
Re > 2300, flow regime is turbulent

In rough pipes (cave conduits may be considered as rough pipes), transition begins even at lower Reynolds number (Steinman, 1999).
Ford & Cullingford (1976) consider flow as laminar when Re < 500 and as fully turbulent when Re > 2000. They consider the flow as partially turbulent at intermediate values.

- Open channel flow
Transmission of karst water through large conduits of epiphreatic zone usually takes place as an open channel flow. Open channel flows in karst aquifer have more in common with surface water than groundwater (Bakalowicz, 2005).

Characteristic of open channel flow is that at last part of the water surface is in contact with atmospheric pressure. There is no hydrostatic pressure in open channels; it is compensated by air pressure.

Free surface flow, whether in the underground or at the surface, may be described by **Manning's equation**, which is a steady state approximation of **Saint-Venant equation** (Steinman, 1999; Prelovšek et al., 2008):

$$i = \frac{n^2 * Q^2}{A^2 R^{4/3}}$$

where i is head loss per unit length [-], n is Manning's roughness coefficient [-], A is wetted area [m^2] and R is hydraulic radius [m].

The equation describes mass and momentum conservation along the whole depth profile of an infinitesimally long stream section. The flow is one-dimensional, stream curvature and bed slope are small, and vertical acceleration is neglected.

In full pipe flow the conduit is characterized by a hydraulic radius. In open channel flow, the hydraulic radius is replaced by wetted perimeter of cross-sectional area of the conduit.

Three types of forces affect water flow in open channels: inertial, viscous (both were already mentioned at full pipe flow) and gravity forces. Gravity force is a consequence of the fact that the flow depth can vary with flow velocity in open channels.

Froude number (F_r) describes the ratio between inertial and gravity forces:

$$F_r = \frac{v}{\sqrt{g h_0}}$$

where h_0 is a hydraulic depth [m]. It is equal to the water depth in a conduit.

According to the Froude number, flow can be considered as sub-critical, critical and supercritical (Steinman, 1999).

$F_r < 1$, than flow is sub-critical or tranquil

$F_r = 1$, than flow is critical

$F_r > 1$, than flow is supercritical

Reynolds number represents the same ratio of inertial and viscous forces as for full pipe flow. But because of the different definition of the hydraulic radius, the transition to turbulent flow occurs at different Re.

The transition from laminar to turbulent flow is gradual, but the transition from sub-critical to supercritical flow is rapid and it creates displacements of the water surface or hydraulic jump. A large amount of energy can be released at the hydraulic jump.

5.2. A simple steady state discrete model, relevant for a karst aquifer with well developed conduit permeability

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The aim of our model is to demonstrate different possible flow scenarios within karst aquifer based on the simple model of discrete conduits and reservoirs. Water flow in model is treated as one-dimensional and conduits have different dimensions, permeability respectively. Attention is given to the various hydraulic behaviours (open channel flow, full pipe flow) of underground water flow through large conduits of different diameters, with regard to the variable input conditions (recharge).

5.2.1. Introduction

Characterization of karst aquifer is a difficult task, because the position and geometry of conduit network which transmit most of groundwater is not known. If the geometry is at least approximately known (or can be predicted) and the recharge into the underground system can be measured (or estimated) then we can make a simplified model.

We should be aware that all estimations can be very approximate and results are not always reliable. The easiest way to reconstruct underground karst water flow is to use models. There are two major approaches: global and distributive, as mentioned in chapter 3: "A brief overview of applied methods". The distributive approach was used in our model.

Before starting any modeling some important features of karst aquifer should be considered: recharge, discharge, geometry of the system, permeability, friction factor and boundary conditions (Kiraly, 2002; White, 2003; Springer 2004):

- Recharge can be allogenic from the sinking streams, autogenic through the epikarst, or a combination of both (Ford & Williams, 1989). Discharge can be measured before a river sinks underground. We should be aware of possible water losses into larger or smaller fractures inside the cave system, recharges as underground tributaries and autogenic infiltration (Springer, 2004).
- Geometry of the model is simplified. Karst water flows through a system of conduits and fractures which have different diameters. Conduit shapes are very irregular and it is almost impossible to predict them. Constrictions between conduits may cause back flooding. Conduits may divide or combine into more or one.
- Permeability is linked with the porosity. In general we distinguish inter-granular, fracture and conduit permeability. More than 90 % of underground karst waters flow through large conduits (Bonacci, 1987).
- Friction happens within water flow and at the contact of water and bedrock. The higher the friction, the lower are flow velocities. Cave walls have a friction factor between 0.028 and 0.13, according to measurements in many caves (Springer, 2004). It is linked also with lithology. Inside one cave system, the friction factor is very variable parameter.
- Boundary conditions which affect discharge flow regime in karst underground are hydraulic head and recharge (Kiraly, 2002).

A brief review of the literature indicates that most models were based on an assumption of water flow through conduits with different dimensions (system consisting of large conduits and restrictions between them). For example, Halihan & Wicks (1998) interpret large conduits as reservoirs with free water surface. Permeability of the whole system is determined by the smallest constriction, through which water is transmitted under pressure (as a full pipe flow). The purpose of such models is to interpret flood response of karst aquifer.
Campbell et al. (2002) used a computer program Storm water management model (EPA, SWMM) to calculate energy losses in the karst underground. They considered both full pipe flow and open channel flow.

The aim here is to demonstrate different possible flow scenarios as mentioned. The model can be divided into two sub-domains. Flow from lake (A) to the underground chamber (B) and the wire (see next chapter “model description and data”) can be considered as an input to the lower conduit system. Second sub-domain represents flow from the wire to the conduit system 2-3-4 and 5-6 (Fig. 5.3), where we assume three different flow scenarios:

- open channel flow in primary conduits (at low recharge)
- full pipe flow in primary conduits (at relatively higher recharge)
- activation of secondary conduits and full pipe flow in all conduits (at high recharge)

The geometry of the system is assumed to be constant, but hydraulic parameters are variable. Relations between water levels (of the lake and underground "reservoirs") and discharge were observed. In three different scenarios, attention will be given to the behavior of underground water flow through large conduits with different diameters at different hydraulic conditions (hydraulic gradient and discharge).

5.2.2. Model description and data

The model represents a system of underground conduits between a higher located lake and a karst spring (Fig. 5.3). Underground conduits are supplied by the lake water. The sinkhole is active all the time in our model, because lake has a positive water balance.

Lake water sinking into the underground flows first through a conduit until it reaches an underground chamber. Water balance of the lake enables full pipe flow through the first conduit.

Water stagnates in the underground chamber. Some rocky barrier, such as a rock-fall causes water stagnation. As a result, an underground karst lake forms. The barrier behaves like a weir. It is long enough, that water cannot reach the chamber's ceiling even during the highest discharges. The water has free surface in the underground chamber during any discharge conditions.

The water spills over the barrier (weir) into the next conduit. It splits into two parts of which the lower conduit is the main and is active all the time. The upper conduit is secondary and it is active only during episodic water conditions. Both conduits join together before the spring. The water emerges at altitude, which is 50 m lower than the bottom of the lake.

The hydraulic model has geometry determined as precisely as possible. All parameters and their typical values are given in Table 1. Geometrical symbols are also shown in Fig. 5.3, where L is length and Φ is a diameter of conduit.

Table 1: Geometrical data and parameters of the model.

GEOMETRICAL DATA	
$Z_{a-min.}$ [m]	102
Z_{0a} [m]	60
H_a [m]	42
Z_b [m]	Z_w+H_{weir}
Z_{0b} [m]	30
Z_w [m]	52
Z_c [m]	12
Z_{split} [m]	42
ΔH_{split} [m]	30
$\Delta H_{3,4}$ [m]	2
ΔH_{split} [m]	30
Φ_1 [m]	3
L_1 [m]	200
Φ_2 [m]	5
L_2 [m]	200
L_2^{split} [m]	150
Φ_3 [m]	5
L_3 [m]	150
Φ_4 [m]	5
L_4 [m]	150
Φ_5 [m]	3
L_5 [m]	150
Φ_6 [m]	3
L_6 [m]	150
trapezium	
h [m]	5
D [m]	2
B [m]	2
m	0.4

FRICTION FACTORS	
Ng	0.03
Ng trapezium	0.11
λ_1 [s/m⅔]	2.6
λ_2 [s/m⅔]	2.2
λ_3 [s/m⅔]	2.2
λ_4 [s/m⅔]	2.2
λ_5 [s/m⅔]	2.6
λ_6 [s/m⅔]	2.6
COEFFICIENTS OF LOSSES	
$\xi_{outflow\ A-1}$	0.2
$\xi_{outflow\ 4-D}$	1
$\xi_{knee\ 2-3}$	0.1
$\xi_{knee\ 5-6}$	0.15
$\xi_{inflow\ 6-4}$	0.15
WEIR	
μ	0.79
b [m]	10

The model tried to represent useful usage of hydraulic equations in karst underground. Our model is a fiction, but anyway very similar features between two karstic poljes are possible. We have few connected poljes in Slovenia. The most famous seasonal lake is in Cerkniško polje. There are a lot of swallow holes at the bottom of the Cerknica Lake and water emerges in many springs few tens of kilometres away at the contact of carbonate Jurassic rocks with quaternary sediments which fill the tectonic basin of Ljubljana moor.

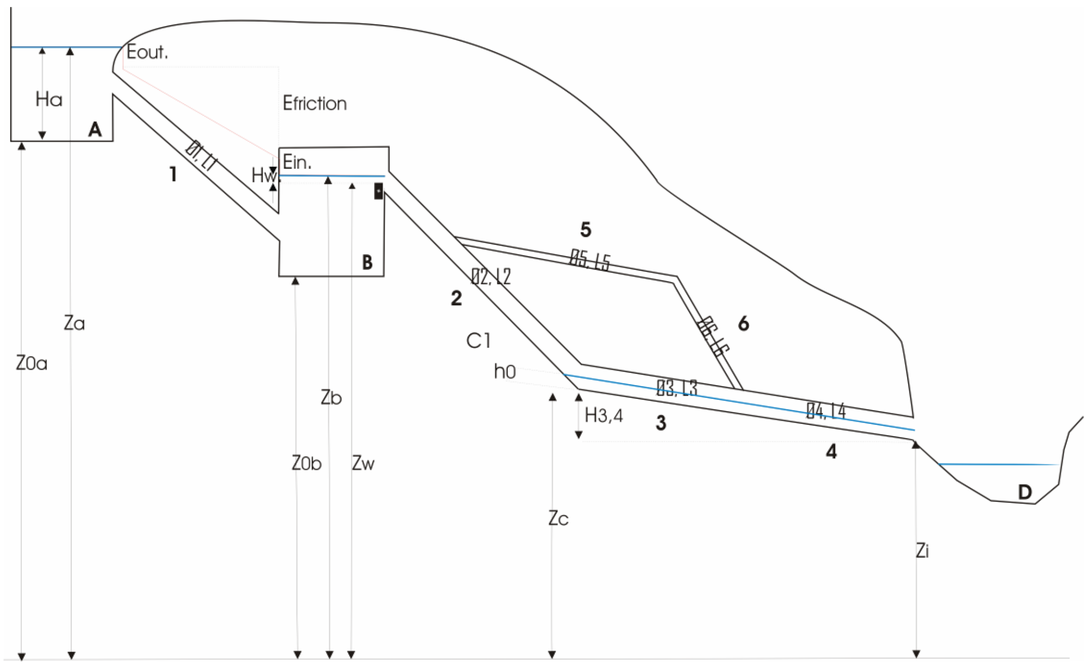

Figure 5.3: Schematic review of underground system.

5.2.3. Scenarios and equations

First, some estimation should be done. Conduit roughness coefficient was estimated as Ng = 0.03 s/m⅓ (Steinman, 1999; Rossman, 2004). We assume limestone walls with a relative high roughness.

Friction factor (λ) depends on conduit diameter and roughness coefficient (Ng). We use connection between friction factor (λ) (after Darcy-Weissbach) and Manning's roughness coefficient (Ng):

$$\lambda = 124{,}6 * \frac{Ng}{\phi^{1/3}} \quad (1.)$$

Values of friction factors are given in Table 1.

5.2.3.1. Flow from the lake to the weir

Domain can be considered as a system of two connected reservoirs. Flow between the reservoirs is full pipe, because water level of the lake is all the time above the sinkhole according to our hypothesis (Fig. 5.3).

In this scenario, water level of the lake and height of water spilling over the weir at some variable discharges were calculated. Flow between two "reservoirs" and spilling over the weir are independent of further hydraulic conditions and the type of flow in conduits (2-3-4) or (5-6).

First some initial discharge must be chosen or calculated, which will be arbitrarily increased. We will then calculate water height at weir (H_{weir}) and losses in the conduit. Finally water level of the lake (Z_a) will be calculated.

Relation between discharge (Q) and flow velocity (v) is described by following equation:

$$Q = A * v = \pi * (\frac{\phi}{2})^2 * v \qquad (2.)$$

A – cross section area of conduit filled with water [m^2]

Φ – pipe diameter [m]

The system of flow between lake (A) into underground chamber (B) through conduit (1) is expressed by Bernoulli's equation (Bögli, 1980):

$$\frac{p_1}{\rho g} + h_1 + \frac{v_1^2}{2g} = \frac{p_2}{\rho g} + h_2 + \frac{v_2^2}{2g} + \Sigma(\Delta E) \qquad (3.)$$

p – hydrostatic pressure [Pa=N/m^2]

ρ – density [kg/m^3]

g – gravitational acceleration = 9,8 m/s^2

h – height above arbitrary comparative surface [m]

Σ(ΔE) – sum of all energy losses.

Hydrostatic pressure exists only in reservoirs (conduits) completely filled with water, otherwise pressure head $\frac{p}{\rho g}$ =0.

Therefore the difference between the potentials in the lake and reservoir is equal to the energy losses in the conduit (Fig. 5.3):

$$Z_a = Z_b + \Delta E \qquad (3.1)$$

where:

$$\Delta E = \Delta E_{\inf low} + \Delta E_{friction,1} + \Delta E_{outflow}$$

ΔE is energy loss. We distinguish friction and local losses (local losses occur at every change of streamline: for example at stream expansion and narrowing, at outflow from a conduit into a larger underground chamber and the opposite, at bends etc.).

Friction losses in the circular conduit are calculated by Darcy-Weissbach equation:

$$\Delta E_{friction} = \lambda \frac{L}{\Phi} * \frac{v^2}{2g}$$

L – pipe length [m]
Φ – pipe diameter [m]

Hydraulic diameter for circular pipe is considered as $R = \frac{A}{P} = \frac{\Phi}{4}$

P – perimeter of cross section [m]

Local losses (inflow and outflow) must be added to get total energy losses. These are given by following equation:

$$\Delta E_{local} = \xi_{local} * \frac{v^2}{2g}$$

ξ – coefficient of local loss

The Bernoulli's equation (3) then becomes

$$Z_a = Z_b + \frac{v^2}{2g} * \left(\xi_{\inf low} + \lambda \frac{L_1}{\phi_1} + 1 \right) \qquad (3.2)$$

where $\xi_{outflow}$ = 1 (Steinman, 1999)

The level Z_b in the reservoir (B) equals to $Z_w + H_{weir}$, where the H_{weir} is the height of the water at the weir (Fig. 5.3). To get some basic, initial discharge, we first assume that water level in reservoir (B) increases only until it reaches the top of the weir, therefore H_{weir}=0 and Z_b=Z_w. After this assumption, we can use equation (3.2) to calculate velocity (v) and then we use equation (2) to calculate initial discharge (Q). After consideration that Z_b=$Z_{w,}$ minimum discharge can be calculated, at some minimum $Z_{a.}$ All following calculations are based on that minimum discharge.
Q_{min}=16.77 m^3/s (initial discharge), according to our calculations (respectively rounded up to 16.8 m^3/s). Arbitrary values are added up to Q_{min}. So the discharge is being increased gradually which is a consequence of rising water level of the lake. Discharge through karst conduit (1) increases proportionally with flow velocity (v) (equation 2) along the conduit (l). Consequently water level in the underground chamber (B) is changing. The higher the discharge, the higher is the water level spilling over the weir (equation 4.1). The weir is a barrier (rock-fall). Water spills over the barrier into next karst conduit.

Discharge over barrier (weir) is calculated by the equation for a perfect weir. Perfect weir (Fig. 5.4) cannot be flooded by downstream water.

$$Q = \frac{2}{3} * \mu * \mathrm{b} * \sqrt{2\mathrm{g}} * H_{weir}^{2/3} \qquad (4.)$$

where
μ – weir coefficient (it can be read from tables in the literature)
b – weir width [m]
H_{weir} – height of spilling water above the weir [m]

Weir coefficient μ was estimated to be 0.79 (Steinman, 1999)

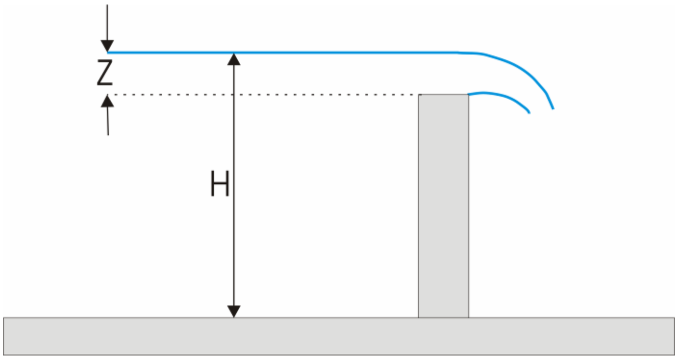

Figure 5.4: Sketch of perfect weir. Z is height of water, spilling above the weir and H is water level.

From equation (4.) H_{weir} can be expressed:

$$H_{weir} = \left[\frac{Q}{\frac{2}{3} * \mu * b * \sqrt{2g}} \right]^{3/2} \qquad (4.1)$$

Water level in the underground chamber (value $Z_{b)}$ is:

$Z_b = Z_w + H_{weir}$ (5)

Calculated value H_{weir} is put in equation (5) to get level of water in the underground chamber (B) (respectively value Z_b) at different discharges. Value Z_b is put into equation (3.2) to get water level of the lake (Z_a) at different hydraulic conditions. Water level of the lake is the parameter which has the main influence on discharge variations within the karst underground.
The function of water levels is shown in Fig. 5.5.

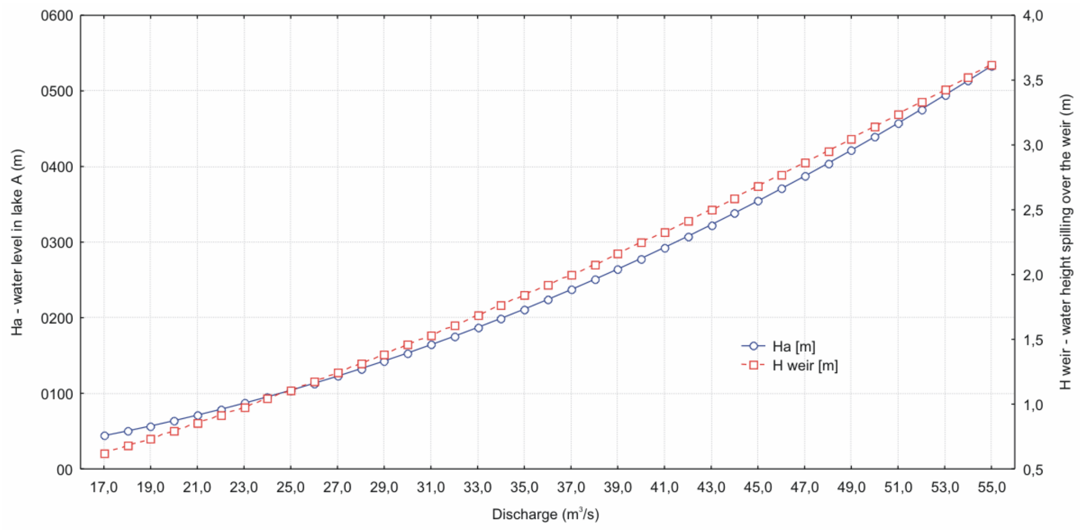

Figure 5.5: Relation between water levels (m) and discharge (m3/s).

5.2.3.2. Scenario 1: open channel flow through conduits (2-3-4) after spilling over the weir

In scenario 1, special interest will be given in transition from open channel flow to full pipe flow and water level heights (h_0) in conduits 3 and 4 (Fig. 5.3). But to consider open channel flow, one condition has to be satisfied: $5 > h_0 \geq 0$ m (because diameter of the conduit is 5 m).

For the simplicity of calculations we assume trapezoidal cross section of conduit 3 and 4 only in scenario 1. All conduits in all other examples have circular cross sections. Furthermore, also roughness coefficient in trapezoidal conduits is changed to Ng=0.11 in scenario 1.

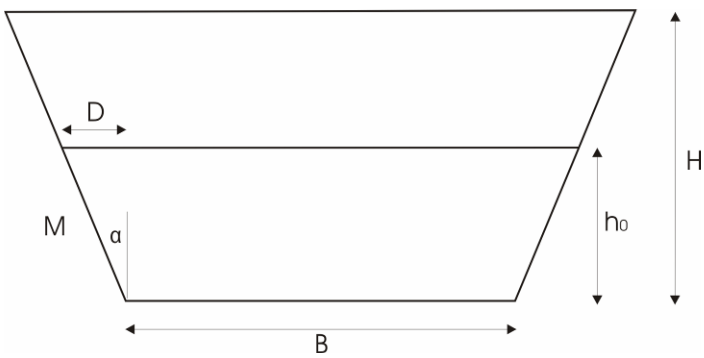

Figure 5.6: Cross section of trapezoidal conduit.

Discharge for open channel flow is calculated after Manning:

$$Q = \frac{\sqrt{I}}{Ng} * \frac{A^{5/3}}{P^{2/3}} \qquad (5.)$$

where A and P are flow cross-section and perimeter of flow. They are given by:

$$A = bh_0 + mh_0^2 \qquad (6.)$$

$$P = b + 2s = \frac{2h_0}{\sin\alpha} = b + 2h_0\sqrt{1+m^2} \qquad (7.)$$

where

$$m = tg\alpha = \frac{D}{h} \qquad \text{see Fig. 5.6}$$

Values D, B and h are given in Table 1

And hydraulic gradient I:

$$I = \frac{\Delta H_{3,4}}{L_{3-4}}$$

Applying equations (6.), (7.) into equation (5.) we get:

$$Q = \frac{\sqrt{I}}{Ng} * \frac{(bh_0 + mh_0^2)^{5/3}}{(b + 2h_0\sqrt{1+m^2})^{2/3}} \qquad (8.)$$

Open channel flow through conduits 3 and 4 is possible until recharge 20 m^3/s, according to our calculations. Both conduits fill up with water during higher discharges and full pipe flow occurs. It is described in scenario 2.

Error as a consequence of simplifying of cross section geometry can be determined. Cross-section of trapezoidal conduit (equation 6) should be similar as possible to the cross-section of circular conduit with diameter 5 m (Fig. 5.7). The ratio between cross-sections areas is trapezium : circle = 20 m^2 : 19.6 m^2.

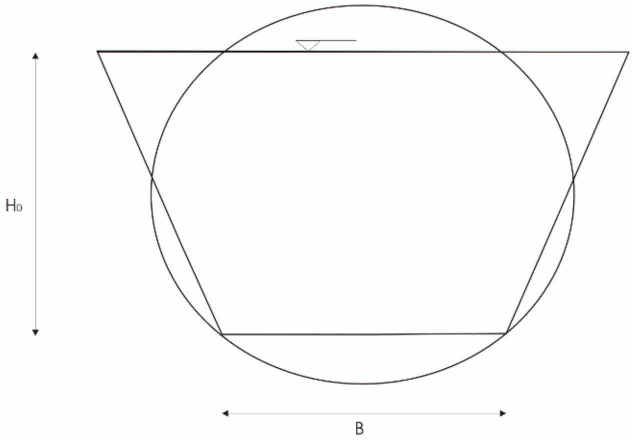

Figure 5.7: Trapezoidal and circular cross-sections should be similar as possible.

5.2.3.3. Scenario 2: full pipe flow through primary conduits only

It is assumed that conduit 2 acts as a reservoir and the water level in it is restricted 30 m>h_c>$\Delta\Phi_3$, otherwise water would start to flow through conduit 5 and 6. Secondary conduits split from the primary at height $h_{split} = h_c = 30$ m (Fig. 5.8).

We would like to find out the boundary discharge, which causes flow trough secondary conduit (5-6). Also correlation between discharge and water level in conduit h_c (considering the condition 30 m >h_c> 5 m) can be determined (Fig. 5.9). First we calculate velocities for selected discharges (using equation (2.): $v = \frac{Q}{0{,}25 * \pi * (\Phi)^2}$) and then water level in conduit 2 (value h_c) using equation (9.1).

$$h_c + \Delta H_{3,4} = \Delta E_{knee} + \Delta E_{friction,3-4} + \Delta E_{outflow} \qquad (9)$$

$$h_c = \frac{v^2}{2g}(\xi_{knee} + \lambda_{3-4}\frac{L_{3-4}}{\phi_{3,4}} + \xi_{outflow}) - \Delta H_{3,4} \qquad (9.1)$$

Full pipe flow through conduits 3 and 4 is possible for discharges above 20 m^3/s. Until discharge does not exceed 43 m^3/s, water does not flow through secondary conduits 5 and 6.

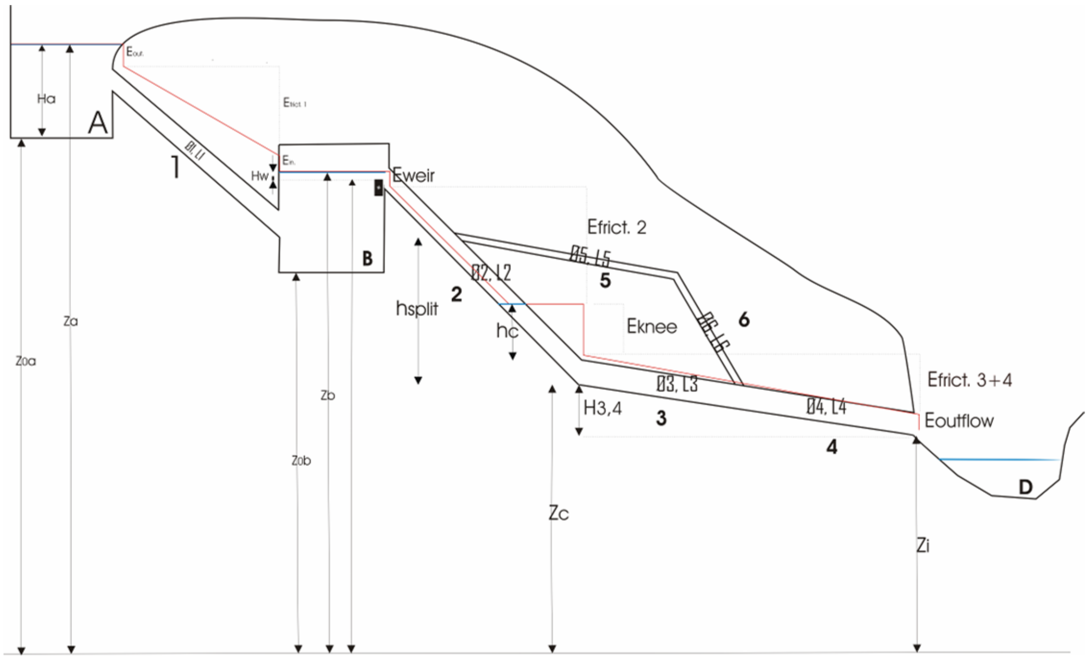

Figure 5.8: Schematic review of scenario 2.

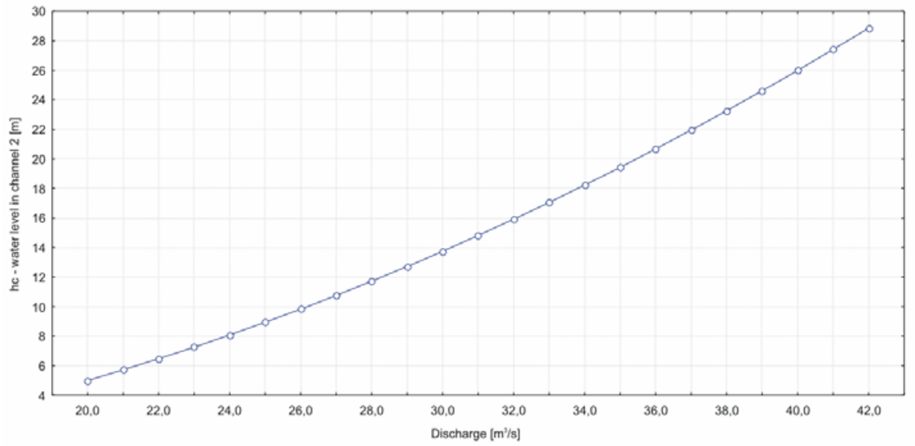

Figure 5.9: Relation between water level in conduit 2 and discharge.

5.2.3.4. Scenario 3: full pipe flow through primary and secondary conduits

The water starts to flow through secondary conduits at discharge 43 m^3/s (accurately 42.9 m^3/s), as was determined in scenario 2. Start of secondary flow should occur at higher discharge in scenario 3, but this does not happen. Water starts to flow through secondary conduits at discharge 41.5 m^3/s according to calculations in scenario 3. The reason is in some simplifications, especially in neglecting friction losses within

conduit 2 in scenario 2. Friction losses are considered in scenario 3, therefore boundary discharges between two scenarios cannot be compared.
Because scenarios 2 and 3 are incompatible, scenario 3 will be used only to find out relation between flow rates in both primary and secondary branch (Fig. 5.11). It is assumed that the total flow rate exceeds 41.5 m^3/s and the flow is full pipe in both branches.
Discharges at the spring are considered to be known. Velocities using equation (12.) are calculated first. Velocity v_{2-3} is in relation with velocity v_{5-6} (equation 11.3). When velocities are known, equation (2) is used to calculate discharges Q_{2-3} and Q_{5-6}. Their sum should be equal to the common Q (equation 10).

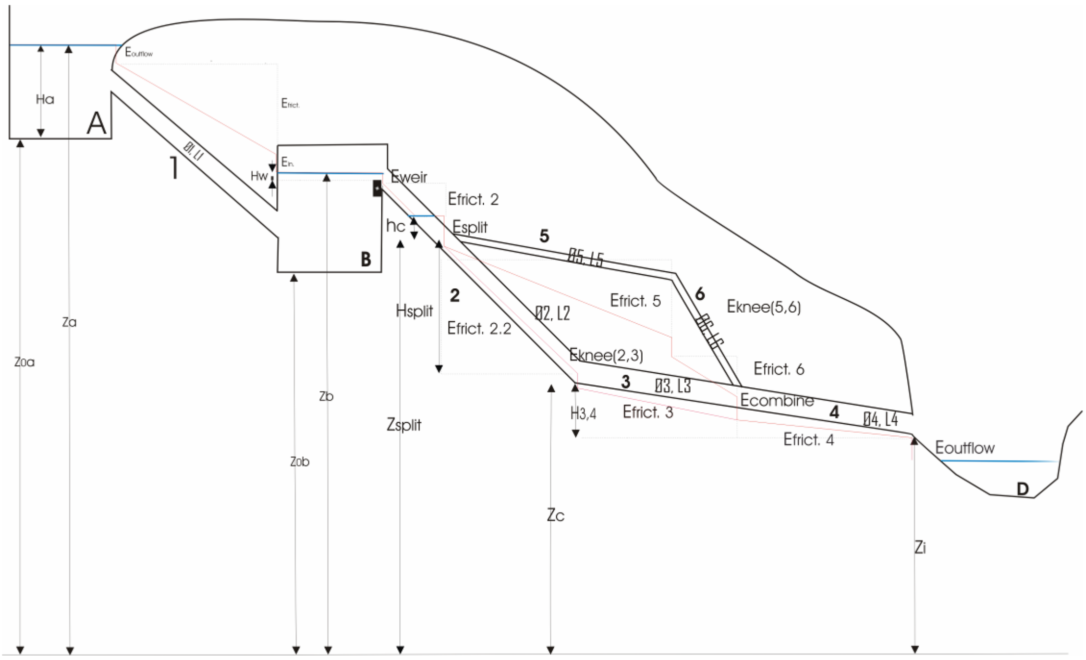

Figure 5.10: Schematic review of scenario 3.

Flow splits to two components:

$$Q = Q_{2-3} + Q_{5-6} \qquad (10)$$

Energy drop along both branches (2-3 and 5-6) is equal (Fig. 5.10):

$$\Delta E_{2-3} = \Delta E_{5-6} \qquad (11)$$

$$\Delta E_{friction,2.2} + \Delta E_{knee(2,3)} + \Delta E_{friction,3} = \Delta E_{friction,5} + \Delta E_{knee(5,6)} + \Delta E_{friction,6} + \Delta E_{combine}$$

(11.1)

$\Delta E_{combine}$ was neglected. Applying equations for friction and local losses we get:

$$\frac{v_{2-3}^2}{2g} * \left(\lambda_{2-3} * \frac{L_2^{split}}{\phi_2} + \xi_{knee(2,3)} + \lambda_{3-4} * \frac{L_3}{\phi_3} \right) = \frac{v_{5-6}^2}{2g} * \left(\lambda_{5-6} * \frac{L_5}{\phi_5} + \xi_{knee(5,6)} + \lambda_{5-6} * \frac{L_6}{\phi_6} \right)$$

(11.2)

The ratio between velocities v_{2-3} and v_{5-6} is written as:

$$v_{2-3} = \sqrt{\frac{\lambda_{2-3} * \frac{L_2^{split}}{\phi_2} + \xi_{knee(2,3)} + \lambda_{3-4} * \frac{L_3}{\phi_3} +}{\lambda_{5-6} * \frac{L_5}{\phi_5} + \xi_{knee(5,6)} + \lambda_{5-6} * \frac{L_6}{\phi_6}}} * v_{5-6} = n * v_{5-6} \qquad (11.3)$$

Where symbol n presents calculated value under the square root.

Employing equation (11.3) and relation $Q = \pi * (\frac{\phi}{2})^2 * v$ in equation (10.) we get:

$$Q = \pi * (\frac{\phi_{2-3}}{2})^2 v_{2-3} + \pi * (\frac{\phi_{5-6}}{2})^2 * (n * v_{2-3}) \qquad (12.)$$

After calculating velocities, equation (12.) can be used to determine discharges Q_{2-3} and Q_{5-6}. Proportion of two discharge components is shown in Fig. 5.11.

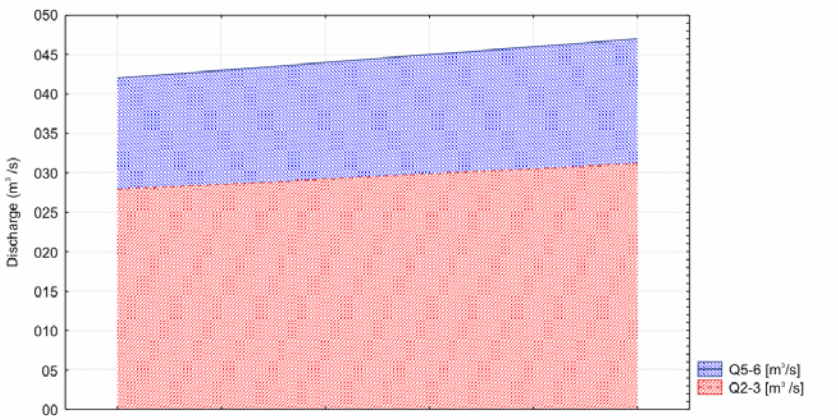

Figure 5.11: Comparison of two discharge components through conduits 5-6 and 2-3. Both components present common discharge.

5.2.4. Conclusion

The geometry of the model had an important role on the relation between water level in reservoirs (lake, underground chamber) and discharge through the system. Our calculations showed that water level should rise for about 280 m to cause flow through secondary conduits 5 and 6, which is also a consequence of geometry. Unreliable water level indicates that the chosen geometry was not optimal.

Scenarios 1 and 2 are used to represent equations for open channel flow and full pipe flow within conduit. When discharge exceeds 20 m^3/s, open channel flow is not possible any more in conduits 3 and 4. A lot of simplifications were used, especially in scenario 1, so a difference between boundary discharges at the transition from open channel flow to full pipe flow could be big. To make calculations easier, we assumed a conduit with trapezoidal cross section for open channel flow only (scenario 1), otherwise conduits cross sections are circular. The difference between the two cross sections with different shapes was only two per cent. Problem of misfit results would be more a consequence of a hydraulic jump. It was solved by changing roughness coefficient in trapezoidal conduit (3-4) (scenario 1). Otherwise roughness coefficients were constant in all conduits for all scenarios.

Scenario 3 was used to find out relations between discharges through primary and secondary conduits. Proportion between two discharges is almost 2:1. Discharge, which causes water flow through secondary conduits should exceed 43 m^3/s or 41.5 m^3/s, depending on neglecting or considering friction losses in conduit 2.

As can be imagined, model calculations are far from optimal, but they may offer some considerations for modeling karst aquifers.

6. LOCAL SCALE STUDY

6.1. Site description

The Pivka is around 20 km long surface river, with catchment area of almost 300 km^2. It emerges in Postojna basin, which is composed of Eocene flysch and thrust of Cretaceous limestone. Basin extends from 750 m to 500 m above sea level and it is surrounded with high karst plateaus (up to 1300 m). The Pivka River sinks to the underground system of Postojnska Jama at the contact between flysch and Upper Cretaceous limestone near Postojna, at the north-eastern margin of the basin (Gams, 2004). It re-emerges in Planinska Jama as the Unica River (Fig. 6.1). Straight line distance between the ponor and the spring is 5.5 km, but length of underground pathway is estimated to be around 10 km (Gams & Habič, 1987). Also the Unica River is a sinking stream, it disappears underground through ponors along the margin of the Planinsko polje and after ten kilometres of underground pathway (straight line) finally rises as the Ljubljanica River. However, significance of the Unica sinking River is discussed in chapters 7.2 and 7.3.

Climate of Postojna basin is transitional, somewhere between continental and mediterranean. Mean annual temperature is 8.4°C, according to data from period 1961-1990 (Fig. 6.2 a), in year 2006 it was 9.9°C. Precipitation maxima are usually two: one in autumn (October, November) and other in the passage of spring to summer (April, May, June; Fig. 6.2 b). Mean amount of annual precipitation is 1578 mm (Gospodarič & Habič, 1976).

The local scale study is focused on drainage of the Pivka River through the Postojnska Jama system exclusively. It is a ponor cave, with one main permanently active conduit system and several secondary conduits (Figs. 6.3 and 6.4). Such secondary conduits extend at various levels, the highest are not active anymore, while conduits at medium levels are active periodically only (at relatively high water conditions). However, drainage takes place also below the known conduit system. But we do not know how, to what extent and at what depth below. The main conduit, whose length is estimated to be around 3.5 km, is relatively easily accessible. There are some exceptions, where passages are accessible to divers exclusively. Anyway, the system of Postojnska Jama includes both water (epiphreatic) and dry (vadose)

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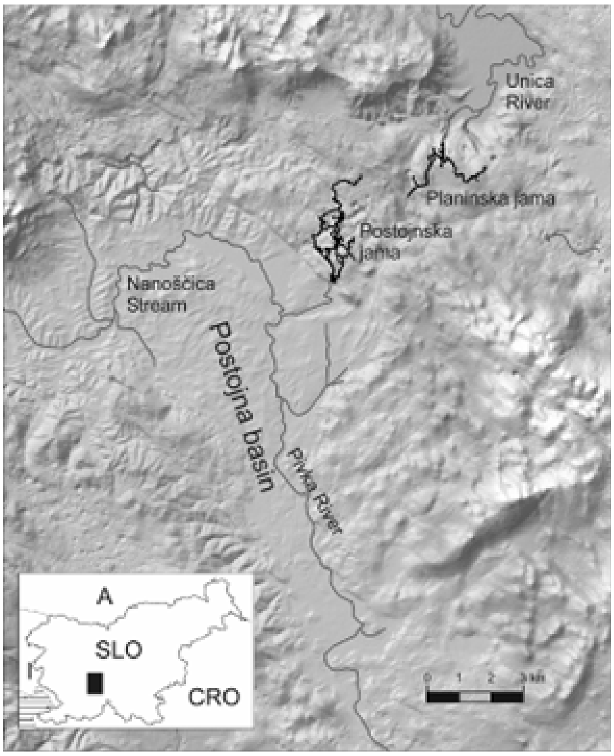

Figure 6.1: Geographic map of Postojna basin. Important rivers and system of Postojnska Jama cave are marked in the map. The Pivka River, with its affluent the Nanoščica stream, flows along Postojna basin and finally disappears underground through Postojnska Jama cave. It emerges in Planinska Jama cave as the Unica River.

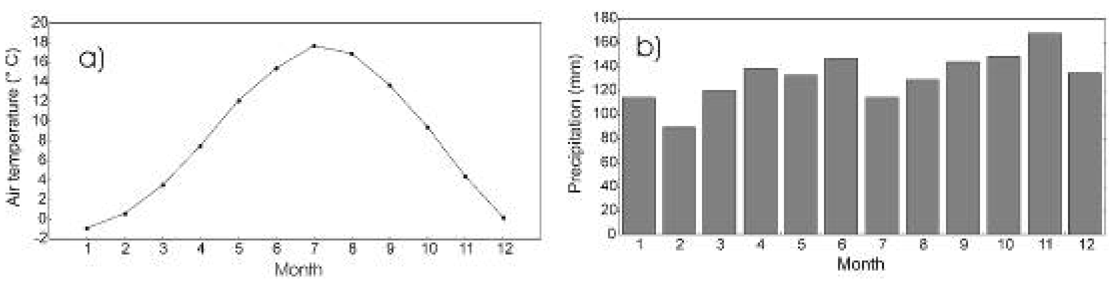

Figure 6.2 a: Monthly mean air temperature in Postojna in 1961-1990 (Reference: Environmental Agency of the Republic of Slovenia).

b: Monthly mean precipitation in Postojna, according to data 1961-1990. Spring and autumn precipitation maxima are not very well expressed in the figure. Snow precipitation in the winter and high evapotranspiration in July and August should be taken into consideration (Reference: Environmental Agency of the Republic of Slovenia).

passages (Figs. 6.3 and 6.4). The length of all water and dry passages is around 20 km (Gams, 2004). Dry passages are accessible to massive tourism; the tourist visit includes a train drive. The cave has been a touristic attraction since 19th century (Hribar, 1955).

Studied epiphreatic conduits of the Postojnska Jama system stretches between the ponor in the south and output phreatic loop in Pivka Jama in the north (Fig. 6.3). Water conduits between the ponor and Pivka Jama are relatively uniform, conduits have large dimensions and they mainly enable open channel flow even at relatively high water conditions. Some phreatic loops occur between Magdalena Jama and Pivka Jama, hence an underground reach of approximately 500 m is not accessible to non-divers. Around 80 m of the system between Magdalena Jama and Pivka Jama still has not been physically researched yet (Fig. 6.3) (Krivic & Praprotnik, 1975). Pivka Jama and also some other parts of the system are accessible also through some secondary entrances, which lead directly to active underground conduits (Fig. 6.4).

Diameter of the conduits in Postojnska Jama ranges from a few metres to around 10 m or locally even more. In Pivka Jama, diameter is around 20 m. Such large conduits may generally transmit the great majority of flood water as open channel flow. Full pipe flow occurs at restrictions only. Such restrictions are mainly significant contractions of the conduits. The most important contractions of the conduit appear in Otoška Jama and in Magdalena Jama (Fig. 6.3). Water flow alternates from open channel to full pipe several times between Magdalena Jama and Pivka Jama. A few phreatic loops appear in this section of the cave system. Length of full pipe flow depends on flow rate.

One of the most important hydraulic restrictions in the underground system is Martel's rock-fall, which blocks pathway of the underground river from the bottom to the ceiling of the conduit. Water has to penetrate through collapsed blocks, or it can find some bypasses, especially at high flow rates.

Not all water flows through the main conduit to Pivka Jama. Some of the flow, at relatively high water conditions, drains through a secondary conduit, which diverge from the main one before Magdalena Jama (Fig. 6.3). This water drains to Črna Jama and converges with the main water flow in Pivka Jama (Sket & Velkovrh, 1981; Habič, 1985). However, some portion of this water flow presumably drains through unknown voids directly toward the spring in Planinska Jama, thus avoiding Pivka Jama (Krašovec, 1981).

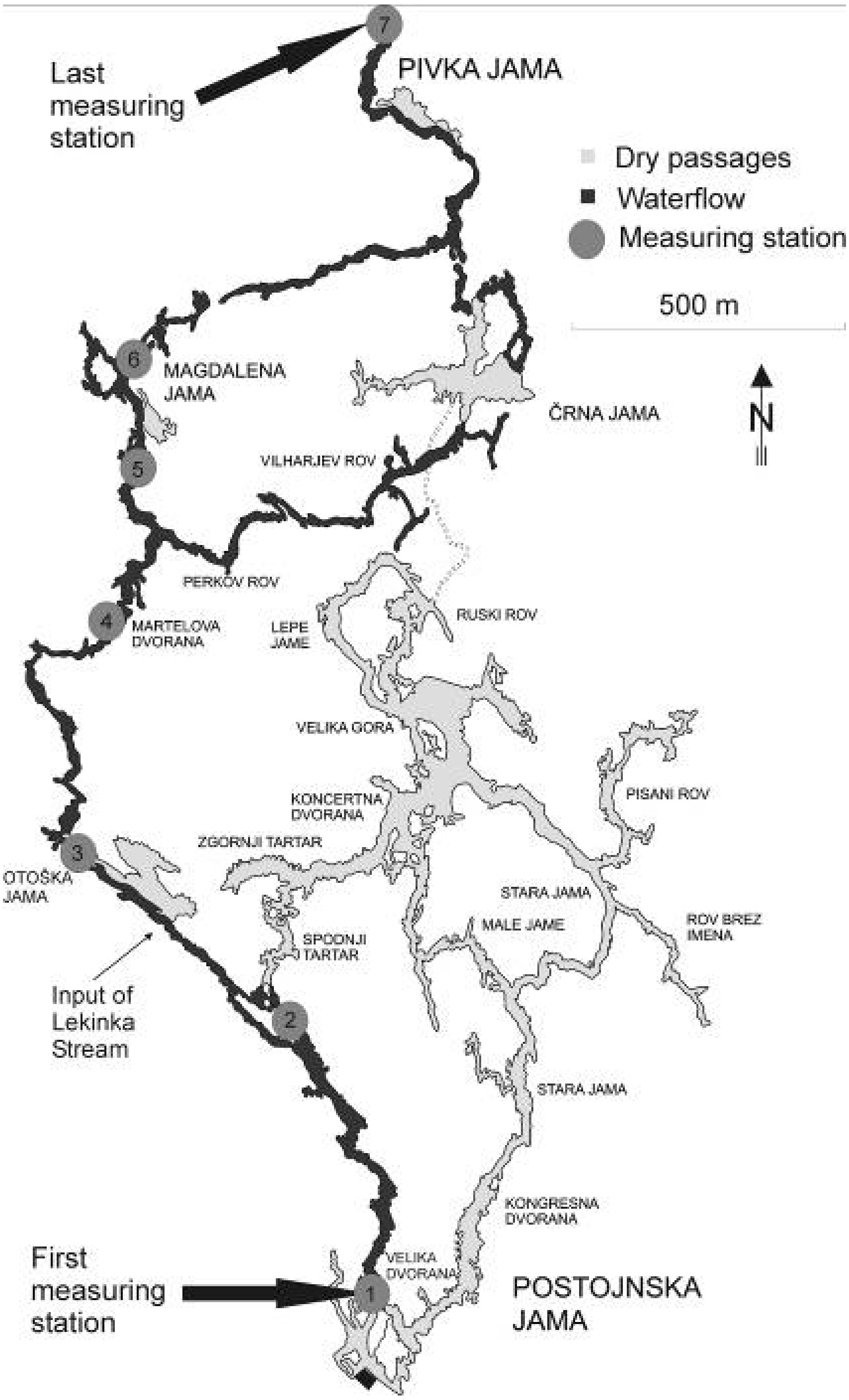

Figure 6.3: Map of Postojnska Jama system with measuring points marked. First data logger is at the ponor, second in Lower Tartar, third in Otoška Jama, fourth just front of the Martel's rock-fall, fifth in Martel's Chamber, sixth in Magdalena Jama and the last one is in phreatic loop of Pivka Jama.

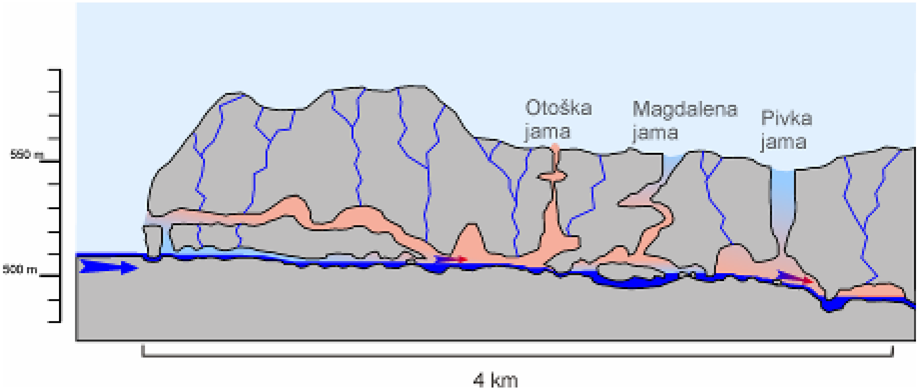

Figure 6.4: Longitudinal sketch of Postojnska Jama system (author of the sketch is Andrej Mihevc).

The phreatic loop at the end of Pivka Jama was explored by divers. A few hundred metres of conduits were discovered downstream from Pivka Jama, but connection with Planinska Jama has not yet been physically proved (Krivic & Praprotnik, 1975; Vrhovec, 2000). Water continuation to Planinska Jama is undoubted and was proved by water tracing (Novak, 1990). Anyway, conduit downstream from output pool in Pivka Jama is accessible to divers only.

Discharge of the Pivka River at the ponor is very variable. It may be less than 100 l/s in the summer, while maximal measured discharges exceeded 60 m^3/s. Mean annual discharge is around 4 m^3/s (Gospodarič and Habič, 1976). The Pivka River presumably does not get any important affluent underground. The most certain is the affluent of the Črni potok Stream ("Black stream") with mean annual flow rate around 100 l/s, while maximal flow rate presumably does not exceeds 1 m^3/s – 2 m^3/s (Prelovšek, 2009). The Črni potok Stream joins the underground Pivka River in Otoška Jama (Fig. 6.3). Also the Studenške ponikve Stream, with similar flow rate to the Črni potok Stream, presumably recharges the underground Pivka River (Habič, 1985).

We presume that contribution of outflow from fissures and matrix into conduits is minor in Postojnska Jama system. The length of monitored underground drainage is relatively short; therefore the total amount of slow outflow from matrix to the conduit flow should be limited. More important role than diffuse flow from matrix to conduit can have autogenic recharge, which penetrates through highly karstified bedrock directly into the underground (Ford & Williams, 1989). Its contribution to total discharge of the underground Pivka River has not been evaluated and is hardly believed to be significant. According to all mentioned assumptions, discharge of the underground Pivka River may be considered as relatively steady along the entire monitored pathway of system. We decided to measure discharge at ponor and in Pivka Jama to verify this assumption. Anyway the difference between both discharges was in the range of error; therefore we can not make any certainly scientific conclusions based on measurements.

6.2. Measuring stations, measured parameters, purpose of measurements

Seven data loggers were installed along underground pathway of the Pivka River to study flow and transport. Water temperature and water level signals were measured by Van Essen (Schlumberger) data loggers called "divers". Instruments were installed at different locations in the underground river (Fig. 6.3). Data were recorded at 10 minutes and 15 minutes intervals.

Stage (water level) was measured at different locations to study hydraulic characteristics of the system and to observe the propagation of flood pulses through the system. Data of water temperature were analysed to determine some parameters such as transit time of water flow, thermal exchange between water flow and surrounding bedrock (also sediments in hyporheic zone).

The first data logger was installed at the ponor and the last one in Pivka Jama, which is around 3.5 km downstream (Fig. 6.3). Height difference between two the most remote stations is approximately 32 m. The most upstream station was just behind the ponor to obtain the input into the system. Input is magnitude of flow rate (water level was calculated into discharge) and thermal properties (temperature) of water. The most downstream station was in front of the phreatic loop at the end of Pivka Jama. The rest of five stations were distributed relatively regularly along the riverbed of the underground Pivka River. Distances between data loggers were about 700 m, 500 m, 600 m, 500 m, 250 m and 1000 m. All distances are approximations, as the system has not been measured properly. As we were interested also in the hydraulic functioning of the system, we tried to find locations where water level may fluctuate significantly during the transfer of flood pulses. Such locations are usually close to restrictions. However, locations were chosen carefully, to satisfy both aspects of research (thermal and hydraulic).

6.3. Methods for the local scale approach

6.3.1. Modeling and application of SWMM

Observed realistic transfer of flood pulse through the Postojnska Jama system may be compared with modeled transfer. For this purpose, “Storm water management model” (SWMM) was applied. It is a computer program, made to model water flow within pipes. Such a model can be applied because water flow through the conduits of Postojnska Jama system is relatively uniform and similar to water flow through pipes.

Input of realistic flood pulse, measured at the ponor, was put in the model with simplified geometry, representing the Postojnska Jama system. Comparison between modeled and realistic hydraulic response can be done and parameters of the model can be changed to adjust both hydraulic responses. Anyway, changed parameters should still be reliable as possible. Peterson & Wicks (2006) made a study of significance of certain parameters to alter hydraulic response of the model. SWMM is minimally sensitive to slope, but slight changes in Manning's roughness coefficient can highly alter the simulated response. Length and width of the conduit have similar significant influence on the hydraulic response, according to Peterson & Wicks (2006).

6.3.2. Data mining method for future prediction of hydraulic response of the Postojnska Jama system

Hydraulic response at all six monitored underground locations is a function of inflow. Hence, characteristic inflow-stage relation can be obtained for each of six locations. According to such relations and known input to the system (discharge), hydraulic response can be estimated without measurements inside the cave.

We build a model based on training data. Predicted results were compared with measured data, to evaluate the reliability of the future prediction.

6.3.3. Diurnal temperature variations of the Pivka River

Water temperature as a natural tracer was applied, to study hydrodynamic (transit times of water flow, water flow velocities) and thermal characteristics (thermal exchange between underground water and surrounding rock massif, sediments in hyporheic zone) of the underground river in Postojnska Jama system. Surface water usually has characteristic temperature properties. The Pivka River has, like other surface flows, diurnal temperature maximum and minimum. Rivers have usually diurnal maximum in the afternoon (due to solar radiation) and diurnal minimum in the morning, when also air temperatures are the lowest. On the other hand, a small volume of water (as the Pivka River usually has) is more sensitive to diurnal variations because the thermal influence of the surroundings is greater (Gu & Li, 2002).

Diurnal variations of the Pivka River are usually in range 0.5°C to 2°C. However, maxima and minima measured at the ponor often appear at the unusual (reverse) part of the day cycle. It may be explained as an anthropogenic factor (pollution with waste water?), because distribution of diurnal variations is totally normal a few km upstream, as proved by measurements.

When water flow with characteristic diurnal temperature variations enters the karst underground, variations can be preserved for some time and length in the underground system, depending on residence time of underground water, flow volume (discharge) and geometry of the cave system (Dogwiler and Wicks, 2005). Hence a temperature signal can be traced in the underground and applied to assess transit time of water, or mean flow velocity consequently, if length of underground pathway is known. Also some equilibrium temperature (thermal exchange) between underground water and bedrock (sediments) may be theoretically estimated, as amplitude of diurnal variations decreases along the underground pathway of the river.

- Transit times and velocity of underground drainage

When water with certain temperature characteristics enters the cave, the temperature signal travels along the pathway of the underground system with velocity supposed to be equal to mean flow velocity. Devices installed at locations along the underground pathway of the Pivka River, measure and store the water temperature signals. Hence diurnal temperature maxima and minima are detected. Certain maximum (or minimum) appears at downstream station with some phase shift, due to its appearance at upstream station (Fig. 6.5). Such phase shift corresponds to time delay, which represents transit time of water between these two stations (Birk et al., 2004). Time delay varies with flow rate. The higher the flow rate, the lower the time delay (water transit time). Consequently, by applying water transit time along the known length of underground pathway, the mean velocity of underground flow for certain reach within the cave can be determined, at specific flow rate. It is also one purpose of this research.

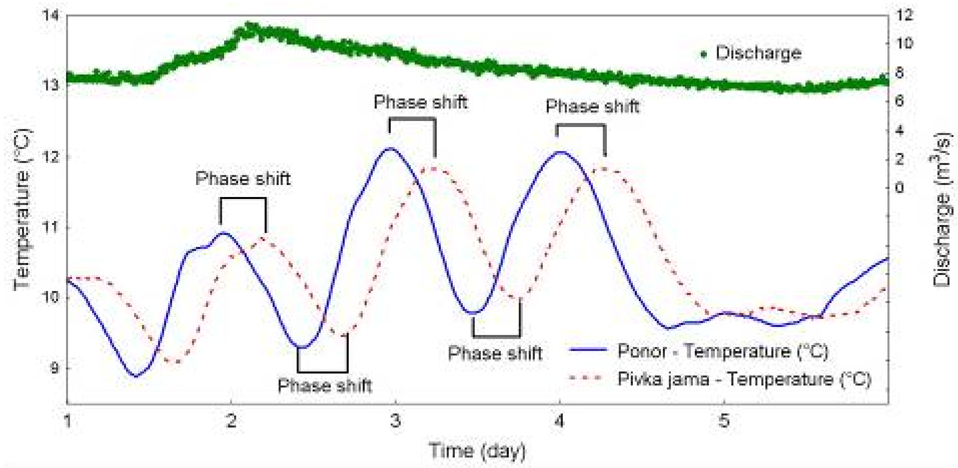

Figure 6.5: Diurnal temperature variations measured at the ponor and in Pivka Jama (3.5 km downstream). Observe the phase shift between the same diurnal maximum or minimum measured at two different locations (blue and red curve). Also discharge is plotted (green curve).

- Temperature equilibrium between underground water and bedrock, sediments

Underground water exchanges heat with its surroundings and tends to establish equilibrium temperature with surrounding rocks and sediments (hyporheic zone) through conductive and advective processes in the underground. The longer the retention (transit) time of the water underground, the more heat is exchanged between media. Water residing in a karst system long enough will fully equilibrate to an ambient temperature that is a direct reflection of mean annual temperature (Dogwiler & Wicks, 2005). Because of this, dampening of variation of water temperature along pathway of the underground Pivka River can be observed. Amplitudes of diurnal variations decrease along the cave system (Fig. 6.5). The difference in amplitude of the same signal, measured at two different locations, would be equal to mean thermal exchange between water and surrounding along certain distance in some perfect and totally isolated underground system. Hence, temperature data can be theoretically used to determine equilibrium temperature which establishes with heat flux between two media. The length required for achieving thermal equilibrium is mainly dependent on retention time of the water (Dogwiler and Wicks, 2005).

6.3.4. Tracer test

Furthermore, a tracer test was done in Postojnska Jama system. Artificial water soluble tracer was injected into the Pivka River, just a few metres in front of the ponor. Transition of the tracer cloud through Postojnska Jama system was recorded by three fluorimeters. First one was in Otoška Jama, the second in Magdalena Jama and the last one in Pivka Jama (Fig. 6.3). Fluorimeters were installed at the same locations, as the data loggers.

The main purpose of the tracer test was to compare the transition of water-soluble tracer (sulphorhodamine) and natural tracer (temperature) within the underground system. The tracer cloud should be traced at all seven locations, as underground temperature, to enable the optimal comparison of transition of two substances within the underground system. This was impossible due to the lack of fluorimeters. But comparison based on three sites is sufficient for our survey.

6.4. APPLICATION OF THE STORM WATER MANAGEMENT MODEL (SWMM) TO STUDY HYDRAULIC RESPONSE OF THE SYSTEM TO FLOOD INPUT

6.4.1. Introduction and representation of the SWMM

Storm Water Management Model (USA EPA, Environmental Protection Agency, www.epa.gov/ednnrmrl/models/swmm/) was primary developed to simulate single event or long-term simulation of runoff quantity and quality through sewer and other drainage systems in urban areas. Hence, runoff in SWMM is transported through a system of pipes, channels, storage devices, pumps and flow regulators. Anyway SWMM has many applications in non urban areas as well (Rossman, 2004). Functioning of underground drainage through a well developed conduit system in karst may be may be roughly described as a system of pipes and channels. Therefore SWMM may be used to model flow and solute transport through a system of conduits in the epiphreatic zone of karst massif, but some requirements should be fulfilled and some limitations should be taken into consideration.

Main requirements and limitations of the SWMM in karst (Campbell & Sullivan, 2002; Peterson & Wicks, 2006; Wu et al., 2008) are:

- Internal geometry of the karst system should be known. Parameters such as conduit geometry (cross-sectional area and length), hydraulic gradient (the slope of conduits) and also the roughness of conduits should be known or at least well estimated. A lot of parameters need to be specified and it is impossible to incorporate their variation into the model completely, even if we are capable measuring them all (very probably not).
- Furthermore, the recharge into the system (allogenic or autogenic) should be measured to obtain input data for runoff through the system. Input to the model can be based on runoff hydrographs and rain gauge stations at the surface of the catchment area.
- Conduit permeability, which drains the great majority of flood water - around 90 % or more (Bonacci, 1987; Jeannin, 2001), appears together with fissure and matrix permeability. Applying SWMM, drainage through fissures and water exchange between matrix and conduits is neglected. But the error, as a consequence of the neglected exchange, should be minor in comparison with other simplifications (geometry and roughness coefficient).

- SWMM operates with constant cross-sectional areas of conduits, while conduits in karst are enlarging continuously by dissolution processes in longer term. Hence SWMM is not adequate to model evolution processes of karst conduits.

6.4.2. Some recent applications of the SWMM in karst

Campbell & Sullivan (2002) applied SWMM to simulate flow and temporal changes of water level for a Stephen Gap Cave (Alabama, USA). The main purpose of the simulation was to estimate losses from a surface stream to the cave. They simulated water levels and flow rates in the cave passages as a function of time. The losses calculated by SWMM showed that rising and falling limbs of the stage – discharge plot followed the same curve (no hysteresis occurred). Campbell and Sullivan concluded that utility of SWMM for analysing cave flows was established. SWMM produced stable solutions with very low continuity errors for Stephen Gap Cave.

Gabrovšek & Peric (2006) applied SWMM to observe the relation between flow and water level (stage) in a system of four sloping conduits with different diameter. Input to the model was linear with symmetric rising and recession limb. The stage – flow curve exhibits hysteresis, which was explained as a consequence of flooding, caused by restrictions.

Flood pulse (discharge), with linearly increasing and decreasing limbs, was additionally put into simple model of large conduit ending with single restriction. Stage response to such linear flood pulse was observed in the large conduit in front of the restriction. The length of the conduit was constant at first (1 km), but height of the restriction downstream was changed. Gabrovšek & Peric observed that as the height of the restriction decreases, the flow through it becomes more and more distorted and the stage curves become distorted in graph H(t). The lower the height of the restriction more significant are flooding and hysteresis (on plot H(Q)). In next phase, they changed the length of the input conduit, but the height of the downstream restriction remained constant. In such a case, stage curves depend on permeability of restriction and on distortion of the flood pulse (an input) due to its propagation through the conduit with open channel flow, according to Gabrovšek & Peric (2006).

Peterson & Wicks (2006) tried to asses the importance of conduit geometry and hydraulic parameters in karst systems using the SWMM. The role of these parameters, to control transport dynamics within the karst aquifer was studied. For this purpose, SWMM was applied to build a model of Devil's Icebox - Conor's Cave system (central Missouri, USA). Conduit geometry and hydraulic parameters were incrementally changed in the model. Output, obtained at certain parameter conditions, was compared to an output measured in the field. They concluded that ten per cent changes in the length or width of a conduit produced statistically significant different fluid flow response. Moreover, even slight changes of Manning's roughness coefficient can highly alter the simulated input. On the contrary, the model is minimally sensitive to the slope and infiltration rates.

Wu et al. (2008) tried to simulate the hydrological response of Shuifang karst spring (China) by SWMM. They made several field surveys (dye tracing, infiltration test, measurement of flow rates at the spring and mapping of the study area) to provide input parameters for SWMM. Modeled hydrographs show good agreement with the hydrographs obtained at the field. Rapid recharge through conduits and slow, low inflow from the fissures and matrix were correctly represented by the model.

6.4.3. Conceptual model of the SWMM

SWMM incorporates several compositional elements, such as rain gauges, subcatchments, junction nodes, outfall nodes, flow divider nodes, storage units, conduits, pumps and flow regulators.

Rain gauges represent the precipitation input to the land surface in SWMM. Land surface is represented by subcathments, which transfer input to groundwater. Some portion of inflow, reaching groundwater, transfers to the transport. Transport compartment is finally represented by a network of conveyance elements and treatment units, which transport water to outfalls (Rossman, 2004).

Description of applied SWMM components

Not all of the available compositional elements were used to build a model of Postojnska Jama system, as we are interested exclusively in transport compartment (aquifer). We applied following elements:

Junction nodes

Conduits of different geometrical properties are joined together by junctions (Fig. 6.6) Junctions therefore represent points of flow divergence and convergence; they can have multiple inputs and outputs. Also external inflows can enter the system at junction. Junctions have no storage.

Essential input parameters of junctions are:
- invert elevation
- height from invert elevation to ground surface (maximal depth)
- initial water depth in junction (by default zero, optionally changed in front of important hydraulic restrictions)
- external inflow data (recharge to the system)
- treatment (concentration of tracer as a pollutant, which is injected to the system at the node)
- ponded surface area when flooded (no ponding by default, ponding may be set optionally)

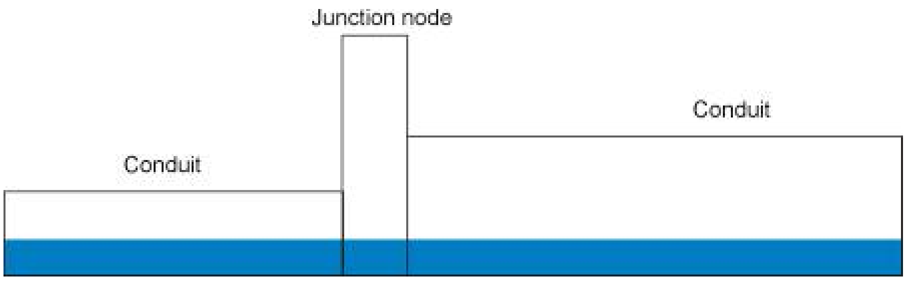

Figure 6.6: Sketch of two conduits of different geometry joined by junction node.

Storage units

Storage units have similar role as junction nodes. In contrast with junction nodes, they represent also some storage facility. The height-area curve can be linear, exponential or tabled, volumetric properties of storage unit can be set by a linear or exponential function. A storage unit may be used as a proxy of underground lake in chamber or along conduit. Or it may represent some similar large pool of stagnant underground water. Underground lakes appear frequently in the system, especially in front of hydraulic restrictions such as breakdowns.
Input parameters for storage units are the same as for junction nodes.

Outfall nodes

Outfalls are final nodes of the drainage system. Invert elevation of the outfall was the only parameter, which was essential for our purpose. Optionally, downstream boundary conditions can be defined for dynamic wave routing.

Conduits

Pipes or conduits of different or equal geometry drain water from one node to another. Program enables selection of several different cross-section shapes for conduits; from regular cross-sectional geometry (circular, rectangular, ellipsoidal etc.) to irregular and customary geometry. Slope of the conduits (hydraulic gradient) is defined by it length and the invert elevation of inlet and outlet nodes. Open channel and full pipe flow within conduits are described by Manning's equation.

Essential input parameters of conduits are:

- conduit length
- cross-sectional geometry
- Manning's roughness coefficient
- offset heights of the conduit above the inlet and outlet node inverts
- Coefficient of entrance and exit losses (losses were supposed to be zero for our purpose)

Flow regulators

Flow regulators are structures used to control and divert flows within the conveyance system. They are typically used for engineering purposes. Appearance of such structures is limited in the karst drainage systems.

However restrictions such as breakdowns, which dammed underground drainage, can behave as weirs (Fig. 6.7). Transverse and side flow type of weirs with rectangular cross-section shape is the most optimal to model underground spilling over the restriction such as breakdown. Applied input parameters for weirs are:

- vertical height of weir opening
- horizontal length of weir crest
- depth of bottom of weir opening from the inlet node invert
- discharge coefficient for central portion of weir (set as default value)

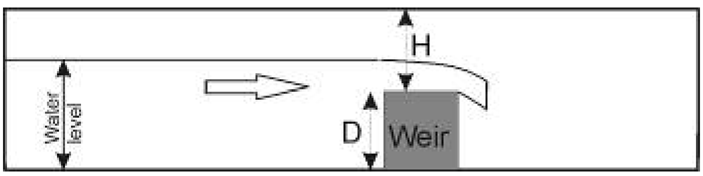

Figure 6.7: Sketch of a weir. *H* is vertical height of weir opening and *D* is depth of bottom of weir opening from the inlet node invert.

Flow routing

Hydrographs (flow) and chemographs (pollutants, tracers) are routed through the modeled system, built of different elements, by the transport process.

Flow routing within a conduit link in SWMM, which is governed by Saint-Venant equations for gradually varied, turbulent and unsteady flow, can be studied by several approaches (Rossman, 2004):

- Kinematic wave routing (solves the continuity equation along with a simplified form of the momentum equation in each conduit. Flow may vary spatially and temporally within a conduit, causing delayed outflow hydrograph, due to the inflow).
- Dynamic wave routing (solves Saint-Venant equation on the basis of continuity and momentum equations for conduits and a volume continuity equation at nodes)
- Steady flow routing (treats flow as uniform and steady for all computed time periods)

Dynamic wave routing was chosen, as it is the only one which can handle pressurized flow, flow reversal, minor losses and backwater effect. Dynamic wave routing produces the most accurate results in comparison with other two types of routing (Rossman, 2006).

Based on conservation momentum and mass conservation of Saint-Venant equations discharge, area and water depth at the outlet of each conduit can be calculated for each time step of flow routing (Peterson & Wicks, 2006).

- **Mass conservation**:

Mass conservation for one-dimensional free surface flow with no lateral flow in the x-direction is given by (de Rooij, 2008):

$$W(h)\frac{\partial h}{\partial t}+\frac{\partial Q}{\partial x}=0$$

where W is top width of the free surface, h is the flow depth, t is time, Q is flow rate and v is velocity (Fig. 6.8).

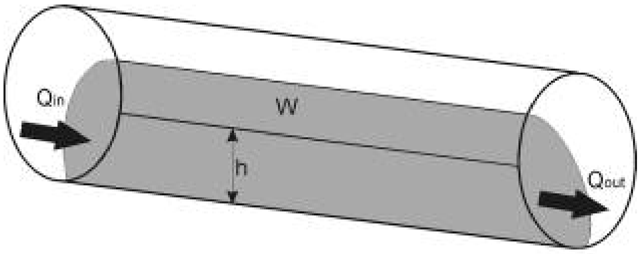

Figure 6.8: Sketch of water flow through conduit. *W* is top width of the free surface and *h* is the flow depth.

- **Momentum conservation:**

Range of change of momentum conservation is equal to the forces acting on it. These forces are gravitational force, force due to the static pressure change, acceleration and friction force (Prelovšek et al., 2007).

$$\frac{\partial h}{\partial x} + \frac{v}{g}\frac{\partial v}{\partial x} + \frac{1}{g}\frac{\partial v}{\partial t} = s_0 - s_f$$

where v is an average velocity across the whole depth profile, s_0 is a channel slope and s_f is a friction slope.

Friction slope s_f, which represents the effects of turbulence and viscosity, is calculated by Manning's equation in SWMM (Peterson & Wicks, 2006):

$$s_f = \frac{n^2 Q^2}{A^2 R^{4/3}}$$

where n is Manning's roughness coefficient and R is hydraulic radius.

Combining both equations, discharge Q may be calculated.

6.4.4. Hydraulic model of Postojnska Jama system

SWMM was applied to simulate the hydraulic response of the Postojnska Jama system to a single or succession of flood inputs. Since the realistic response was measured at several locations within the system, the main purpose was to build a model which would give such a hydraulic response at each selected location, that would be as much as possible similar to the realistic one measured by data loggers.

The model is based on the relatively well known internal geometry of the system and realistic input time series (discharge measured at ponor). One of the most essential parameters, roughness coefficient was only estimated, due to the lack of data of its (unknown) variation within the underground system.

6.4.4.1. Structure of the model of Postojnska Jama system

Schematic sketch of a model is shown in Fig. 6.9. Only the main, permanently active conduit system of the model is represented in this figure. We assumed also divergence of water flow in some parts of the underground system. These parts with secondary channels (bypasses) are shown in Figs. 6.10, 6.11 and 6.12.

The model of drainage network consists of 20 conduits, 4 weirs, 6 junctions, 10 storage units and one final outfall. Parameters of all elements are shown in Tabs. 2 and 3.

Junctions are applied mainly in the first part of the system and are replaced by storage units in the inner part of the system, where flow becomes more obstructed by hydraulic restrictions. Ponding is much intensive in this section of the cave, where several pools appear. Water can be a few metres deep in such pools even at base flow and drainage extremely slow.

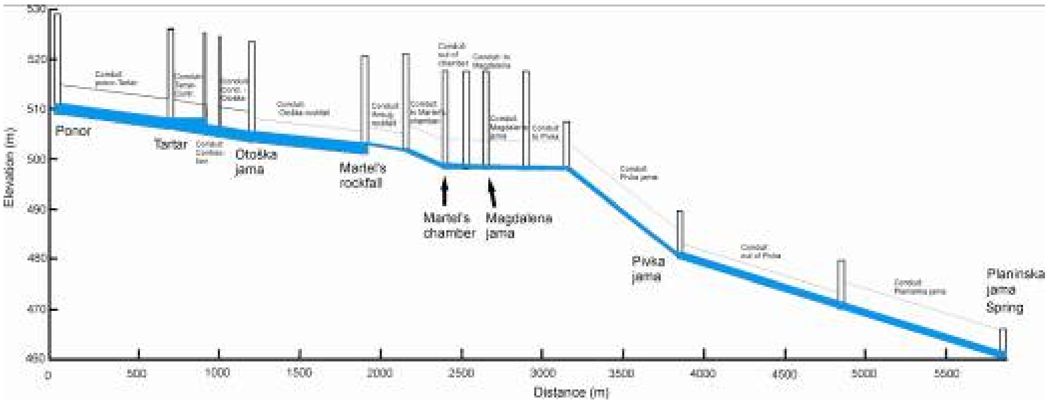

Figure 6.9: Longitudinal cross-section of the underground Pivka River system. Only the main, permanently active conduit system is represented in the figure.

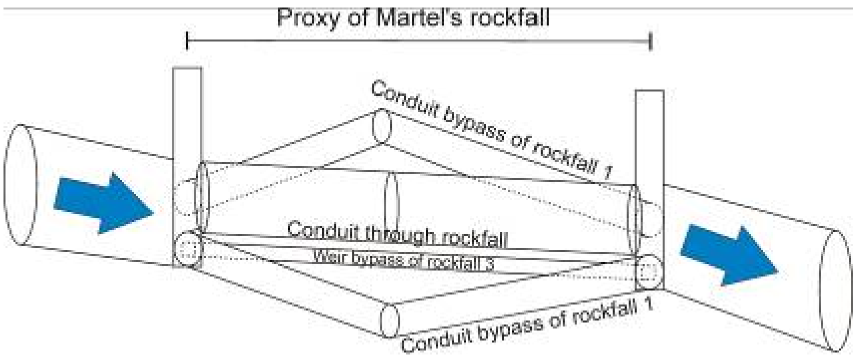

Figure 6.10: Flow through Martel's rock-fall was modeled as a flow through a relatively low permeable conduit. Bypasses, which avoid significant hydraulic restrictions, often occur in karst aquifers. Hence, three bypasses were incorporated into the model.

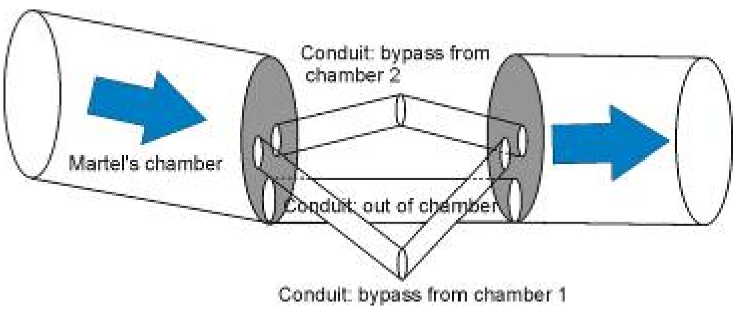

Figure 6.11: Geometry of Martel's chamber is well known. The main, permanently active conduit has relatively low permeability. There are another two conduits, situated at higher elevation, which become active at relatively high water conditions.

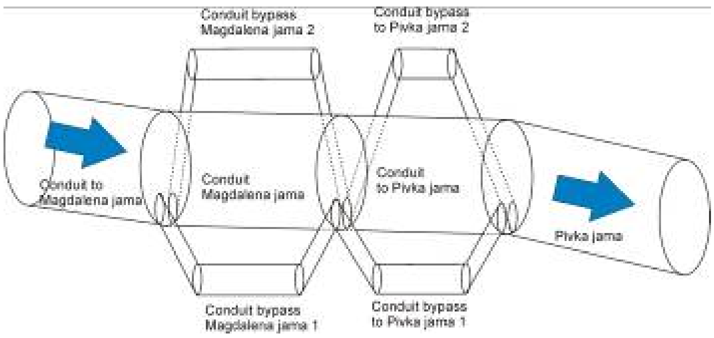

Figure 6.12: Several phreatic loops appear in the reach between Magdalena Jama and Pivka Jama, hence this reach is accessible to divers only. We have very limited data about the geometry of this part of the cave. However, divergence of underground flow to bypasses is possible there. We assumed bypasses of different length: 500 m (bypasses marked with number 1) and 1000 m (bypasses marked with number 2), while length of main conduits is only 250 m.

Table 2: Geometrical parameters of conduit system, representing a model of Postojnska Jama.

Type and name of conveyer	Cross-sectional dimensions [m^2]	Length [m]	Roughness [-]	Inlet offset [m]	Weir opening [m]
Conduit: ponor-Tartar	6 x 10	700	0.035	0	/
Conduit: Tartar-Contraction	6 x 10	240	0.035	0	/
Conduit: contraction	3 x 3	20	0.035	0	/
Conduit: Contraction-Otoška	6 x 10	240	0.035	0	/
Conduit: Otoška-rock-fall	5 x 5	700	0.035	0	/
Conduit: through rock-fall	4 x 4	250	0.035	2	/
Conduit: bypass of rock-fall 1	2 x 2	300	0.035	3	/
Conduit: bypass of rock-fall 2	2 x 2	300	0.035	0	/
Weir: bypass of rockfall 3	/	/	/	0.5	1 x 1
Conduit: to Martel's chamber	6 x 10	250	0.035	0	/
Conduit: out of chamber	1.5 x 1.5	125	0.035	0	/
Conduit: bypass chamber 1	2x2	125	0.035	2	/
conduit: bypass from chamber 2	3x3	125	0.035	3	/
Conduit: to Magdalena	6 x 10	125	0.035	0	/
Conduit: Magdalena Jama	6 x 10	250	0.07	0	/
Conduit: bypass Magdalena 1	2 x 2	500	0.035	0	/
Conduit: bypass Magdalena 2	2 x 2	1000	0.035	0	/
Conduit: to Pivka	6 x 10	250	0.07	0	/
Conduit: bypass to Pivka 1	2 x 2	500	0.035	0	/
Conduit: bypass to Pivka 2	2 x 2	1000	0.035	0	/
Conduit: Pivka Jama	6 x 10	700	0.035	0	/
Conduit: out of Pivka	3.5 x 3.5	1000	0.035	0	/
Weir: out of Pivka	/	/	/	0	5 x 0.1
Conduit: Planinska Jama	6 x 10	1000	0.035	0	/

Table 3: Hydraulical parameters of nodes in a model.

Type and name of node	Invert elevation [m]	Maximal depth [m]	Initial depth [m]
Junction: ponor	509	20	0
Junction: Tartar	506	20	0
Junction: Contraction 1	504.75	20	0
Junction: Contraction 2	504.5	20	0
Junction: Otoška Jama	503.5	20	0
Junction: rock-fall	501	20	0.5
Storage after rock-fall	501.5	20	0
Storage unit: Martel's chamber	498	20	0.2
Storage unit: after M. chamber	498	20	0
Storage unit: bypass after M. chamber	498	20	0
Storage unit: Magdalena Jama	498	20	0.5
Storage unit: after Magdalena 1	497.9	20	0
Storage unit: after Magdalena 2	497.8	10	0
Storage unit: Pivka Jama	480	10	0
Storage unit: after Pivka	470	10	0
Storage unit: bypass after Pivka	480	10	0
Outfall: Planinska Jama spring	460	/	/

Overflowing (i.e. activation of secondary conduits, situated at higher levels) definitely occurs at least in some parts of the cave; hence weirs were applied to simulate overflowing. Weirs in the SWMM link two adjacent (nearby) storage units or nodes as an overflow. Overflow from primary into secondary conveying system can occur at relatively high flow rates only in our model, while all base flow drains through primary conduits. However secondary and primary conduit systems converge together at first next downstream node in our model.

Inflow to the modeled system is direct. It means that surface runoff enters the system through the most upstream junction (ponor) as an allogenic input, and it drains underground through system of conduits and nodes to final outfall. Allogenic recharge was calculated by measurements of water level of the Pivka River at the ponor. This discharge represents an input time series for the model.
Dry weather recharge of the system and ground water infiltration are also possible in SWMM, but have not been applied in our model, even if in reality both occur. Contribution of such inflows is minor and may be easily neglected for the modeled purposes. The Črni potok sinking stream could contribute some percentages of water to base flow of underground Pivka. Presumably minor is also autogenic recharge from the surface area. Contribution of the outflow from matrix is undoubtedly

negligible due to the relatively short length of the system. This was already discussed in chapter 6.1.

6.4.4.2. Parameters settings

- The slope of the riverbed (which may be also considered as a proxy of hydraulic gradient at relatively low water conditions) is not a constant in the system of Postojnska Jama; it varies spatially in the underground system. For example, conduits have cascade morphology (alternation of steps and pools) in the first part of the underground system, which reflect in relatively fast alternation of local hydraulic gradients (at base flow conditions) (Fig. 6.13).

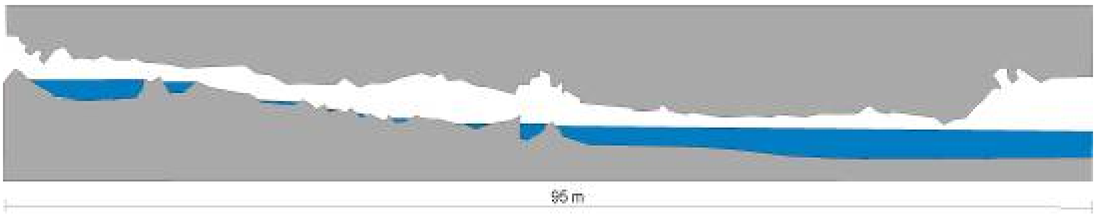

Figure 6.13: Longitudinal profile of a small section of conduit between Tartar and Otoška Jama. Morphology of the riverbed of the conduit is cascade, due to alternation of steps and pools. Water level in the sketch corresponds to base flow conditions. There is important contraction (channel narrowing) on the right end of the figure.

Hydraulic gradient is locally much more stable in other, more downstream parts of the underground system, where pools with length of few hundred metres appear. Gradient is almost negligible along such pools; all gradient can be attributed to the short, intermediate stream reaches between two pools.

Like every model, ours is a simplified picture of reality. Of course it is not possible to include all the geometry variations of a natural cave system to the model. Therefore, variations were simplified by dividing the system into a few major segments, each having some average, characteristic slope.

Hydraulic gradient along the river is closely related to the channel slope at the base flow. This is not valid during significant floods when the total head becomes almost uniform along some parts of the system (Fig. 6.14).

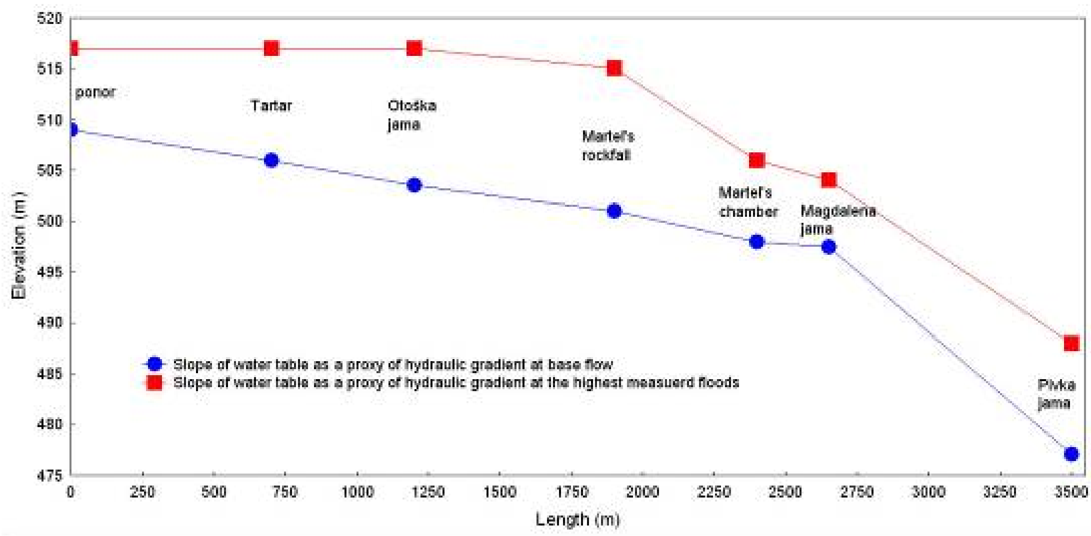

Figure 6.14: Total head at seven monitored locations in Postojnska Jama system at base flow condition (blue points) and at extreme flood condition (red points). Slope of the water table among the seven monitored stations, as a proxy of hydraulic gradient, is also depicted.

- Geometry, especially cross-section of conduits, is very irregular and variable. Therefore its variation can not be modeled at all. This parameter was probably simplified the most. Rectangular cross-sections of all conduits was applied to the model. Only dimensions and length of such conduits was different. Small dimensions of cross-section were attributed to parts of the underground system, where the most significant hydraulic restrictions occur.

- There are no data about actual values of roughness coefficient in Postojnska Jama system. We can assume only that it varies within the system. Values of Manning's roughness vary between 0.015 and 0.07 in natural streams (Schulze et al., 2005). There is much less data about Manning's roughness for underground conduit systems. It is often considered as a constant value for modeling purposes, due to lack of data and to simplify the models. Peterson & Wicks (2006) estimated it to 0.035 for the model purpose (the model of Devil's Icebox-Conner's Cave basin - USA). The same value was applied also for riverbed and bank of the underground Pivka River.

6.4.5. Hydraulic response of the Postojnska Jama system to flood pulses: comparison of realistic and modeled (SWMM) response

A succession of realistic flood pulses with different magnitude, measured at the ponor was put to the described model. We chose time series from March to end of May 2008 and routed it through the model. This discharge time series include 12 distinctive flood pulses, with maximal discharge 32 m^3/s (Fig. 6.15).

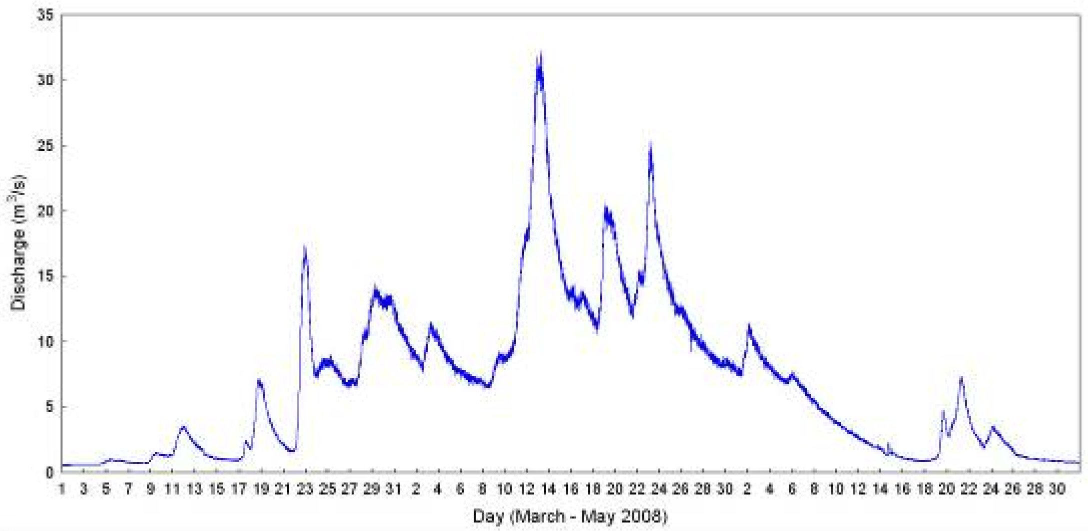

Figure 6.15: Discharge time series from March to May 2008 was routed through the SWMM model of Postojnska Jama system.

Hydraulic response of the model at certain locations, where data loggers have been installed, was observed every 10 minutes during the transition of discussed time series. Dynamic wave routing had the time step of 30 seconds, but the reporting had the same interval as realistic measurements in the system; i.e. 10 min. Therefore realistic and modeled hydraulic responses were compared.

Magdalena Jama was not monitored in discussed time period (March – May 2009) (Fig. 6.16), hence another discharge time series from October to December 4th 2009 (Fig. 6.17) was routed through the model to compare modeled and realistic hydraulic response of Magdalena Jama with reporting interval of 15 min.

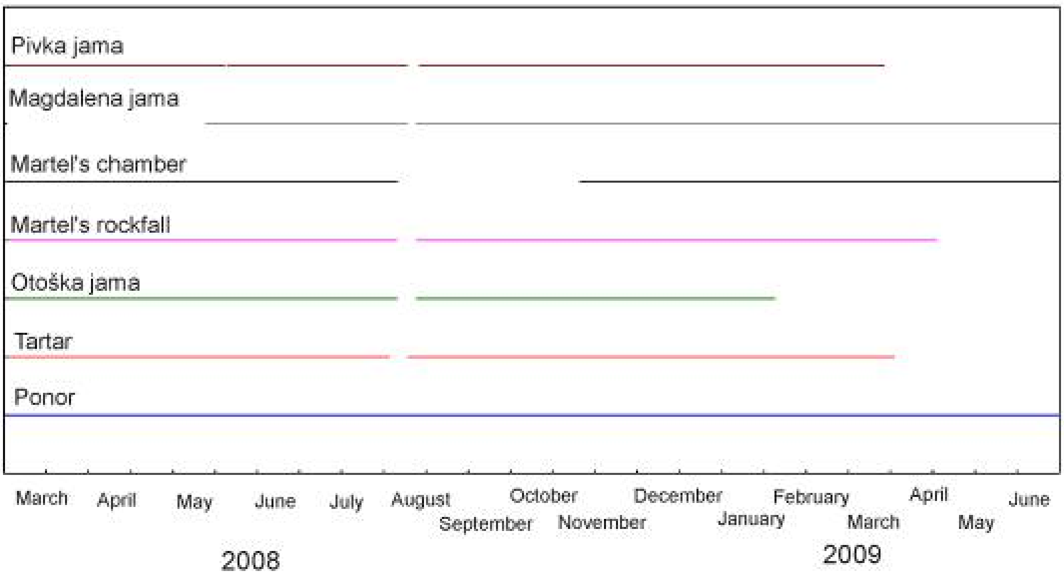

Figure 6.16: Distribution of measurements at seven stations in Postojnska Jama system.

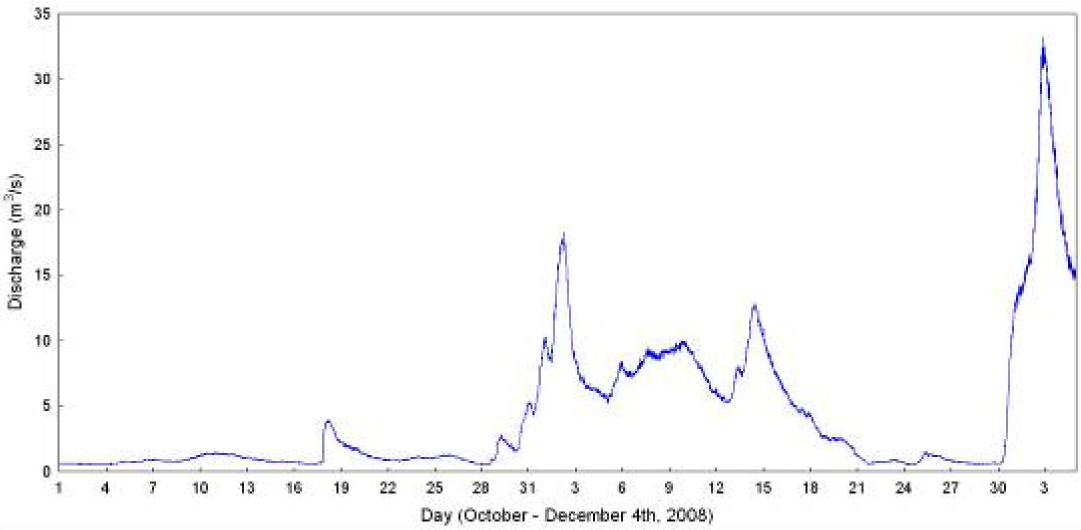

Figure 6.17: Discharge time series from October to December 2008 was routed through the SWMM model of Postojnska Jama system, to observe modeled hydraulic response of Magdalena Jama.

We compared measured and modeled stage curves at all selected stations. Moreover measured and modeled inflow Q (m^3/s) - stage H (cm or m) relations were plotted and compared with each other. H(Q) relation in any part of the system directly depends on inflow and geometry of the conduits, which are situated downstream from monitored micro-location. Therefore the shape of H(Q) curve is different in front of different hydraulic restrictions, which are of special interest for our study. The shape of H(Q) curve strongly depends on local channel geometry, which varies with the height of the water at each location. For example flood waters can find more permeable bypasses at higher levels.

6.4.5.1. Tartar

The most upstream part of the cave system is highly permeable; we put to the model only one hydraulic restriction (contraction of the conduit). One contraction is in reality situated downstream from Tartar, however it is still large enough to drain a great part of flood waters approximately up to 20 m^3/s, without occurrence of ponding (see Fig. 6.13, contraction is in the right part of the figure). Assumption is based on H(Q) relation in Tartar (Fig. 6.18). Water level increases relatively gently dependent on flow rate. Increase becomes steeper at flow rates above 20 m^3/s, which can indicate significance of ponding caused by the hydraulic restriction situated downstream from Tartar. However, the most important hydraulic restriction within the monitored system is the Martel's rock-fall, located approximately 1200 m downstream from the Tartar monitoring station. Ponding caused in front of Martel's rock-fall can induce increase of water level at Tartar and even at the ponor.

- Comparison of measured and modeled data in Tartar

The model of the most upstream section of the cave system consists of large conduit (6 m x 10 m), which is contracted (3 m x 3 m) for a short length (20 m) in section between Tartar and Otoška Jama. Hence flow of flood water through such contraction is restricted. Ponding, which in reality occurs in Tartar at flow rates above 20 m^3/s, may be explained by the discussed contraction or some other hydraulic restriction situated downstream from Tartar. We assumed in our model that the discussed contraction induces ponding in Tartar. Comparison of the model data with real data shows good fitting, modeled values are underestimated when ponding occurs (at inflow above 18 m^3/s - 20 m^3/s) (Figs. 6.19 and 6.20).

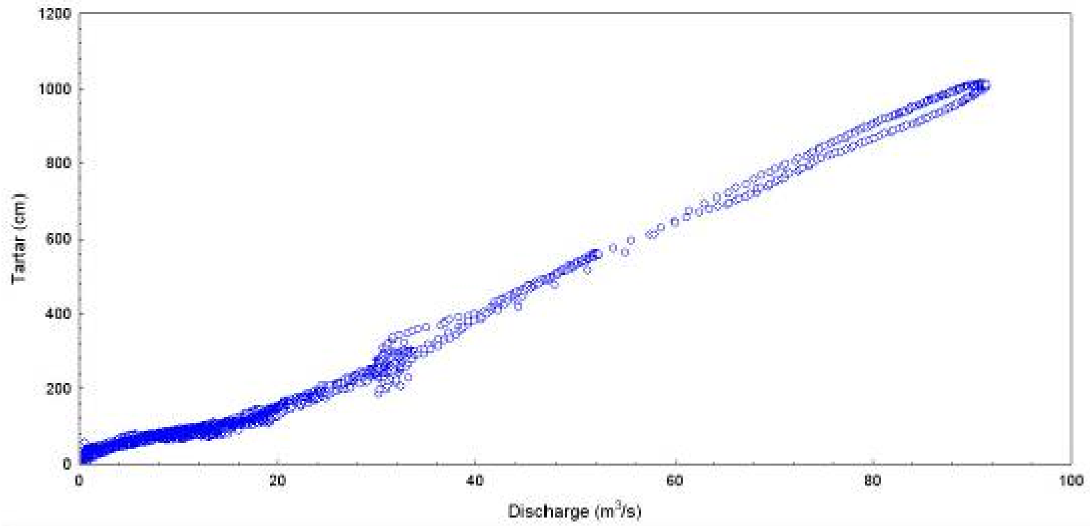

Figure 6.18: Stage in Tartar depends mainly on topography of underground channel, till inflow increases to around 20 m^3/s. At higher inflows ponding occurs and inclination of H(Q) curve becomes steeper.

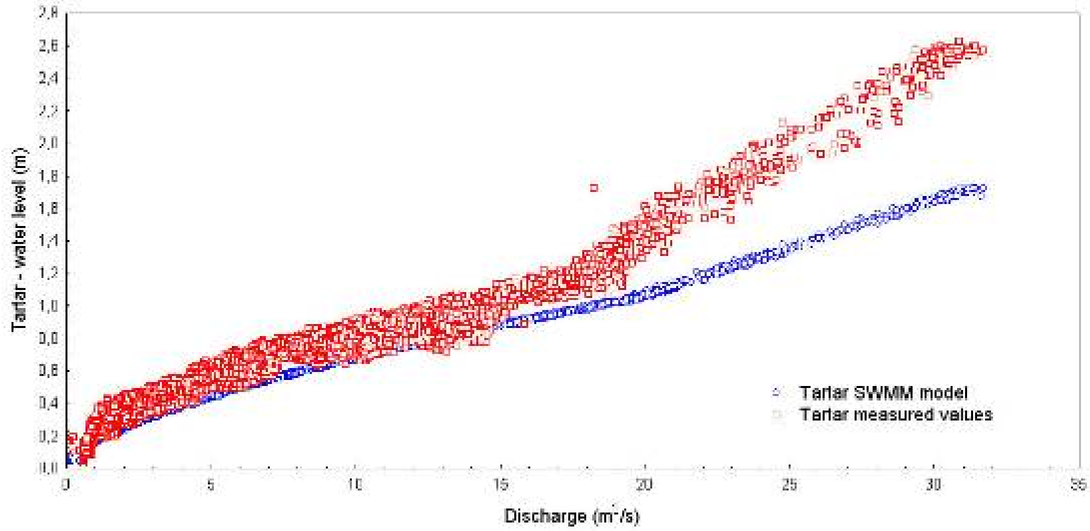

Figure 6.19: Measured and modeled data fit well when flow is below 20 m^3/s. At higher flow rates, local hydraulic restriction causes ponding.

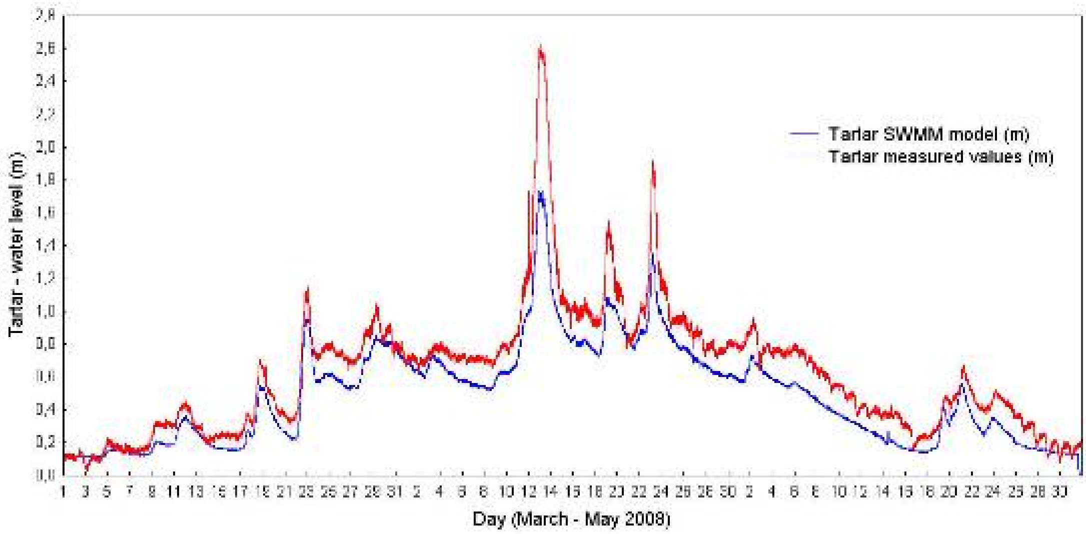

Figure 6.20: Comparison between measured and modeled stage in Tartar for period March – May 2008. The highest measured stages (above 1.2 m) correspond to increase of water level caused by ponding.

6.4.5.2. Otoška Jama

Hydraulic response in Otoška Jama is very similar to that in Tartar. This part of the cave is well permeable. But stage (H) – inflow (Q) relation in Otoška Jama is influenced already by ponding at lower flow rates than in Tartar (Fig. 6.21). Such influence occurs at flow rate above about 8 m^3/s. Also there are some local conduit contractions downstream from Otoška Jama, which may cause ponding. However ponding undoubtedly occurs also in front of relatively low permeable Martel's rock-fall. This rock-fall is situated approximately 700 m downstream from Otoška Jama.

- Comparison of measured and modeled data in Otoška Jama

Otoška Jama has very similar hydraulic characteristics to Tartar, the only difference is that ponding occurs at lower inflow in Otoška Jama than in Tartar. We believe that ponding of water in Otoška jama is mainly result of ponding, which occurs in front of Martel's rock-fall downstream. Hence fitting between measured and modelled hydraulic response in Otoška Jama depends on reliability of the model in front of Martel's rock-fall. This model is represented in continuation. The error of the model of Otoška Jama increases with magnitude of inflow (Figs. 6.22 and 6.23), due to overestimation of rock-fall permeability in the model.

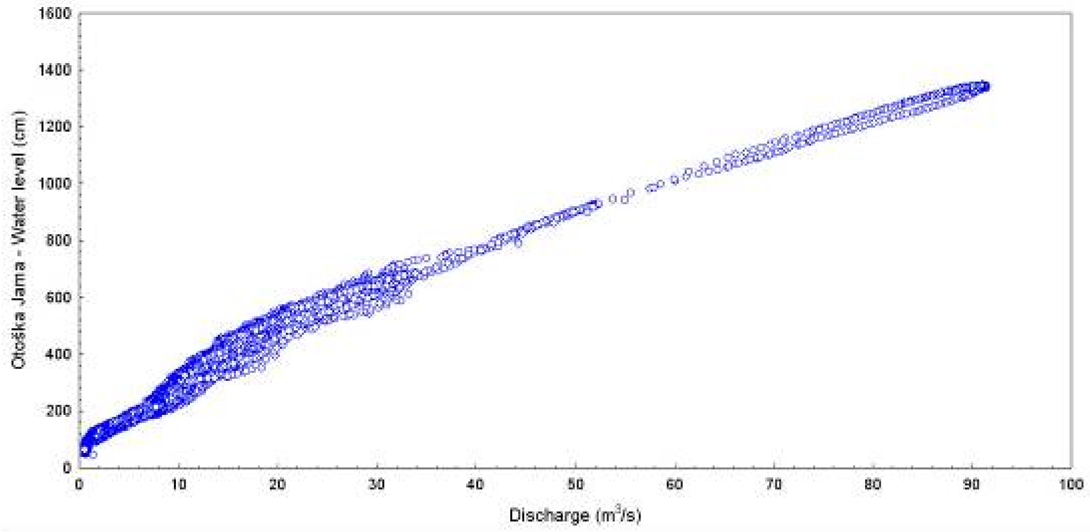

Figure 6.21: Similar as in Tartar, stage in Otoška Jama in first phase depends on inflow and topography of underground channel. Later, at inflow around 8 m^3/s, ponding assumably occurs.

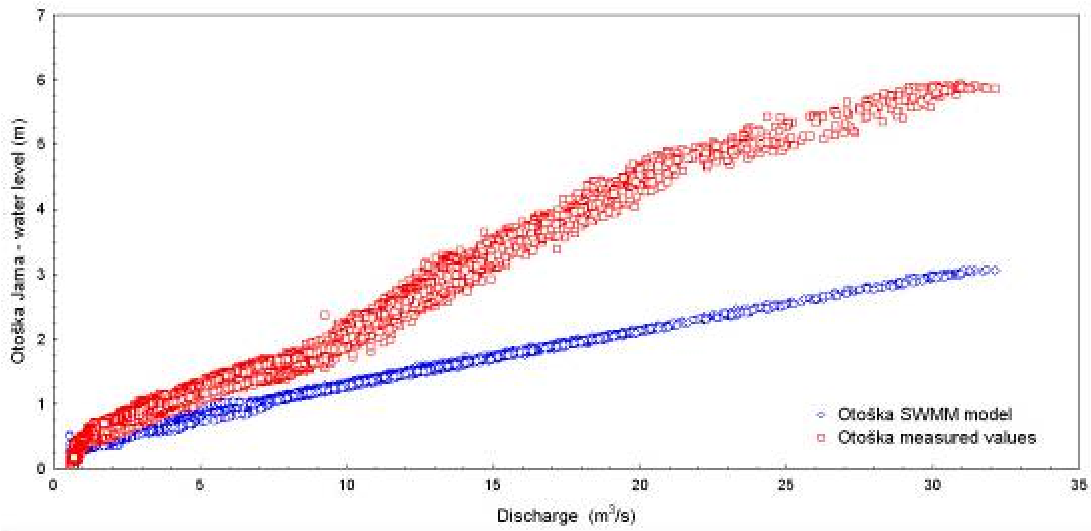

Figure 6.22: Measured and modeled data (in Otoška Jama) fit well when flow is below 8 m^3/s - 10 m^3/s. At higher flow rates, hydraulic restriction causes ponding. However this ponding is underestimated in a model.

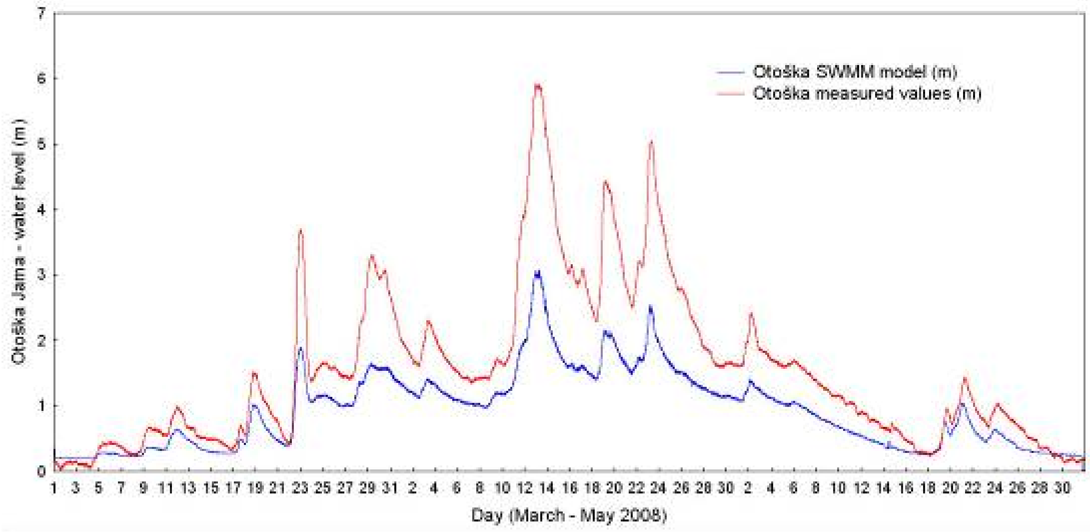

Figure 6.23: Comparison between measured and modeled stage in Otoška Jama for period March – May 2008. All measured stages higher than 2 m are associated with ponding, which was underestimated in a model.

6.4.5.3. Martel's rock-fall

Martel's rock-fall greatly obstructs the pathway of the underground Pivka River, as it stretches from the bottom of the conduit up to the ceiling. But water does not only penetrate through rock-fall, it also finds other pathways to traverse the rock-fall (at relatively high flow rate). However, Martel's rock-fall most probably represents the most important hydraulic restriction in the system of Postojnska Jama. Fluctuations of water level are the highest in front of the relatively low permeable Martel's rock-fall. Water level increases up to 14 metres (Fig. 6.24), according to our measurements (March 2007 - July 2009).

- Comparison of measured and modeled data in front of Martel's rock-fall

Drainage through porous media, such as breakdown, can not be directly modeled by SWMM, but Darcy flow looks like minor or even negligible (Fig. 6.24). Drainage takes place mainly through several bypasses. There is one bypass through which explorers can reach conduits on downstream side of the rock-fall. Because of the bypasses, divergence was applied in the model. Single conduit splits to four secondary conduits with different permeability (cross-section) and they converge together before next measuring station. Secondary conduits appear at different absolute heights; hence some of them are active at floods only (Fig. 6.10).

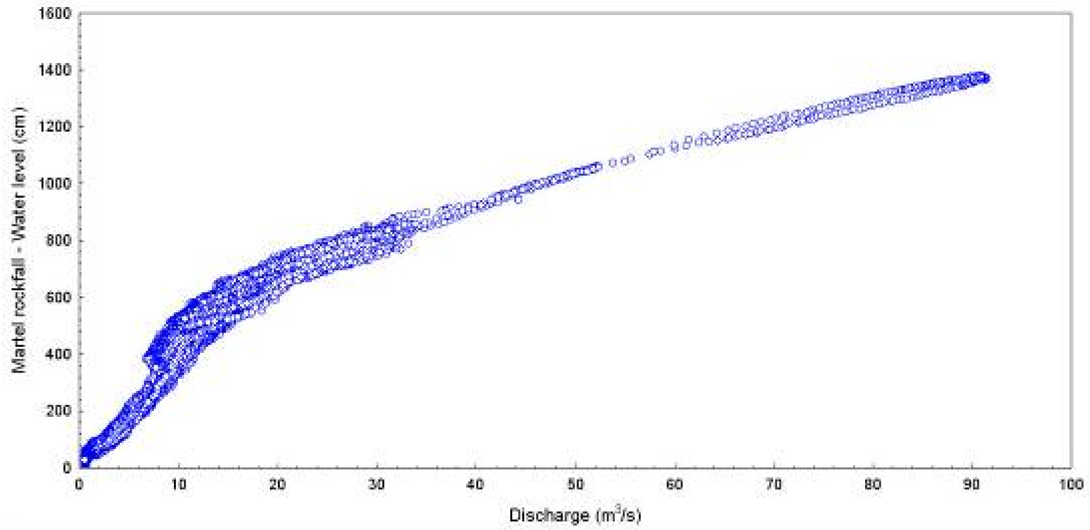

Figure 6.24: Stage rises relatively rapid with increasing discharge in front of the Martel's rock-fall. Inclination of stage-discharge curve becomes relatively gentle at the highest discharges, when water flows over higher bypasses.

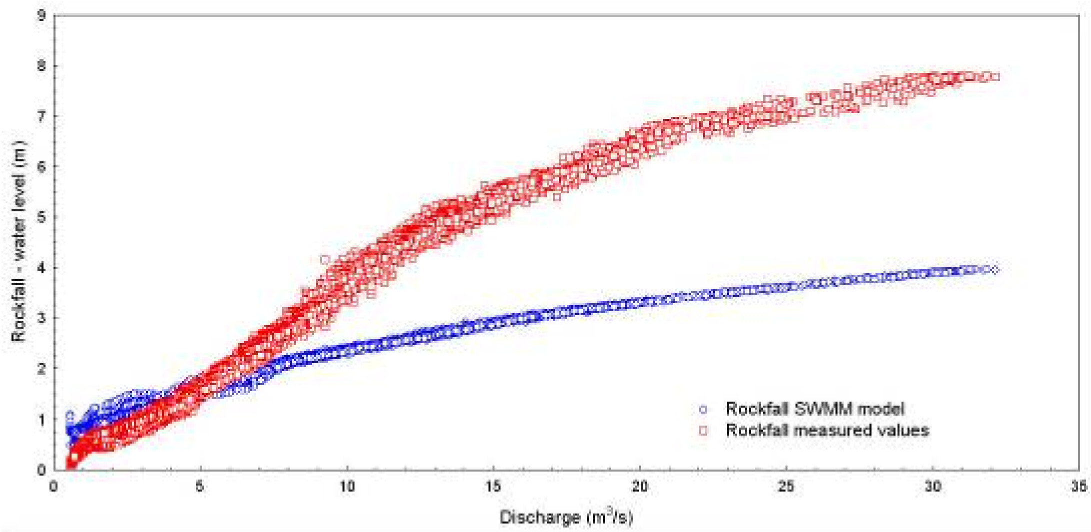

Figure 6.25: Modeled and measured H(Q) curves have similar shape, but modeled data are highly underestimated at higher flow rates.

Two compared stage – flow curves do not really fit together (Fig. 6.25). However, hydraulic response of model of Martel's rock-fall shows some relatively good correlation with realistic response at low flow rates, while correlation is low at high flow rates. Water levels are highly underestimated in the model during high inflows (Figs. 6.25 and 6.26). As SWMM deals with conduit permeability exclusively, permeability of the model is much higher than real permeability of the rock-fall. It may be one of reasons for low fitting at high discharges. Another reason is that geometry of bypasses may be oversized in the model. Instead of a few bypasses, there may be tens of them, but of relatively low diameter.

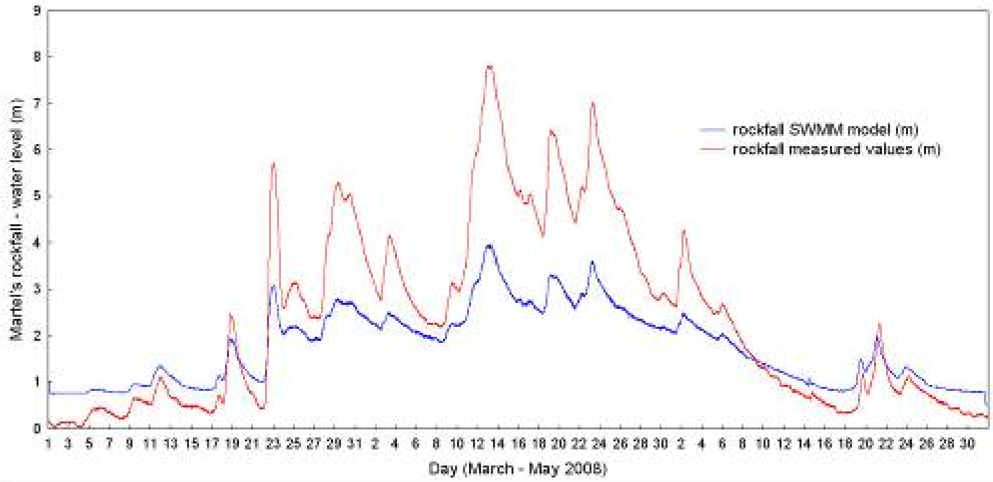

Figure 6.26: Comparison between measured and modeled stage in front of Martel's rock-fall for period March – May 2008. Permeability of the model is higher than real permeability of the rock-fall, as can be seen from differences in modeled and measured stages.

6.4.5.4. Martel's chamber

Outflow from Martel's chamber takes place through at least three known conduits, which occur at different levels. At flow rates below around 1 m^3/s – 2 m^3/s, the water drains out from the chamber laterally – via small conduit, which becomes fully flooded during each significant flood inflow (Fig. 6.27). Consequently, water level in a monitored pool increases, till it reaches a conduit at higher level. At the highest flow rates, additional conduits activate (Fig. 6.11). All these conduits presumably joins together somewhere in Magdalena Jama, downstream.

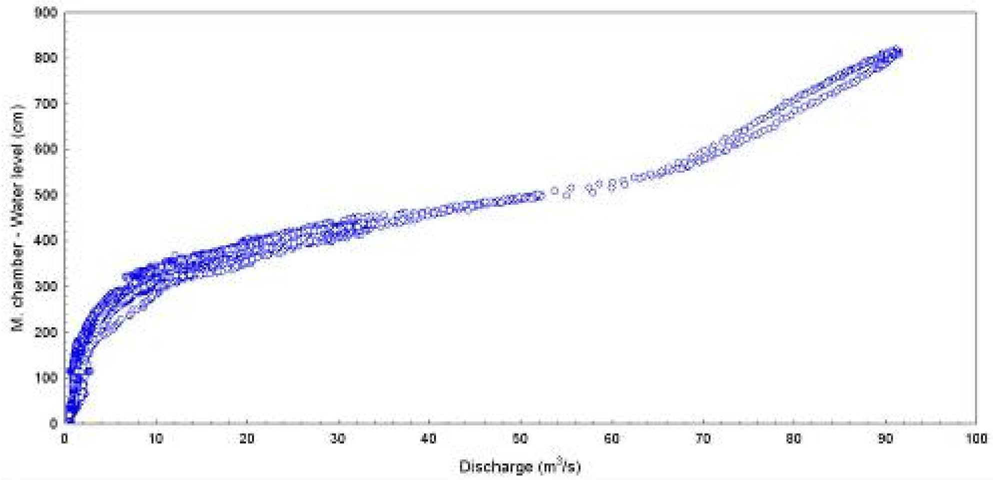

Figure 6.27: Stage in Martel's chamber is the most sensitive to relatively low inflows. Permanently active conduit, which drains water out of the chamber, is narrow and therefore low permeable. Later overflowing occurs.

- Comparison of measured and modeled data in Martel's chamber

The model, which represents outflow from Martel's chamber, is built of a single conduit, which diverges to three conduits. Water spills to two of them at sufficient flow rates only, as they are situated at higher levels (Fig. 6.11).

Modeled hydraulic response is very similar (or almost identical) to the real response (Fig. 6.28). The only problem is the altitude of water level at low water conditions (water level is overestimated in the model) (Fig. 6.29).

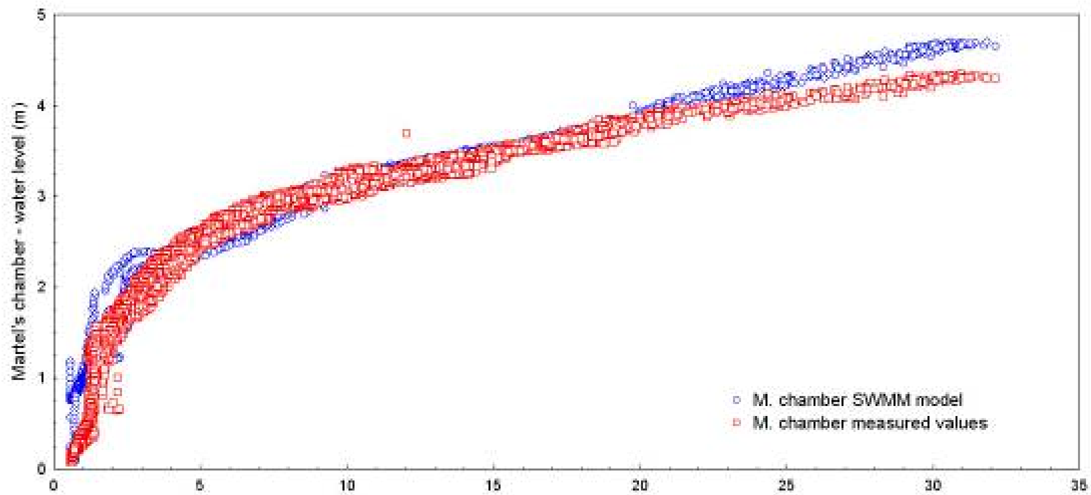

Figure 6.28: Modeled and measured H(Q) curves fit very well.

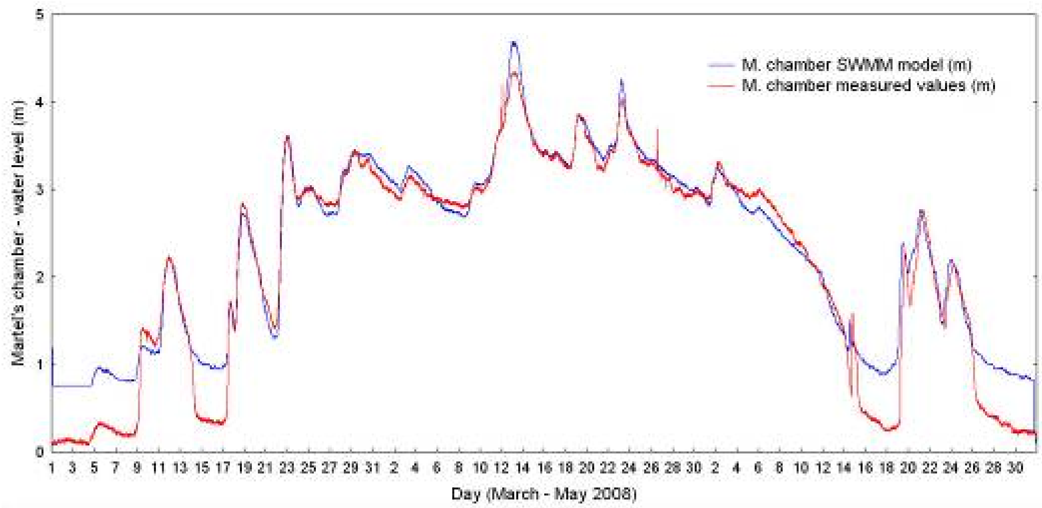

Figure 6.29: Comparison between measured and modeled stage in Martel's chamber for period March – May 2008. Modeled and realistic stages do not fit well at the lowest water conditions only.

6.4.5.5. Magdalena Jama

Water flow distributes laterally over a larger area in Magdalena Jama. It is distributed within many lateral and parallel conduits and pools. Hence, of all six stations, fluctuations of water level are the lowest in Magdalena Jama. Outflow from the Magdalena Jama takes place through several phreatic loops, which appear in downstream direction toward Pivka Jama. Stage – inflow relation, obtained in Magdalena Jama, is linear (Fig. 6.30). Phreatic loop looks capable to transmit all inflowing water synchronically, which would be a reason for a linear relation.

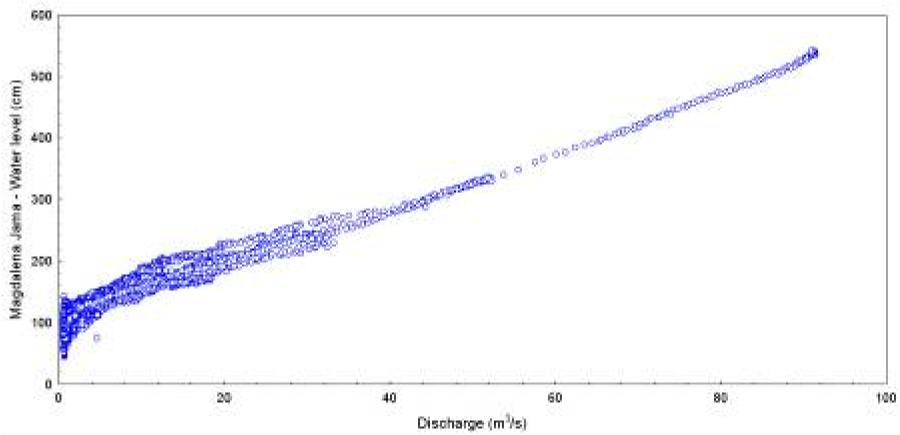

Figure 6.30: Stage increases linearly with inflow in Magdalena Jama

- Comparison of measured and modeled data in Magdalena Jama

Magdalena Jama and its downstream part were modeled as a part of system with negligible hydraulic gradient. Outflow from Magdalena Jama takes place through one main channel and two secondary channels in our model.

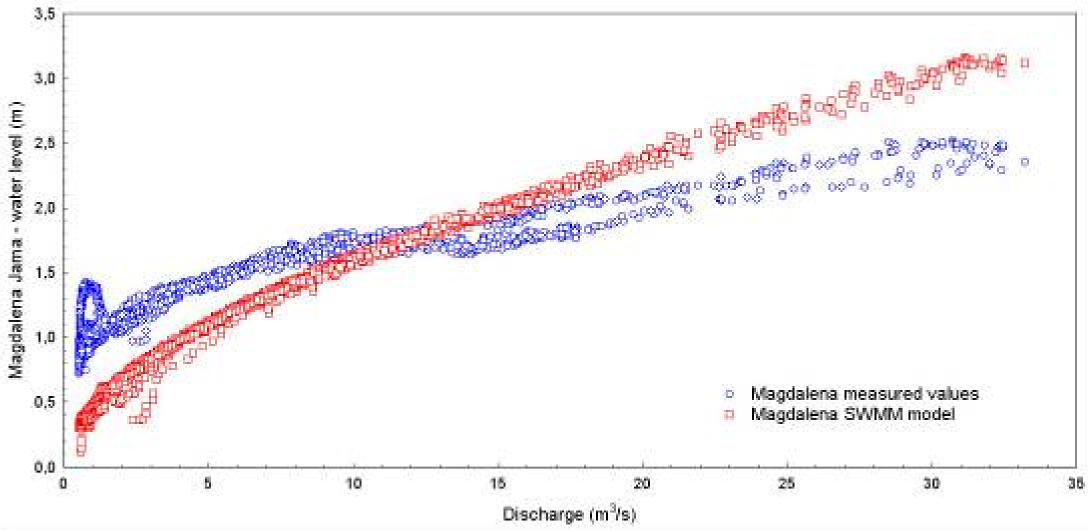

Figure 6.31: Measured and modeled data fit well together, due to not complicated, almost linear H(Q) relation in Magdalena Jama.

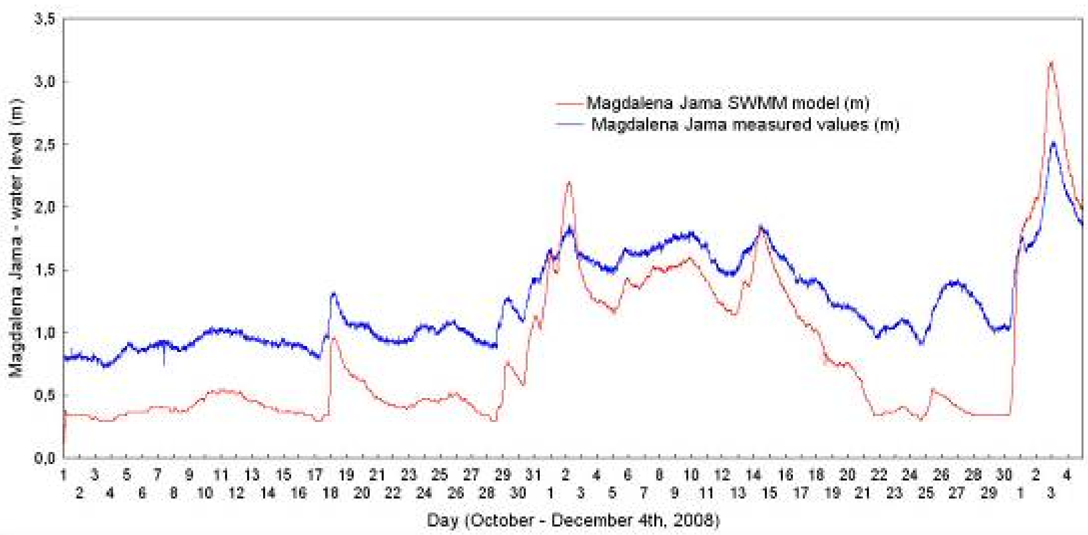

Figure 6.32: Comparison between measured and modeled stage in Magdalena Jama for period October – December 4th 2008. Magdalena Jama was not monitored in period March - May 2008, as were all other parts of the system.

Modeled hydraulic response is similar as measured one, differences occur only in magnitude of increase of stage during transition of flood pulses (Figs. 6.31 and 6.32). Modeled stage is underestimated at inflows below 10 m^3/s and overestimated at higher inflows. Error of modeled hydraulic response does not exceed 1 m, but fluctuations of water level are low in Magdalena Jama (of a few metres only).

6.4.5.6. Pivka Jama

The pool, situated directly in front of a phreatic loop, was monitored in Pivka Jama. All inflowing water is relatively easily transmitted downstream through the phreatic loop, toward Planinska Jama (spring), which is situated around 3.5 km downstream. H(Q) relation is almost totally linear in Pivka Jama (Fig. 6.33). There is not much known about the geometry of conduits between Pivka Jama and Planinska Jama for they are largely still unexplored.

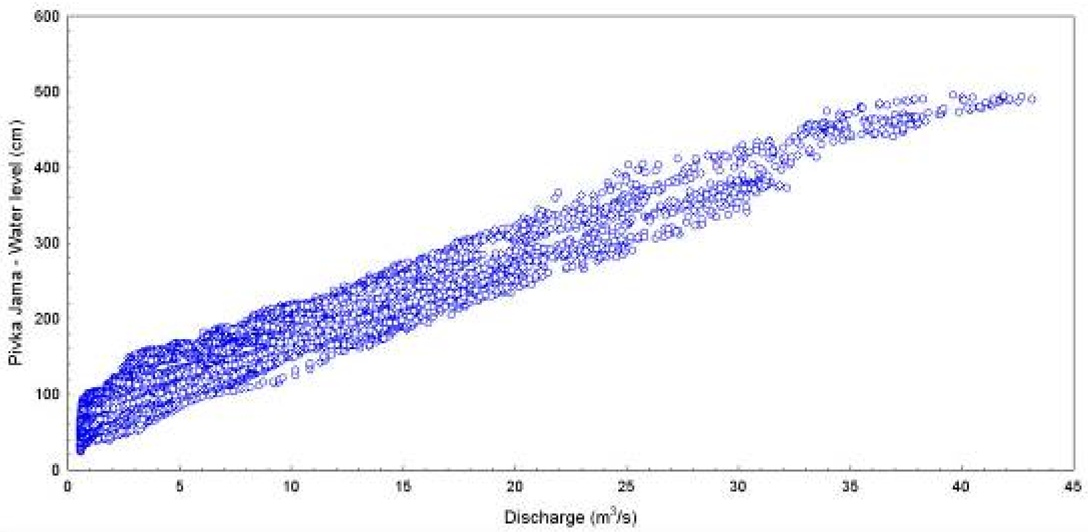

Figure 6.33: Stage increases linearly with inflow in Pivka Jama.

- Comparison of measured and modeled data in Pivka Jama

In a model, we assumed combination of outflow through relatively narrow conduit (relatively low permeable) and spilling to a neighbour chamber, from where water drains unrestricted.

Fitting between measured and modeled responses was relatively good, with correlation coefficient r = 0.992. Fitting was the best at this station (Fig. 6.34).

Modeled values are totally similar as measured ones; they are only underestimated for around 0.5 m (Figs. 6.34 and 6.35).

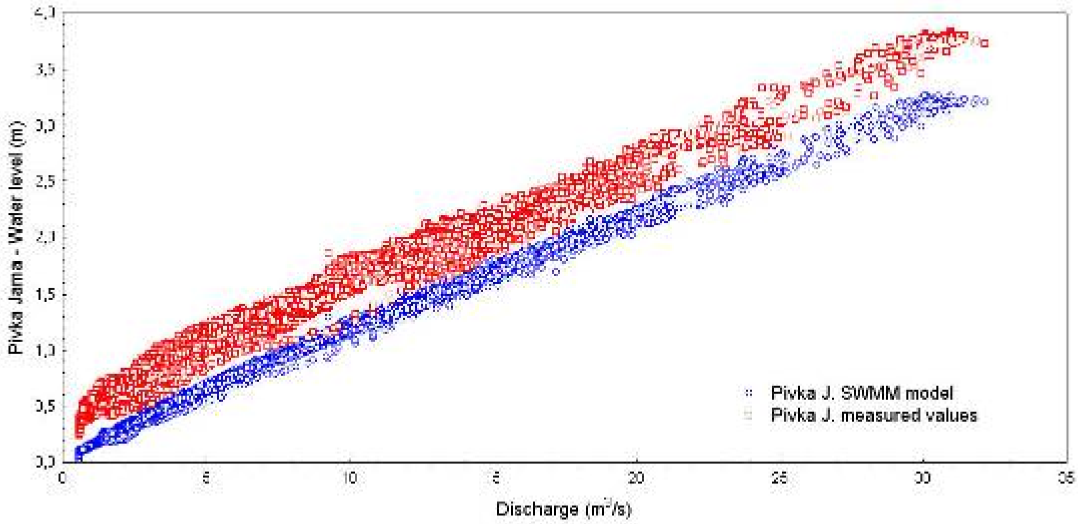

Figure 6.34: Measured and modeled data would fit together perfectly in Pivka Jama, if modeled data were not slightly underestimated.

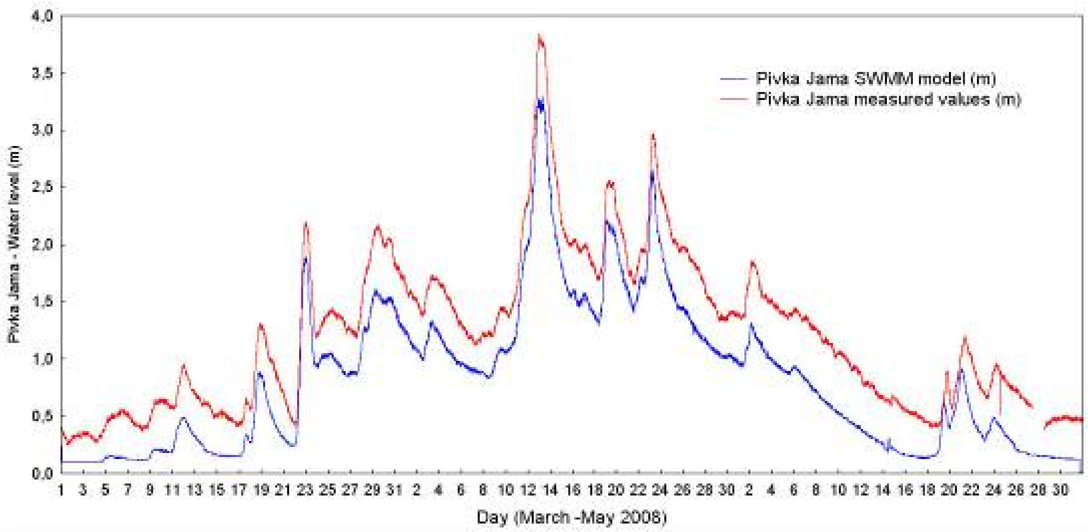

Figure 6.35: Comparison between measured and modeled stage in Pivka Jama for period March – May 2008.

6.4.6. Conclusion

Correlation coefficient, as a measure of comparison between measured and modeled hydraulic responses, is not totally reliable for our purpose. Correlation coefficients are significantly high (above 0.95) at all six places (Tab. 4). Such high correlation is mainly a consequence of input applied in the model. As the input is based on real (measured) data, it is quite logical that modeled response is in high correlation with measured hydraulic response in Postojnska Jama.

However, if we compare only relative values of the correlation coefficient between modeled and measured hydraulic response, we observe that the highest correlation was obtained for the most downstream location monitored in Pivka Jama. But also flow and stage are in good linear relation in Pivka Jama (Fig. 6.34). Such linear relation can be explained as a segment, while the curve should change its shape at higher discharges, as were measured.

Also Magdalena Jama, just upstream from Pivka Jama, has similar hydraulic characteristics to Pivka Jama. Outflow from Magdalena Jama is also controlled by phreatic loops and there is also linear H(Q) relation, probably for the same reason. However, measured and modeled responses show the lowest correlation there. The reason should be in very low range of stage fluctuation in Magdalena Jama. Significance of air pressure variation on measured stage is higher; consequently also an error may be higher.

Correlation between measured and modeled hydraulic response is also relatively low at Martel's rock-fall. We know for some bypasses, but hydraulics should be much more complicated there, as our model does not really represent good approximation of hydraulic processes, which take place at Martel's rock-fall.

Hydraulics of the most upstream monitored locations (Tartar and Otoška Jama) is non-complicated. Hydraulic response to increased inflow is directly influenced by topography of underground channel. At higher inflows, significant ponding occurs in Otoška Jama and also in Tartar. Ponding may be a consequence of some local restrictions (contractions of the conduit), which appear between Tartar - Otoška Jama and between Otoška Jama - Martel's rock-fall. But the most significant ponding certainly occurs in front of Martel's rock-fall.

Ponding in Otoška Jama is certainly caused by Martel's rock-fall. Height difference between Otoška Jama and Martel's rock-fall is 2.5 metres only. It was observed that water level increases for 2.5 m in front of the rock-fall at inflow rate approximately 8

m^3/s (it is flow rate which coincides with the beginning of ponding in Otoška Jama, see Fig. 6.22). Hence ponding at the Martel's rock-fall undoubtedly affects stage in Otoška Jama at such such discharge conditions (Figs. 6.36 and 6.37).

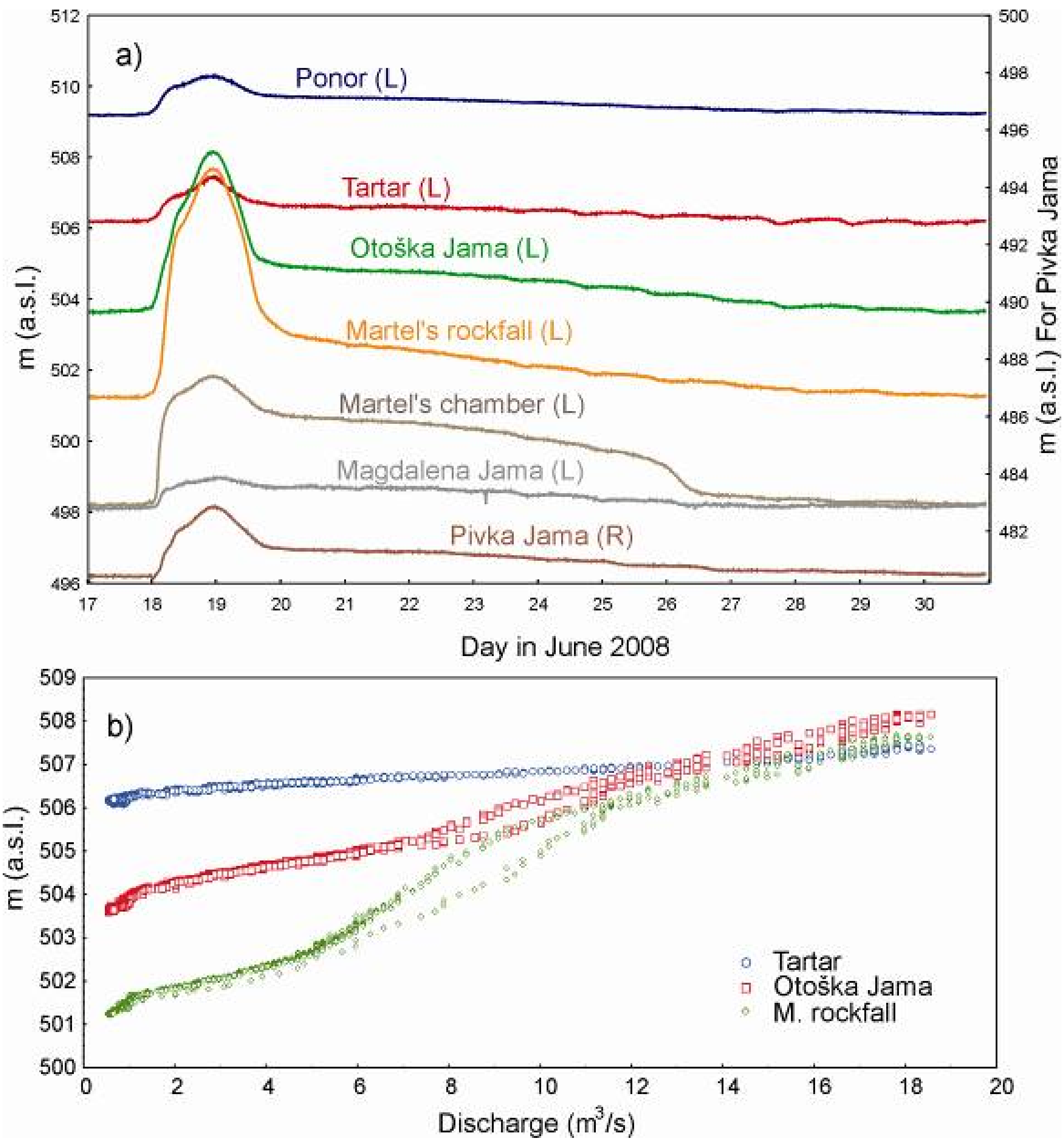

Figure 6.36 a, b: Example from June 2008. Ponding, which takes place in front of Martel's rock-fall, affects also the absolute height of water level in Otoška Jama and in Tartar upstream. The absolute height of water level is almost equal at all three locations during floods. Note that the absolute height of water level in Pivka Jama (a) is represented on right scale and not on the left as for other stations.

Similar may be assumed also for data logger in Tartar, which is situated 6 m higher then logger in front of rock-fall. Water level increases for 6 m in front of the rock-fall at flow rate around 18 – 20 m^3/s and ponding in Tartar begins (Figs. 6.18, 6.36 and 6.37).

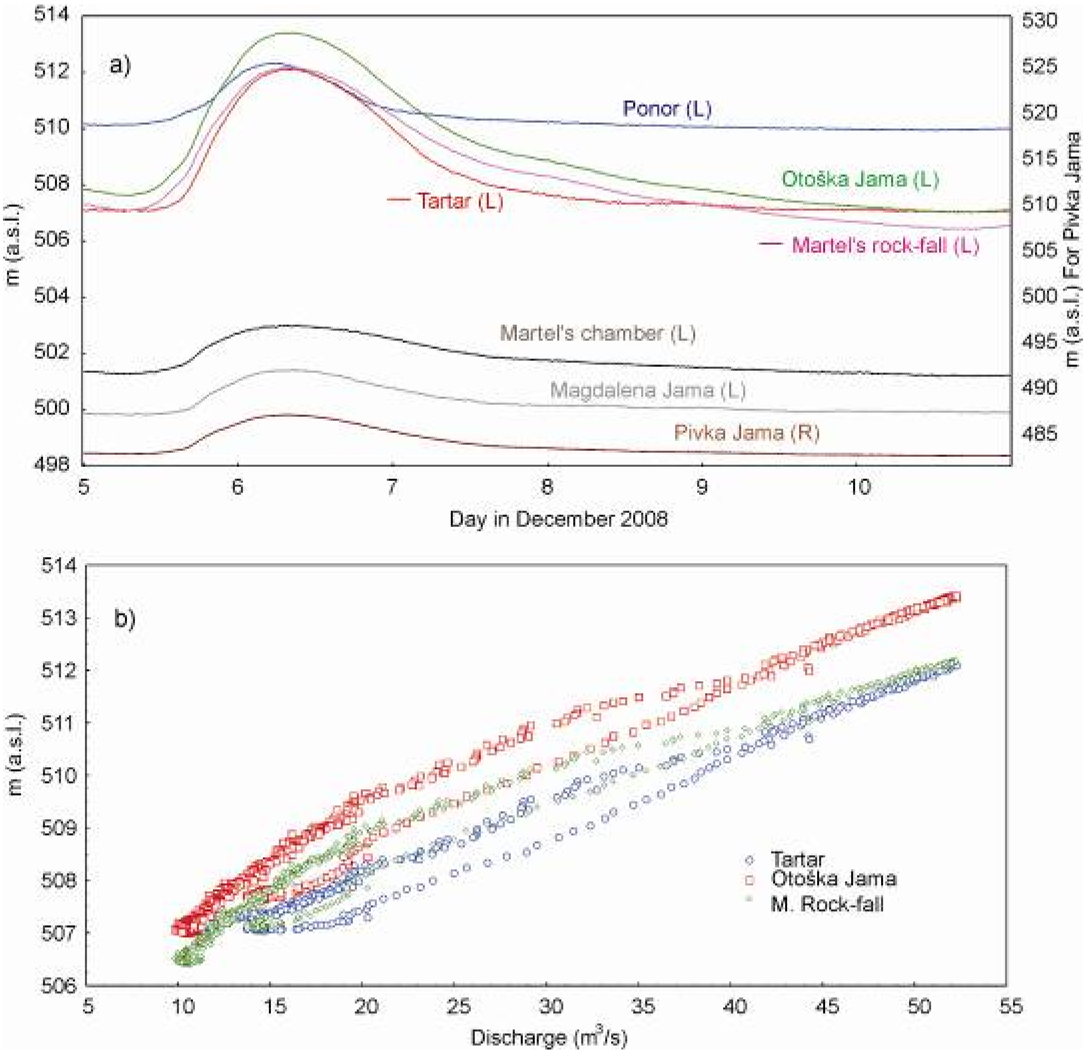

Figure 6.37 a, b: Example from December 2008. Ponding, which takes place in front of Martel's rock-fall, affects also the absolute height of water level in Otoška Jama and in Tartar upstream. The absolute height of water level is almost equal at all three locations during floods. Note that the absolute height of water level in Pivka Jama (a) is represented on right scale and not on the left as for other stations.

A good example of evaluation of SWMM in a conduit karst system is the model of Martel's chamber. Outflow from the chamber is well known, as it is mostly governed by three differently permeable conduits situated at different heights (Fig. 6.11). All three conduits were incorporated in a model. Correlation between measured and modeled hydraulic response could be higher, as two variables fits almost 100 %, but deviation occurs at low water conditions and reduces the relative value of the correlation coefficient.

Table 4: Correlation between modeled and real response of the water level regarding to variable inflow time series.

	Tartar	Otoška Jama	Martel's rock-fall	Martel's chamber	Magdalena Jama	Pivka Jama
Correlation coefficient	0.9595	0.9821	0.9875	0.9816	0.9547	0.9912

6.5. NUMERICAL PREDICTION OF HYDRAULIC RESPONSE OF THE POSTOJNSKA JAMA SYSTEM TO FLOOD INPUTS – APPLICATION OF DATA MINING ALGORITHM

Hydraulic response of the underground system to the flood input was measured at six monitored locations, as mentioned. The response at each of these locations is directly associated with magnitude of the flood input of the Pivka River (the flow rate). Hence, if the input (flow rate) is known, the hydraulic response at any of discussed locations within the cave system may be predicted. For this purpose, data mining technique was applied to predict hydraulic response of the system at known variable flow rates.

6.5.1. Data mining

Data mining technique is generally extraction of implicit, previously unknown, and potentially useful information from data. Computer programs sift through databases automatically, seeking regularities or patterns. Strong patterns, if found, will likely generalize to make accurate predictions on future data (Witten & Frank, 2005).

The **input to a data mining** is a single flat table comprising of columns and rows. Our input consists of two columns, which represent attributes. First attribute is the flow rate of the Pivka River (which is assumed to be spatially constant along pathway of Postojnska Jama system and temporally variable of course) and the second is water level at a certain monitored location. Generally, particular value of water level at each monitored location corresponds to a certain flow rate.

The **output of a data mining** algorithm is a pattern or a set of patterns that are valid in the given data. Patterns can be given in different forms, such as equations, classification and regression trees or rules. Form depends on applied data mining task (Džeroski, 2001). Main data mining task are predictive modeling (classification and regression), clustering (grouping similar objects) and summarization (association rules).

We applied predictive modeling (regression). The task of **regression** is concerned with predicting the value of one field from the values of other fields. The target field is called the class (dependent variable), while the attributes represent independent variables. A set of data is taken as input and a model is generated. Such a model is used to predict values of the class for new data.

A part of the data, called a **training set**, is typically used to generate a predictive model. The remaining part, which is reserved for evaluating the predictive performance of the learned model, is called the **testing set**. This testing set is used to estimate the performance of the model on new data. Hence the validity of the patterns may be estimated on new data (Džeroski, 2001).

Numeric prediction

Numeric prediction may be represented in the form of decision trees (Fig. 6.38). Such trees have hierarchical structure, where each internal node contains a test on an attribute. Each branch corresponds to an outcome of the test and each leaf node gives a prediction for the value of the class variable (Džeroski, 2001).

Leaf nodes give a classification that applies to all instances that reach the leaf, or a set of classifications, or a probability distribution over all possible classifications. To classify an unknown instance, it is routed down the tree according to the values of the attributes tested in successive nodes. When a leaf is reached, the instance is classified according to the class assigned to the leaf (Figs. 6.38 and 6.39).

Trees, which are used for numeric prediction, store at each leaf either a class value (that represents the average value of instances that reach the leaf, in which case the tree is called a ***regression tree***), or a linear regression model (that predicts the class value of instances that reach the leaf, in which case it is called a ***model tree***). Hence, the only difference between regression tree and model tree induction is that for the latter, each node is replaced by a regression equation instead of a constant value (Witten & Frank, 2005).

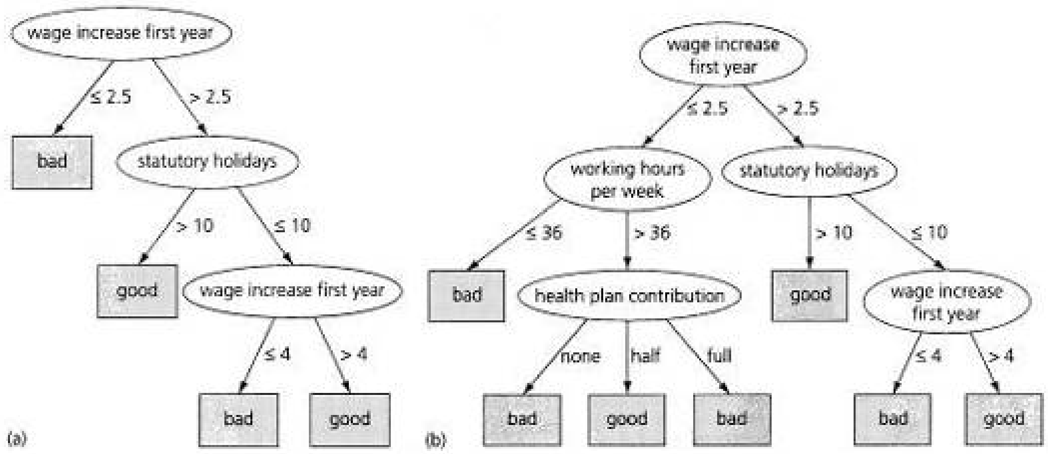

Figure 6.38: An example of a decision trees (from Witten & Frank, 2005).

Regression and model trees are constructed by first using a decision tree induction algorithm to build an initial tree. However, whereas most decision tree algorithms choose the splitting attribute to maximize the information gain, it is appropriate for numeric prediction to instead minimize the intra subset variation in the class values down each branch. Once the basic tree has been formed, consideration is given to pruning the tree back from each leaf (Witten & Frank, 2005).

According to type of data we deal with, model trees were applied to predict future hydraulic response of the Postojnska Jama.

Model trees

Model trees are essentially decision trees with linear models at the leaves, as mentioned (Fig. 6.39). A model tree was used to predict the value for a test instance. The tree is followed down to a leaf, using the instance's attribute values to make routing decisions at each node.

The leaf contains a linear model based on some of the attribute values, and this is evaluated for the test instance to yield a raw predicted value (Witten & Frank, 2005). Raw values are not used directly. Smoothing process is used to compensate for the sharp discontinuities that otherwise inevitably occur between adjacent linear models at the leaves of the pruned tree. This may be a particularly problem for models constructed from a small number of training instances. The number of training instances was relatively high in our model, ranging between 23,000 and 33,000.

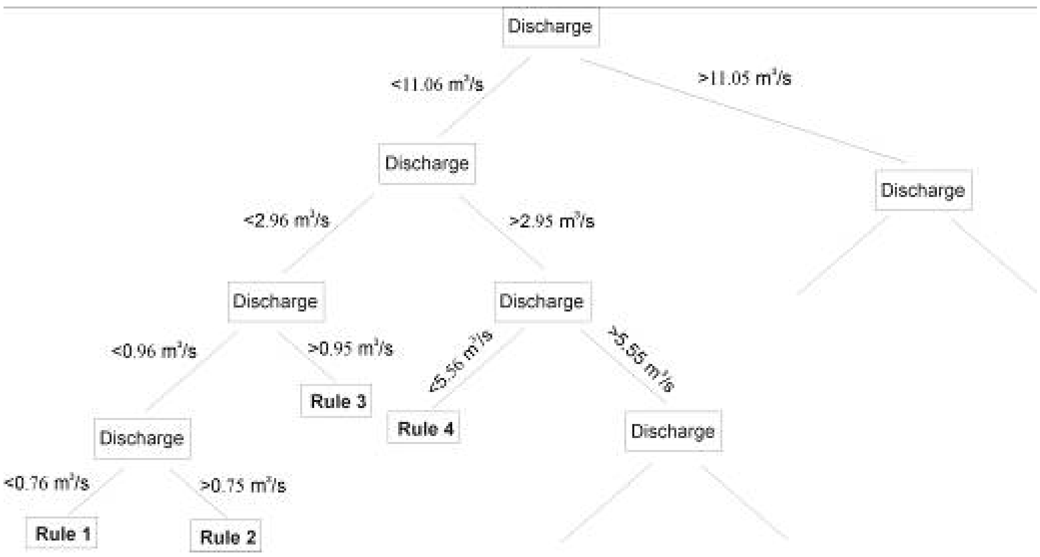

Figure 6.39: example of a model tree (see rules for Tartar in appendix 1).
Where rule 1 is Y = 0.0624 * X + 18.8491; rule 2 is Y = 34.958 * X - 7.0836; rule 3 is Y = 7.6432 * X + 21.6957 and rule 4 is Y = 7.0929 * X + 24.2996.
Y is a water level and X is a discharge.

Smoothing is accomplished by producing linear models for each internal node, as well as for the leaves. Once the leaf model has been used to obtain the raw predicted value for a test instance, then that value is filtered along the path back to the root, smoothing it at each node by combining it with the value predicted by the linear model for that node.
Smoothing, which substantially increases the accuracy of predictions, is calculated as (Witten & Frank, 2005):

$$p' = \frac{np + kq}{n + k}$$

where
p' is the prediction passed up to the next higher node,
p is the prediction passed to this node from below,
q is the value predicted by the model at this node,
n is the number of training instances that reach the node below,
k is a smoothing constant.

- Building the model tree

The splitting criterion is used to determine which attribute is the best to split that portion *T* of the training data that reaches a particular node. It is based on treating the standard deviation of the class values in *T* as a measure of the error at that node and calculating the expected reduction in error as a result of testing each attribute at that node. The attribute that maximizes the expected error reduction is chosen for splitting at the node. The expected error reduction, which we call SDR for *standard deviation reduction,* is calculated by (Witten & Frank, 2005):

$$SDR = sd(T)\sum_{i}\frac{|T_i|}{|T|} * sd(T_i)$$

where $T1$, $T2$, . . . are the sets that result from splitting the node according to the chosen attribute.

The splitting process terminates when the class values of the instances that reach a node vary very slightly. It happens when standard deviation represents only a small fraction (not more than 5%) of the standard deviation of the original instance set. Splitting also terminates when just a few instances remain (four or less). Obtained results should not be very sensitive to the exact choice of these thresholds (Witten & Frank, 2005).

6.5.2. Application of model trees

Plots of stage (water level) versus flow rate were depicted and studied in a previous chapter, where hydraulic characteristics of all monitored locations were discussed.

The same relations (stage – flow rate) were applied also for predictive modeling. However, only part of the data, which include several flood pulses of different magnitude (from the lowest and up to the highest recorded – 90 m^3/s), were incorporated into the six models as a training set of data. We left some amount of data to test the accuracy of the models. Models were built for each monitoring location separately. Amount of incorporated data ranged between 23,000 and 33,000. All these data are from year 2008. The reason for different amount of incorporated data is that monitoring did not take place simultaneously in all 2008 at all six stations. The training sample is supposed to be large enough, otherwise the accuracy of the sample, which is used for testing would be low (Witten & Frank, 2005). The sample, which was used for such testing, consists mainly of data from autumn 2008 and winter 2008 - 2009 (except for Pivka Jama station, which was monitored also in years 2006 and 2007).

6.5.3. Results of the model

We built model trees by using M5 algorithm (WEKA, www.cs.waikato.ac.nz/ml/weka/) for each of six underground monitored locations. The number of instances applied in a model for each station is shown in a Tab. 5. Evaluations there are based on training data; all trees are pruned and obtained models are smoothed.

Table 5: Evaluation of data on training set.

	Tartar	Otoška Jama	Martel's Rock-fall	Martel's chamber	Magdalena Jama	Pivka Jama
Correlation coefficient	0.995	0.996	0.9881	0.990	0.965	0.987
Mean absolute error (**variance**)	7.212	11.304	22.3077	12.670	8.590	7.009
Root mean squared error **(SD)**	11.153	16.266	35.7237	20.663	11.324	9.488
Relative absolute error	14.17%	9.01%	12.32 %	9.53%	32.84%	14.47%
Root relative squared error	10.37%	8.99%	15.37 %	13.88%	26.04%	15.92%
Total Number of Instances	24879	24959	33694	26124	23120	30577

6.5.3.1. Tartar

Stage – flow rate relation mainly depends on topography of the Tartar chamber and amount of ponding in front of hydraulic restrictions situated downstream (see previous chapter No. 6.4).

Fitting of a model to a training set of data is shown in Fig. 6.40. Data from March 1st till July 31st 2008 and from December 2008 were incorporated in the training set (Fig. 6.41).

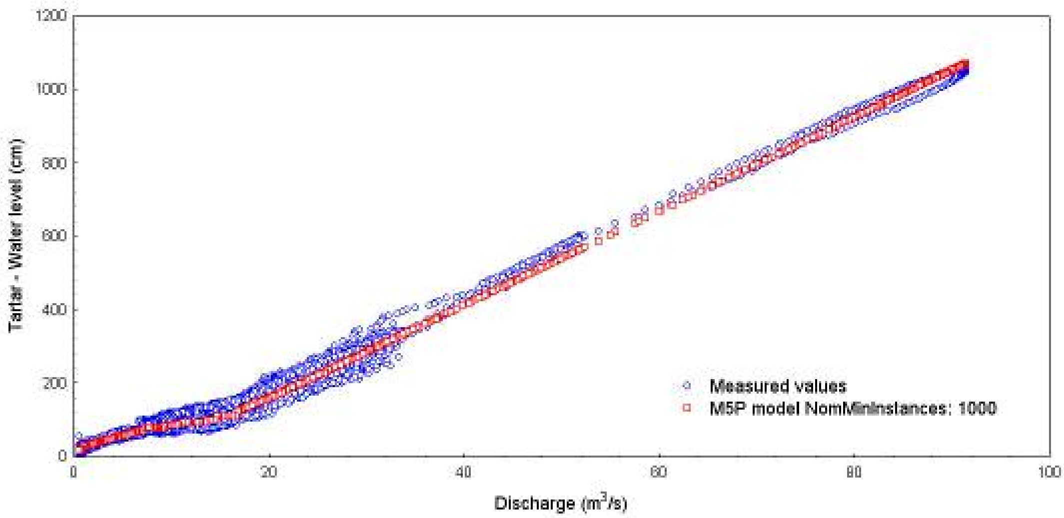

Figure 6.40: Figure shows stage (H) versus flow rate (Q) relation for Tartar (Station No. 2). Blue markers represent measured relation (training set of data) and red markers represent model based on training set of data.

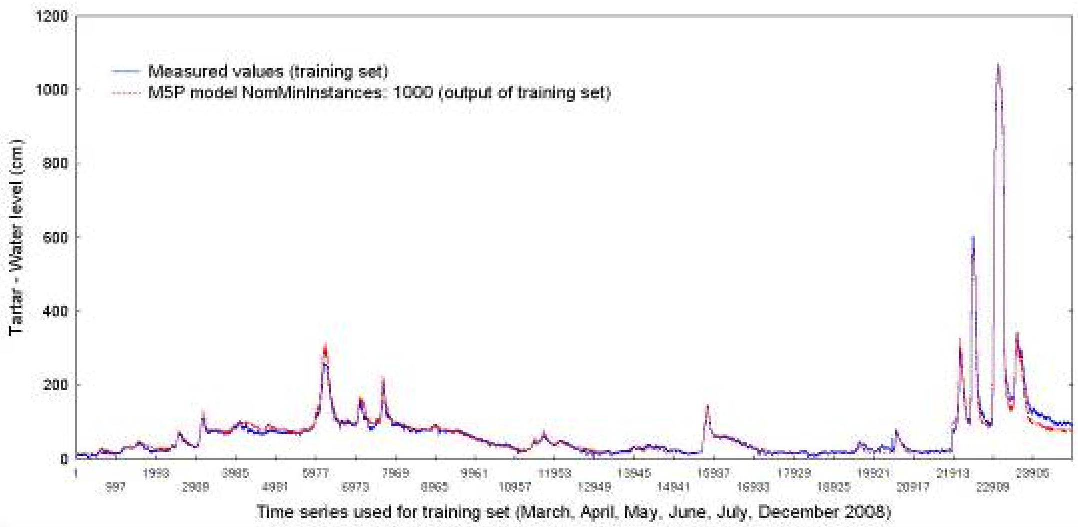

Figure 6.41: Data, which were used for training set (blue curve) and corresponding modeled data of Tartar (red curve).

Output of the M5P data mining algorithm is a model tree, which is written in a form of 14 rules (see appendixes at the end). Each rule corresponds to a certain leaf of the model tree.

- Future prediction or testing of model tree on new data

Data from September, October, November (all 2008), January and February (both 2009) were used to test the model. Scattering of testing set of data is significant, as can be seen in Fig. 6.42. In contrast, the model does not predict any scattering at all, which diminishes the fitting between the model and real hydraulic response of the underground Pivka River at Tartar. According to comparison of real and modeled stage – flow rate relations, the stage is generally underestimated for 20 to 40 cm.

This can be seen also in Fig. 6.43, where fitting of two stage curves varies with time. However, fitting is generally statistically significant, with correlation coefficient 0.9871, as the shape of both curves is almost equal.

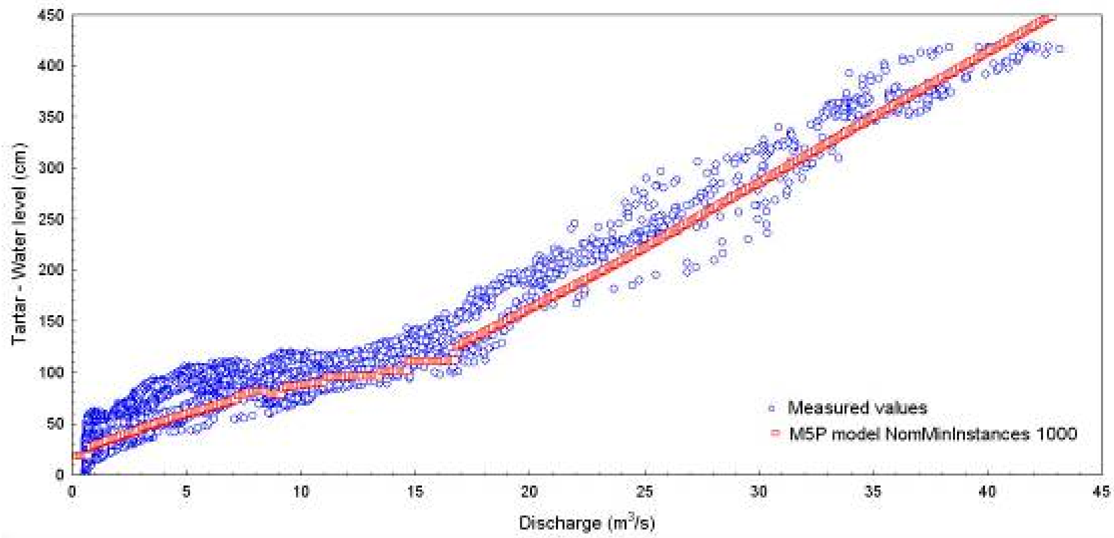

Figure 6.42: Evaluation of model (red markers) on testing set (blue markers). Testing set are data from September, October, November (all 2008), January and February (both 2009).

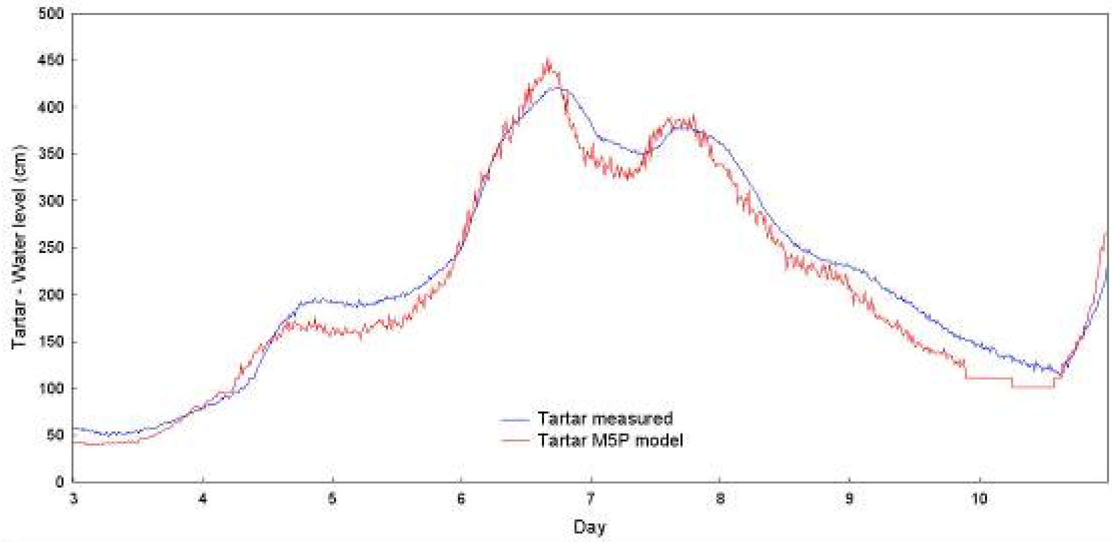

Figure 6.43: Fitting between real data and model based on testing set (flood pulse from February 3rd – 10th, 2009). Correlation coefficient is 0.9871.

6.5.3.2. Otoška Jama

Stage – flow rate relation in Otoška Jama (station No. 3) (Fig. 6.44) is similar as in front of Martel's rock-fall (station No. 4), which is situated 700 m downstream from Otoška Jama.

Data from March, April, May, June, July and December 2008 were used to build a model (red markers) based on training set (blue markers) (Figs. 6.44 and 6.45).

Twenty rules were obtained after the analysing of data by M5P algorithm (see appendixes).

- Future prediction or testing of model tree on new data

Data measured in period between September and November 2008 were compared with the modeled data (Fig. 6.46). A low amount of data were applied for the testing set, which is because the data logger did not work properly in 2009 in Otoška Jama. Hence data for 2009 are missing. Flood pulse from October 28th – November 4th 2008 is represented in Fig. 6.47, instead of flood pulse from February 2009 (as at all other stations).

Modeled water level is higher than the measured one, except near base flow conditions, where fitting is almost perfect (Figs. 6.46 and 6.47).

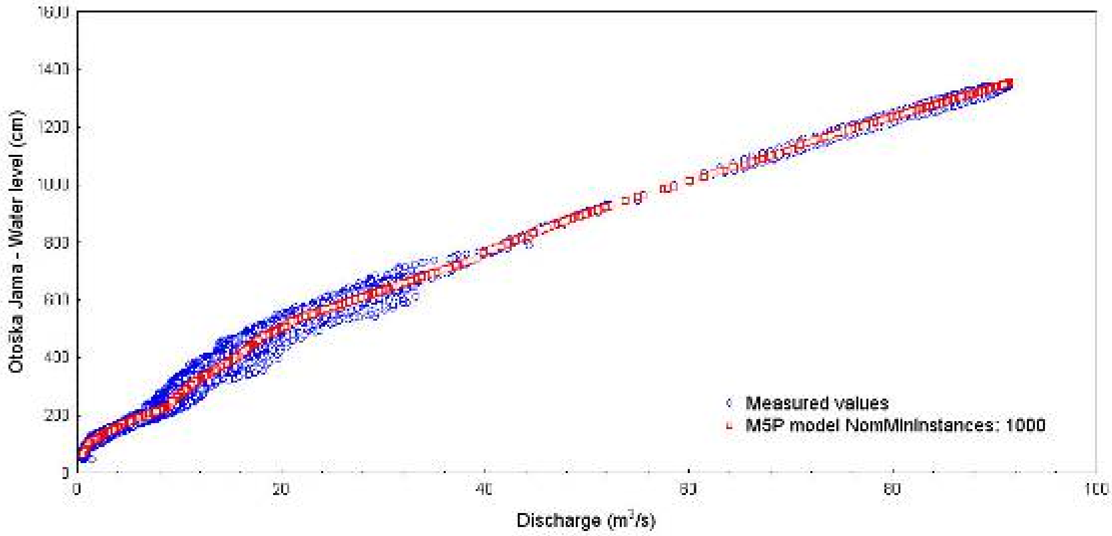

Figure 6.44: Stage (H) versus flow rate (Q) relation for Otoška Jama station (Station No. 3). Blue markers represent measured relation (training set of data) and red markers represent model based on training set of data.

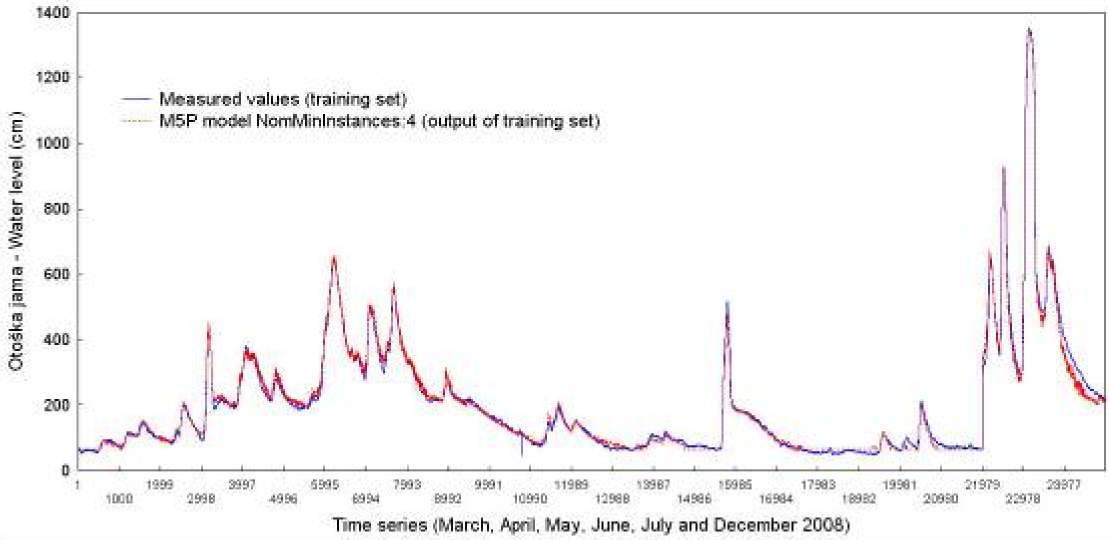

Figure 6.45: Data which were used for training set (blue curve) and corresponding modeled data of Otoška Jama (red curve).

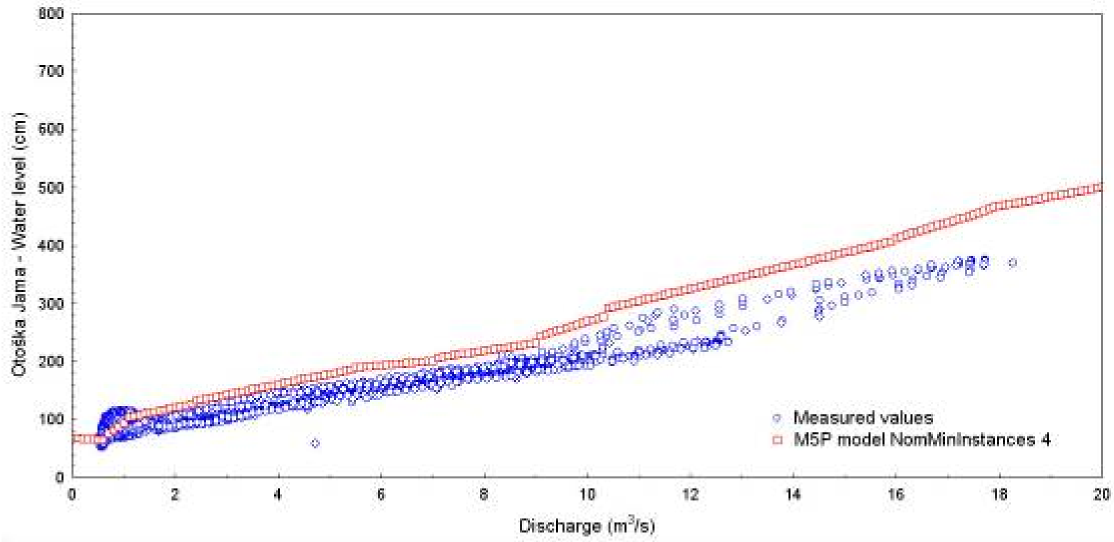

Figure 6.46: Evaluation of model (red markers) on testing set (blue markers). Testing set are data from September, October and November 2008.

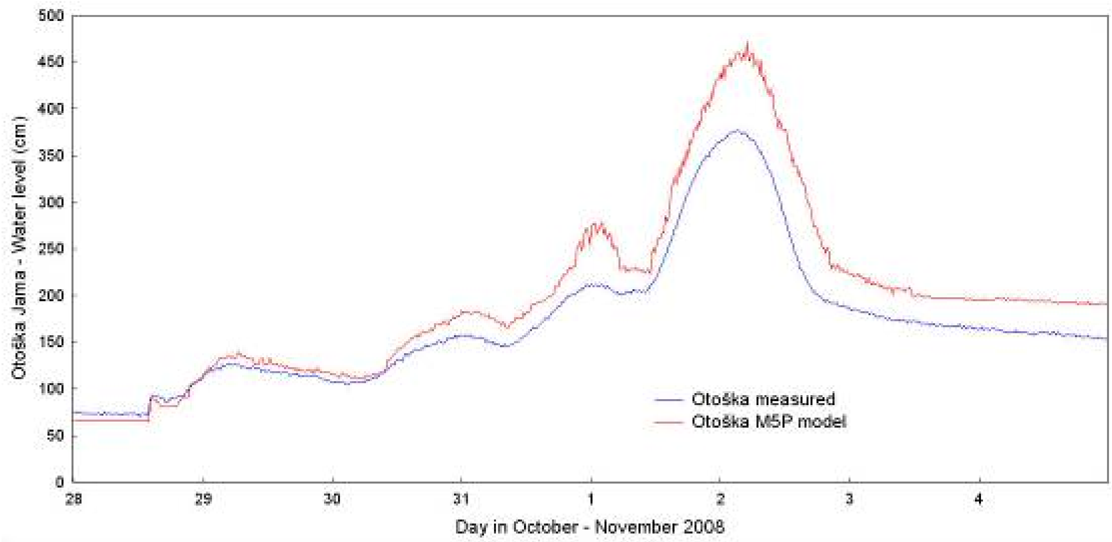

Figure 6.47: Fitting between real data and model based on testing set (flood pulse from October 28th –November 4th 2008). Correlation coefficient is 0.9913.

6.5.3.3. Martel's rock-fall

Fluctuations of water level are the highest in front of Martel's rock-fall. Water presumably drains through several bypasses to avoid rock-fall.

Data from March, April, May, June, July and December 2008 were used to build a model (red markers) based on training set (blue markers) (Figs. 6.48 and 6.49).

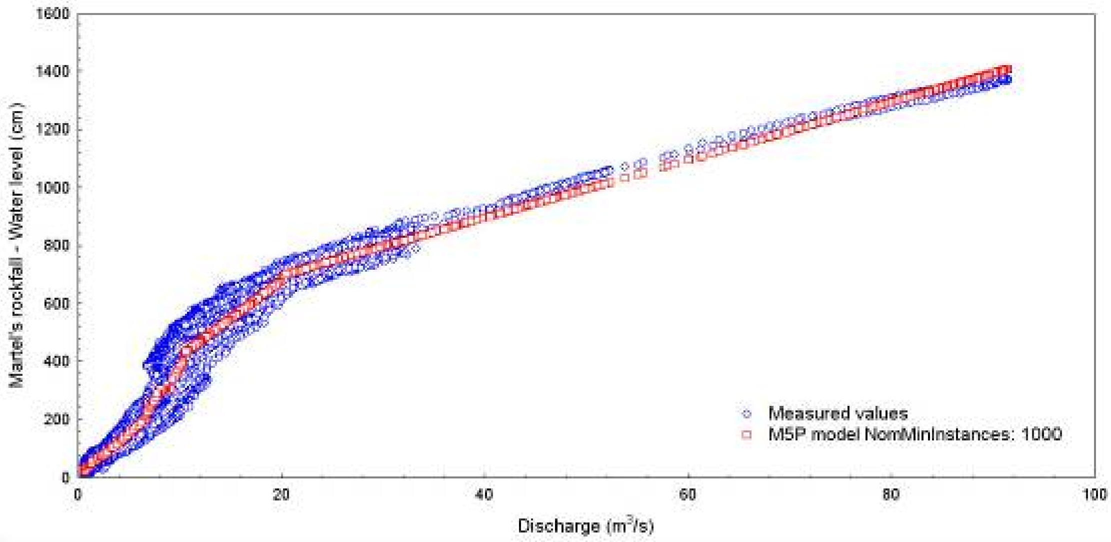

Figure 6.48: Relation stage (H) versus flow rate (Q) for station situated in front of Martel's rock-fall (Station No. 4). Blue markers represent measured relation (training set of data) and red markers represent model based on training set of data.

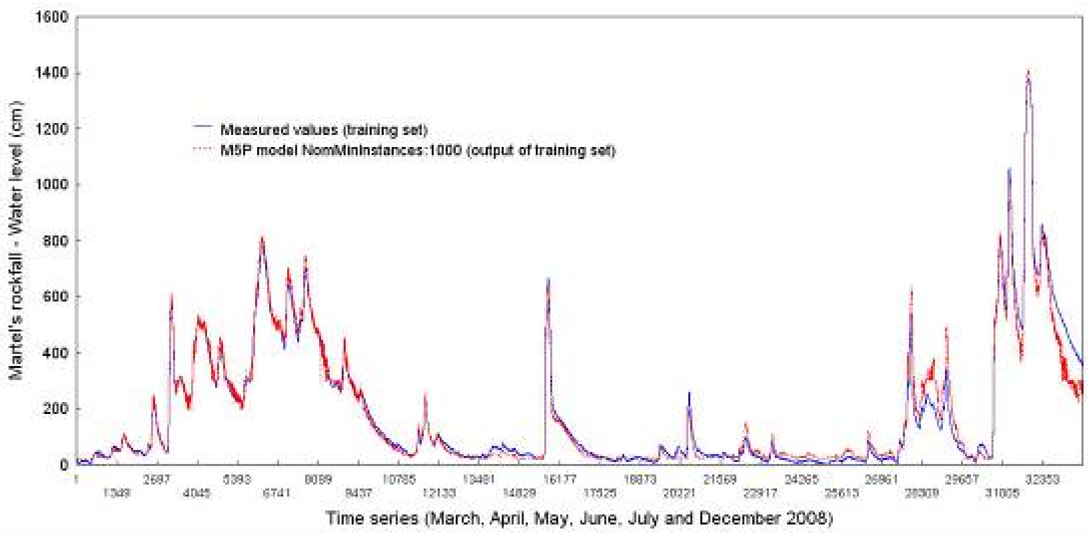

Figure 6.49: Data which were used for training set (blue curve), and corresponding modeled data of Martel's rock-fall (red curve).

A model tree for station in front of Martel's rock-fall is made from 16 rules (see appendixes).

- Future prediction or testing of model tree on new data

Scattering of measured data is high, as can be seen from stage – flow rate relation in Fig. 6.50. This relation is based on data obtained between September – November 2008 and January – February 2009. Modeled curve fits well to realistic curve obtained by measurements; however water level may be underestimated or overestimated at certain flood events (Fig. 6.51).

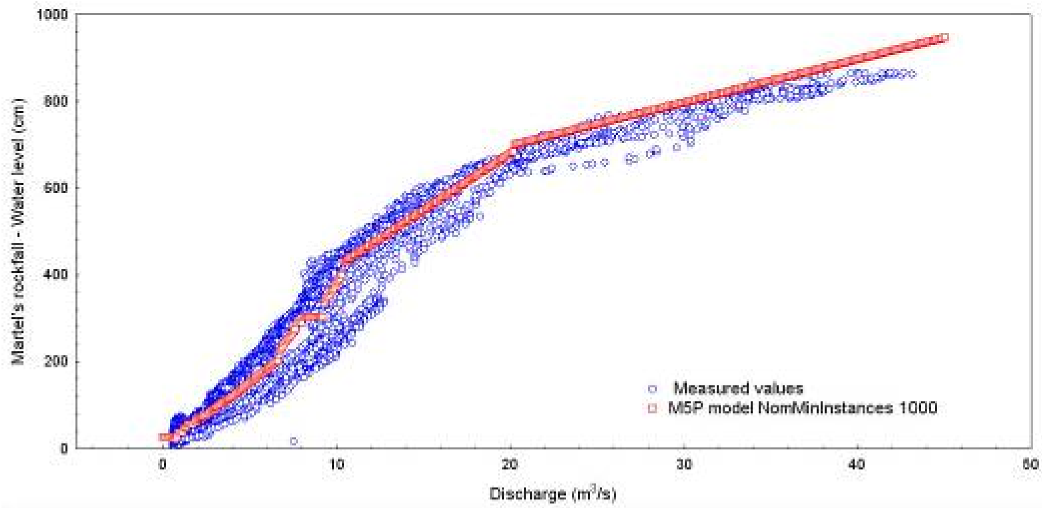

Figure 6.50: Evaluation of model (red markers) on testing set (blue markers). Testing set are data from September, October, November (all 2008), January and February (both 2009).

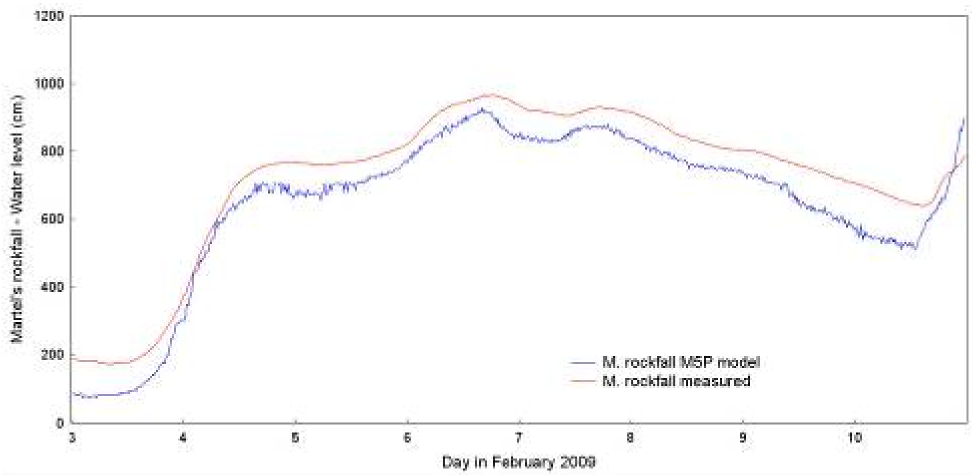

Figure 6.51: Fitting between real data and model based on testing set (flood pulse from February 3rd – 10th, 2009). Correlation coefficient is 0.9889.

6.5.3.4. Martel's chamber

Hydraulic characteristics of Martel's chamber (Fig. 6.52) are directly associated with (low) permeability of temporally active conduit and activation of periodically active conduits on higher altitude.

Training data, on which the model was built, are from March, April, May, June, July, November 19th – 30th and December 2008 (Fig. 6.53).

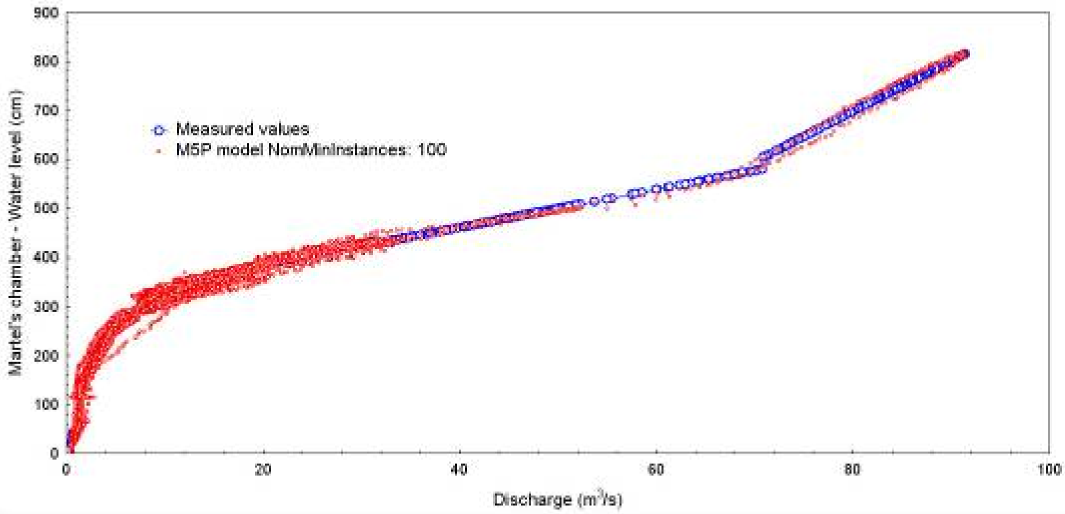

Figure 6.52: Relation stage (H) versus flow rate (Q) for Martel's chamber (Station No. 5). Blue markers represent measured relation (training set of data) and red markers represent model based on training set of data.

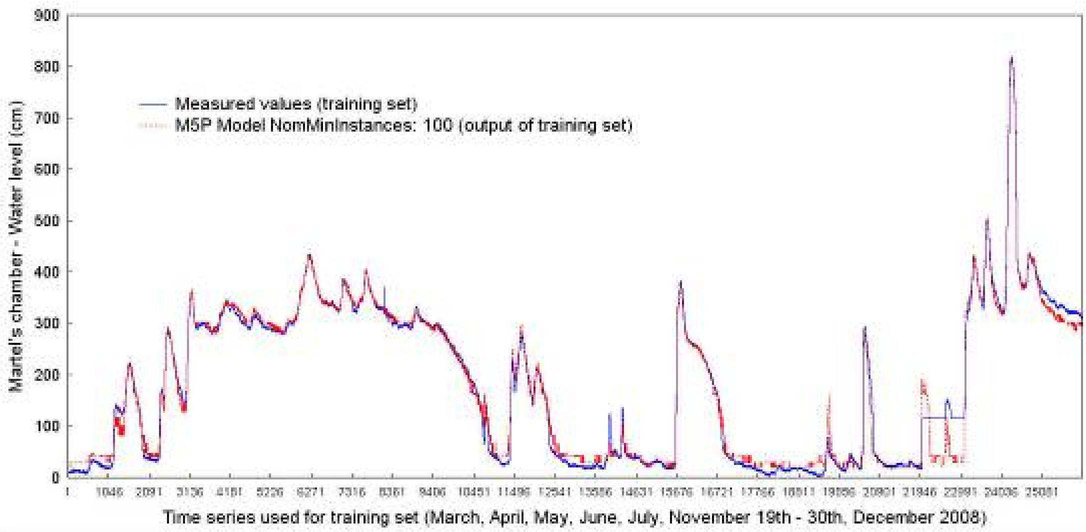

Figure 6.53: Data, which were used for training set (blue curve) and corresponding modeled data of Martel's chamber (red curve).

After the processing the data, we obtained a model tree, which is built from 22 rules (see appendixes).

- Future prediction or testing of model tree on new data

Hydraulic response of Martel's chamber to flood inflow (Figs. 6.54 and 6.55) is very predictable, as was described in chapter No. 6.4. Curve of stage – flow rate relation is gentle first and becomes significantly steeper when the flow rate exceeds 2 m^3/s or 3 m^3/s. Swallow capacity of primary conduit is exceeded, water increases rapidly, till conduits at higher level activate. Problem with the model may occur only at the transition from base flow to flood input (range of flow rates 0 m^3/s – 3 m^3/s) (Fig. 6.54). Fitting between measured data and model is good at higher flow rates (water levels respectively) (Fig. 6.55).

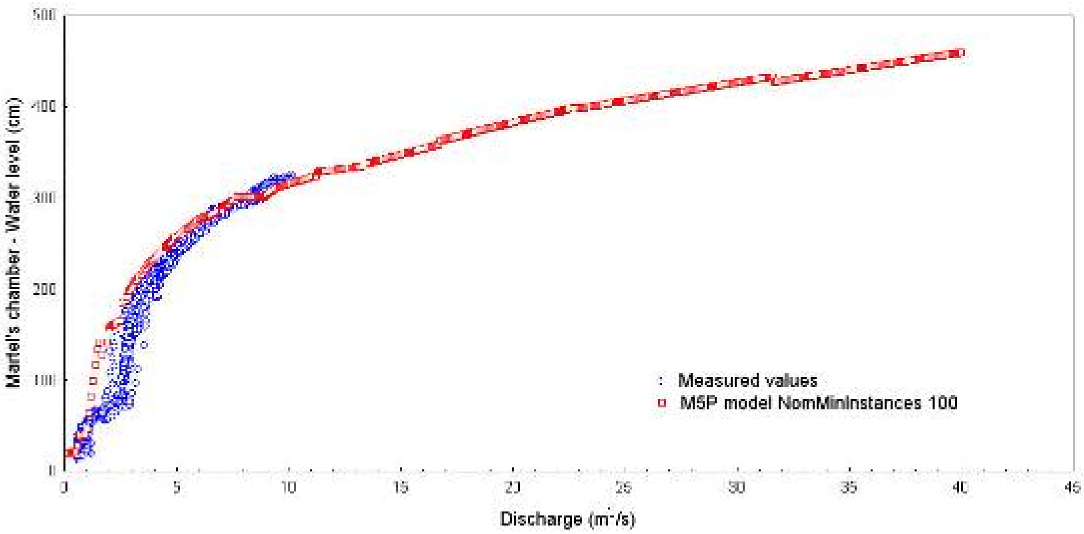

Figure 6.54: Evaluation of model (red markers) on testing set (blue markers). Testing set are data from April (10^{th} – 30^{th}), May and June 2008.

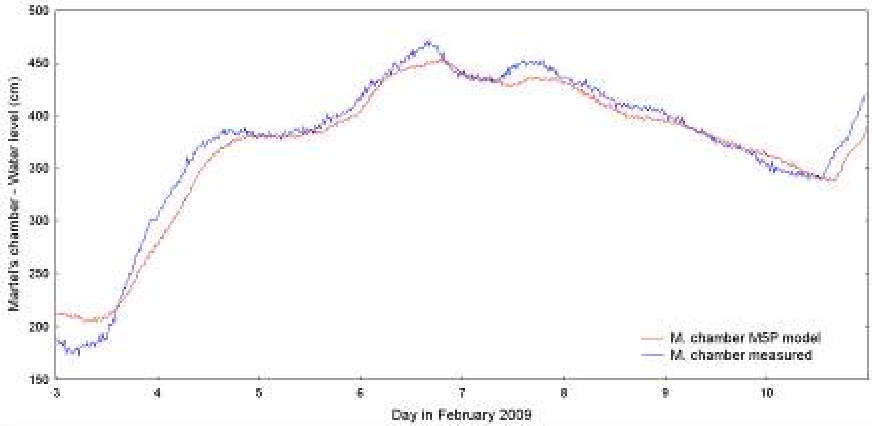

Figure 6.55: Fitting between real data and model based on testing set (flood pulse from February 3rd – 10th, 2009). Correlation coefficient is 0.9846.

6.5.3.5. Magdalena Jama

Training test consist of data from June to December 12th 2008, as can be seen in Figs. 6.56 and 6.57. Fluctuations of water level are relatively low in Magdalena Jama, because of morphology of the conduit (wetted perimeter is much higher than at other stations). Scattering of data at certain flow rate is high.

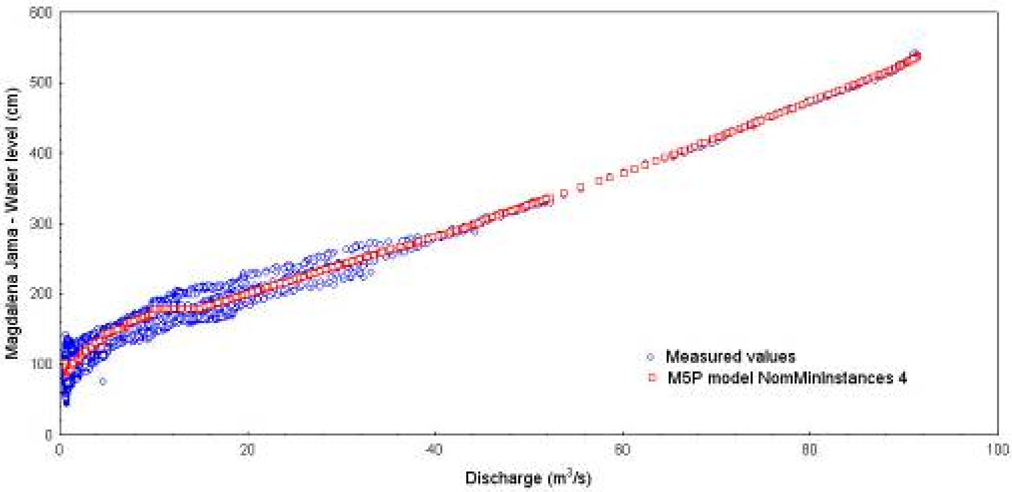

Figure 6.56: Relation stage (H) versus flow rate (Q) for Magdalena Jama (Station No. 6). Blue markers represent measured relation (training set of data) and red markers represent model based on training set of data.

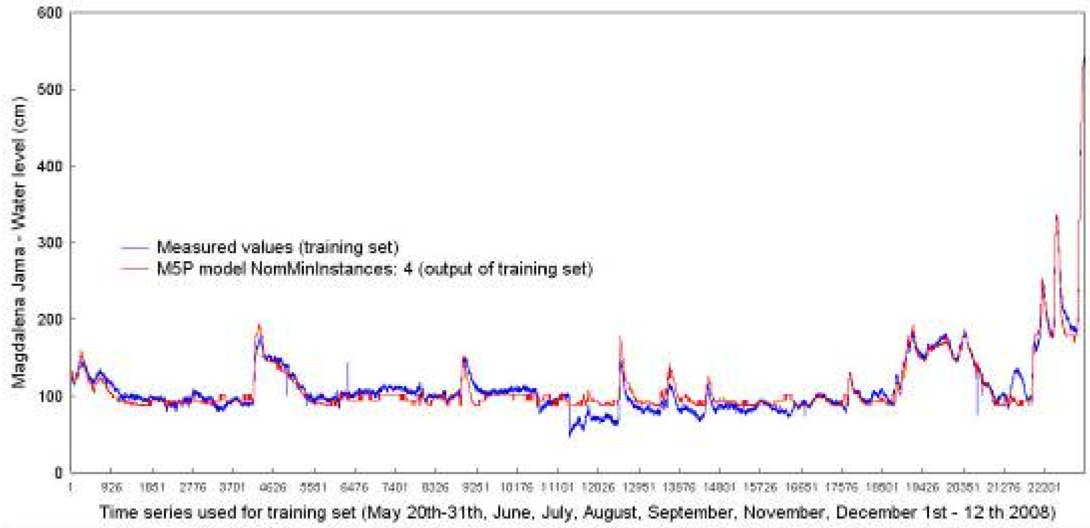

Figure 6.57: Data which were used for training set (blue curve) and corresponding modeled data of Magdalena Jama (red curve).

Model tree of Magdalena Jama is made from 21 leaves, rules respectively (see appendixes).

- Future prediction or testing of model tree on new data

Data of six months (January – June 2009) were applied for testing the model. Variability of discharge induces low fluctuation of water level, as can be seen from Fig. 6.58. Scattering of measured data is high; it is mainly attributed to error of the device. Hence, fitting between model and real data is the lowest there in comparison with other five stations. Fitting is relatively good at higher water levels (Figs. 6.58 and 6.59), when flow rates are high also. But there are relatively fewer data at such condition. The more the data, the higher is the scattering (Fig. 6.58).

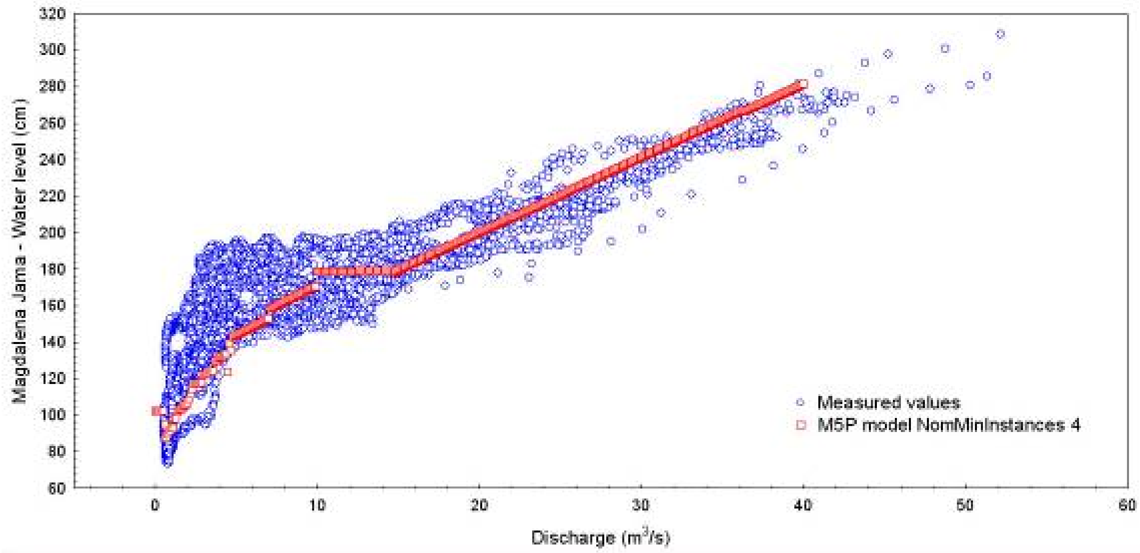

Figure 6.58: Evaluation of model (red markers) on testing set (blue markers). Testing set are data from January - June 2009.

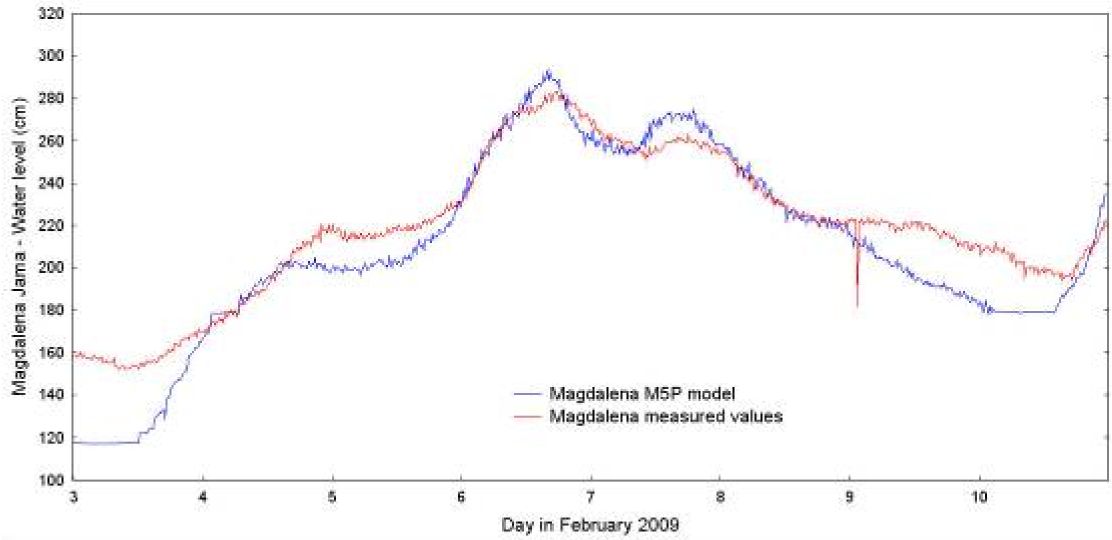

Figure 6.59: Fitting between realistic data and model based on testing set (flood pulse from February 3rd – 10th, 2009). Correlation coefficient is 0.9698.

6.5.3.6. Pivka Jama

Similar to Magdalena Jama, Pivka Jama has significant linear stage – flow rate relation also (Fig. 6.60). Training set consists of data from March to November 2008 in Pivka Jama (Fig. 6.61). The highest flow rates and stages from December 2008 were not incorporated for a very simple reason. It was impossible to measure the highest flow rates at the ponor in December 2008, as water was stagnant there. For this purpose, flow rate was roughly estimated due to linear relation between flow rate and stage, which is characteristic for Pivka Jama at least at range of flow rate 0 to 40 m^3/s. However we assumed that this relation remains linear at much higher flow rates also.

Because of this, data from December 2008 were not incorporated in training set, as the model would over fit some of training data.

Model tree regression gives 22 rules for stage – flow rate relation in Pivka Jama (see appendixes).

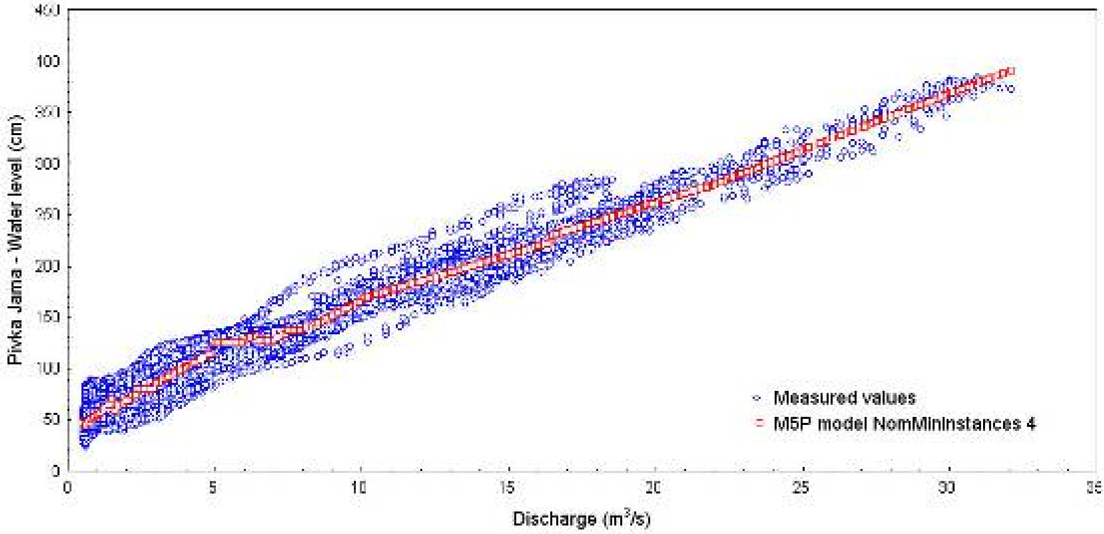

Figure 6.60: Relation stage (H) versus flow rate (Q) for Pivka Jama (Station No. 7). Blue markers represent measured relation (training set of data) and red markers represent model based on training set of data.

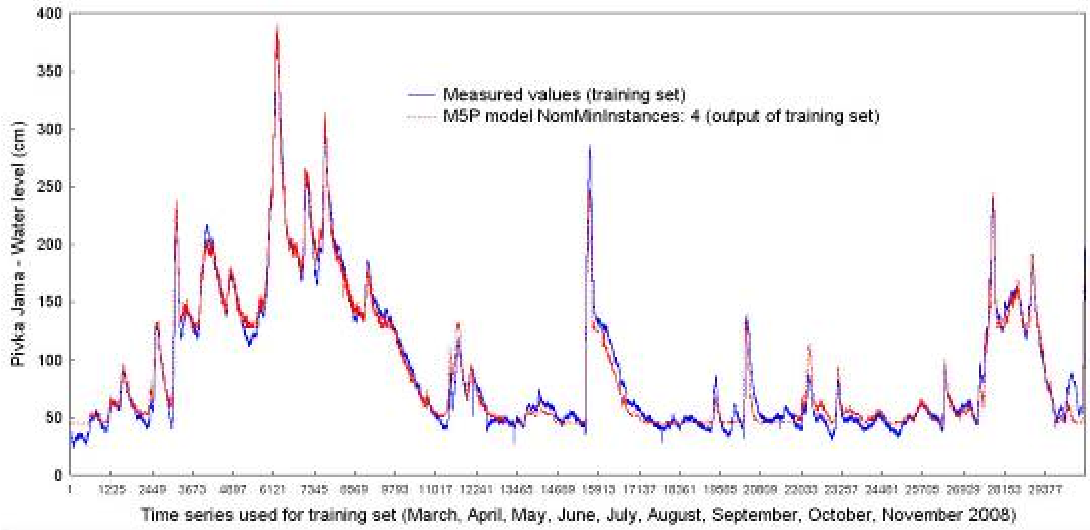

Figure 6.61: Data which were used for training set (blue curve) and corresponding modeled data of Pivka Jama (red curve).

- Future prediction or testing of model tree on new data

Predictive data are generally underestimated, due to the testing set of data, which are from period September - December 2007 and from February 2009. Fitting of predictive data to testing ones is better at the lowest flow rates 0 m^3/s – 5 m^3/s (Fig. 6.62). Otherwise, predictive data are generally underestimated for 0.5 m, as can be seen also form Fig. 6.63.

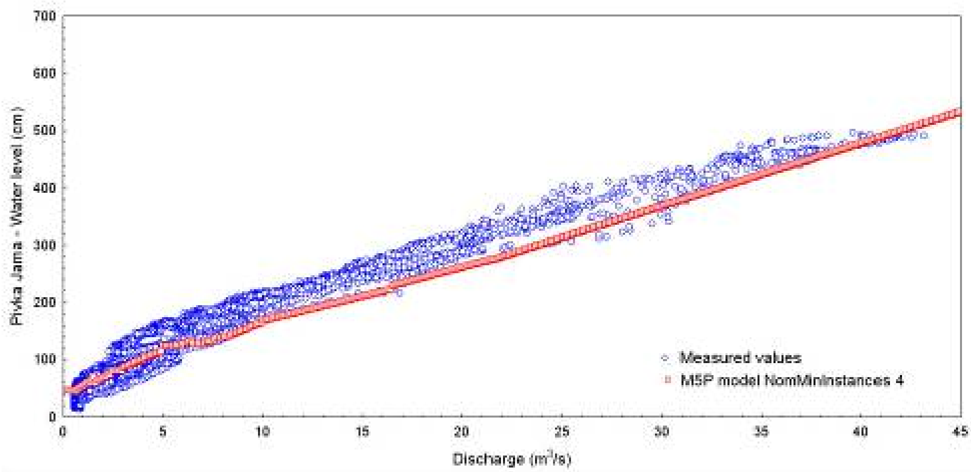

Figure 6.62: Evaluation of model (red markers) on testing set (blue markers). Testing set are data from September, October, November, December (all 2007) and February 2009.

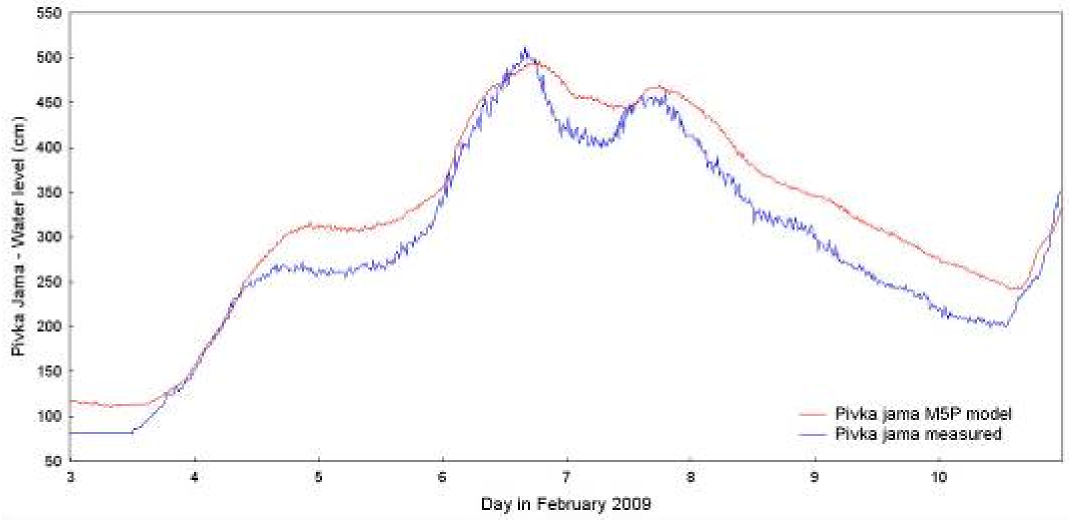

Figure 6.63: Fitting between realistic data and model based on testing set (flood pulse from February 3rd – 10th, 2009). Correlation coefficient is 0.9839.

6.5.4. Conclusion

Fitting between training data and models is statistically significant at all six locations. However, when we deal with correlation coefficient, the same caution should be taken in consideration as was discussed in conclusion of the previous chapter. Correlation coefficient ranges from 0.99 (Tartar, Otoška Jama, Martel's chamber) down to 0.96 (Magdalena Jama) (Tab. 5). Error may be referred to different reasons such as:

- error of the device – measured values of water level may become overestimated for several decimeters, especially during and after transition of flood pulses (i.e. that water level of base flow is overestimated after some period of measurements).
- hysteresis caused by the time lag between measurements of the flow rate at the ponor and the stage at locations situated several hundred metres downstream from the ponor.
- error caused by human factor (data loggers were stopped and re-installed several times at each location. They were even moved for a few metres in Otoška Jama and Martel's chamber. Data from the logger should be calibrated to values prior every mentioned change. However, error increases after each such calibration).

6.6. SOLUTE AND HEAT TRANSPORT IN NATURAL STREAMS

6.6.1. Theoretical background of controlling processes

Solute transport is a movement of dissolved chemicals in the environment, for example in rivers or streams, in the unsaturated zone and in saturated ground water aquifers (Anwar, 2008).

Solutes and heat in free-flowing fluid are transported by **advection** and **dispersion** along with the fluid. Dissolved mass and heat (ions and molecules) move along with the flowing ground water. For our needs solute and heat are not considered to carry momentum, they move instead as passive scalars (Sukop et al., 2006).

Advection is the transport of a property of water (e.g. temperature) or dissolved substances due to the flow of water. Water flow is of different types. Depending on the type it can be described by various equations (Darcy, Hagen-Poiseuille, Darcy-Weisbach equation) (see also chapter 5).

Dispersion is a process of mixing that causes a zone of mixing to develop between a fluid of one composition (or temperature) that is adjacent to or being displaced by a fluid with a different composition (or temperature). A zone of mixing gradually develops around the advective front. Dispersion moves some tracer behind and some tracer in front of the advection front. In other words, dispersion spreads solutes longitudinally and transversely with respect to the selected streamline. The size of the zone of mixing increases as the advective front moves further from the source (Schwartz & Zhang, 2003).

Dispersion occurs in underground water because of two processes: diffusion and mechanical dispersion.

- *Diffusion* is a molecular mass transport, which results from movement of particles along concentration gradients. For instance, a drop of ink in a cup of clear water will smear out over time until the ink concentration is uniform. Dispersion and diffusion result in the same mathematical description as we will see later.

- *Mechanical dispersion* is a process of mixing that occurs because of local variations in velocity around some mean velocity of flow. For instance, if a particle moves through a porous medium, differences in pore sizes, friction effects and differences in transport lengths can cause local fluctuations. Mechanical dispersion is an advective process also.

Mass (or temperature) occupying some volume becomes gradually more dispersed with time, as different fractions of mass and heat are transported in varying velocity regimes. The fluid flow velocity is the main control on mechanical dispersion in karst conduits. Longitudinal mechanical dispersion is approximately proportional to velocity. Mass and heat spreads also lateral to the direction of mean underground-water flow. One component of lateral spreading occurs in the horizontal plane and the second in the vertical plane (Schwartz & Zhang, 2003).

Both processes are independent and additive. Therefore, dispersion can be written in the form of Fick's law, which describes the chemical mass flux as proportional to the gradient in concentration (Schwartz & Zhang, 2003; Socolofsky & Jirka, 2004).

For most transport problems related to our study the effects of mechanical dispersion are much greater than diffusive components (Sinokrot & Stefan, 1993; Gu & Li 2002; Schwartz & Zhang, 2003).

Both field and laboratory experiments prove that mass spreading tends to have a Gaussian distribution (Fig. 6.64). The position of the mean of the concentrations distribution represents transport at the linear ground-water velocity. The variance of the distribution is proportional to the dispersion in the system. The two dimensional spread of a tracer in a unidirectional flow field results in elliptically shaped distribution of concentration (Fig. 6.64). It is normally distributed in longitudinal and transverse direction; however longitudinal dispersion is greater than transverse dispersion. For these reason, concentration distribution in three dimensions forms ellipsoids of revolution (Schwartz & Zhang, 2003).

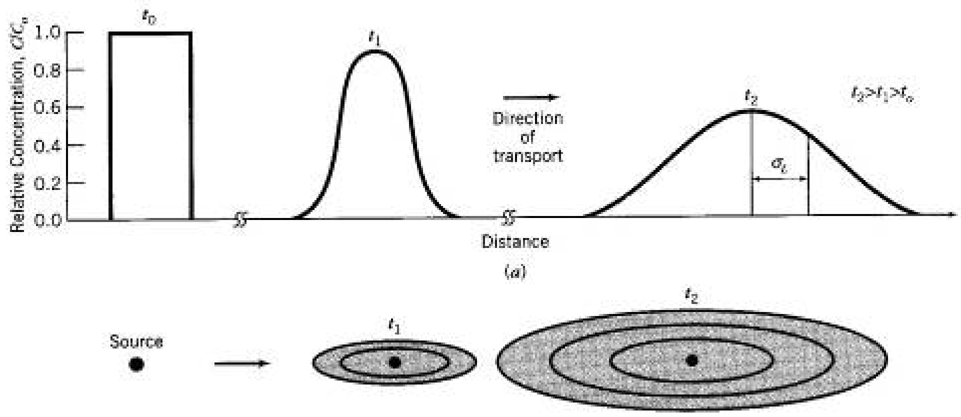

Figure 6.64: Variation in concentration of tracer spreading in one-dimensional and two-dimensional constant velocity flow system. Variation of concentration has Gaussian distribution (from Schwartz & Zhang, 2003).

6.6.2. Transport of mass in open channel streams

When soluble tracer is released into a stream, it mixes with upstream-coming fresh water and is transported downstream (Li, 2004). Such soluble tracer behaves in the same manner as the actual water particles (Field, 2002). It means that soluble tracers can be used to simulate the transport and dispersion of solutes in streams, because they have virtually the same physical characteristics as water (Jobson, 1996).

Just after the injection, dispersion and mixing of a tracer in a receiving stream take place in all three dimensions of the channel (Fig. 6.65). Vertical and lateral diffusion can be referred as a mixing and the longitudinal elongation of the tracer cloud can be referred as longitudinal dispersion. Longitudinal dispersion is a process which continues indefinitely with distance, while vertical and lateral mixing is a finite process (Jobson, 1996). Longitudinal dispersion, which has great impact on evolution of tracer or solute is controlled by the spatial distribution of underground water velocities in a conduit aquifer. Velocities on the other hand are dependent on recharge rate, the conduit cross-section and aquifer structure (Morales-Juberias et al., 1997). Vertical mixing is much faster than lateral mixing. Vertical mixing is completed rapidly within a distance of river depths. Lateral mixing is usually complete within a relatively longer distance. When mixing is complete, tracer concentration can be assumed to be uniform in the cross-section of river channel (Jobson, 1996) (Figs. 6.65 and 6.66).

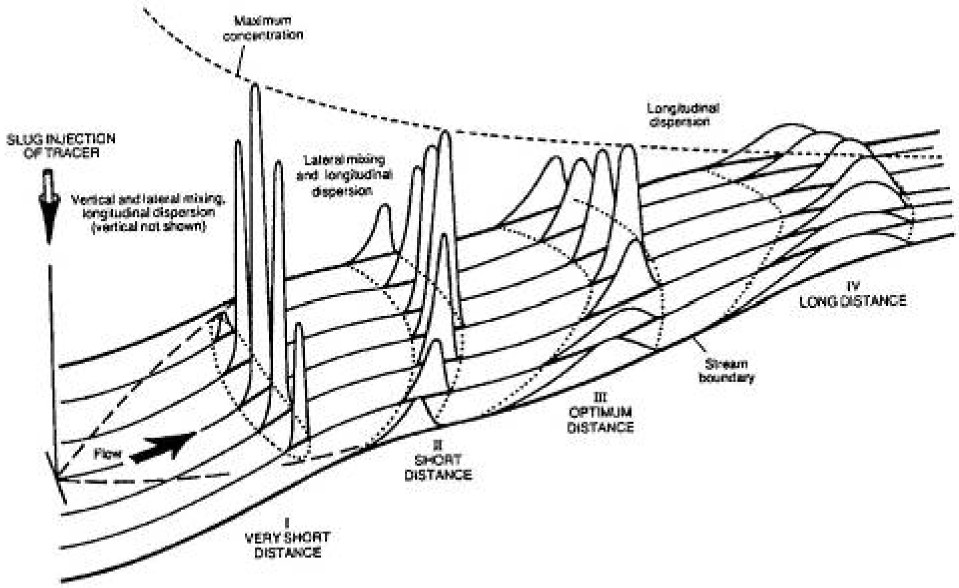

Figure 6.65: Distribution of water soluble tracer downstream from injection point. Lateral mixing and longitudinal dispersion occur (from Field, 2002).

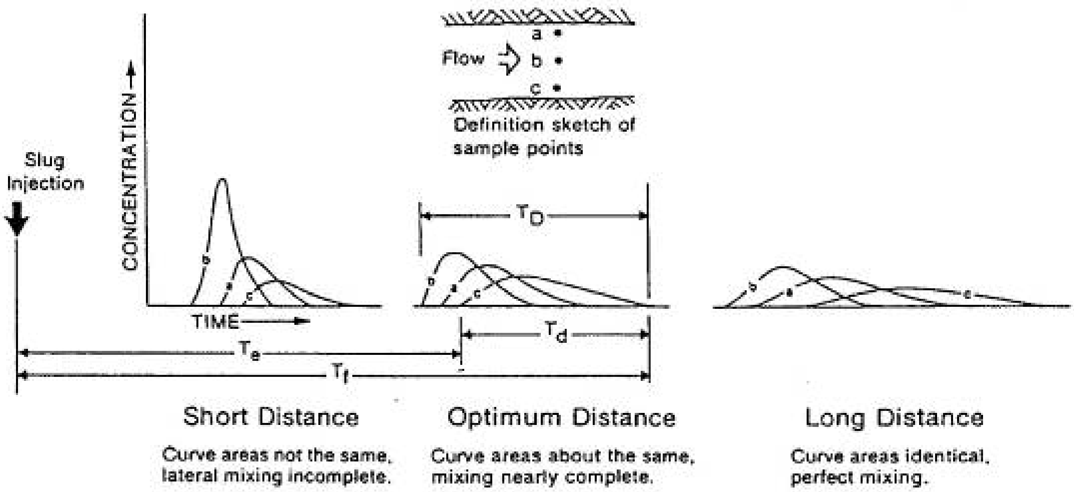

Figure 6.66: Rate of mixing is a function of distance from injection point (from Field, 2002).

Breakthrough curve represents a time-dependent concentration at a receptor. Breakthrough behaviour is a result of complex interplay between mechanical dispersion, diffusion and advection, which is controlled by head gradients and the fundamental pore scale of a system. Porosity can range from small pores to conduits with a diameter of several tens of metres. Flow is generally advection-dispersion dominated in fracture-conduit zone and diffusion-dispersion controlled in the matrix zone. This reflects in asymmetric geometry of breakthrough curves. The rising limb is sudden due to the conduit flow and the long tail is often due to slow diffusion from the matrix region (Anwar, 2008).

Not only surface streams, but also underground rivers have a characteristic ***hyporheic zone***. Significant portions of water and dissolved chemicals may interchange with the hyporheic zone, i.e. porous banks and bed sediments (figure of hyporheic zone follows in the continuation). De Smedt (2007) made a model, which consists of an advection-dispersion equation for transport in the main channel with a sink term describing diffusive solute transfer to the hyporheic zone. It means that solute transport in a stream is affected by exchange with hyporheic zone. The solution of a model enables us to predict the temporal and spatial evolution of tracer concentration (breakthrough curve) downstream from injection point.

Interpretation of the breakthrough curve of artificial water-soluble tracers released in open channel stream is usually based on analytical solution of a one-dimensional ***mass transport equation***. Such is the following advection-dispersion equation (Morales-Juberias et al., 1997; Runkel, 1998; Birk et al., 2002; Marion & Zaramella, 2005; Sukop et al., 2006; De Smedt, 2007; Kovacs & Sauter 2007):

$$\frac{dC}{dt} = -v(\vec{u}C) + D\nabla^2 C$$

where $-v(\vec{u}C)$ is a advection equation and $D\nabla^2 C$ is a dispersion equation.

The advection-dispersion equation is further transformed:

$$\frac{dC}{dt} = -v\frac{dC}{dx} + D\frac{d^2C}{dx^2} + Exchange$$

$$A\frac{dC}{dt} = AD\frac{d^2C}{dx^2} - Q\frac{dC}{dx} + Exchange$$

Exchange is absorption and desorption of the mass to the streambed and the diffusion flux of solute entering the hyporheic zone (Runkel, 1998). The most widespread approach considers a one-dimensional advection-dispersion equation in combination with first-order mass exchange between the river and a lumped stagnant storage zone, with a mass exchange flux assumed to be proportional to the difference in a solute concentration between the river and the stagnate storage zone (De Smedt, 2007):

$$Exchange = \alpha(C_h - C) = LD_h\frac{dC_h}{dz} \qquad [\text{mol m}^{-2}\,\text{s}^{-1}]$$

where:

D is the dispersion coefficient [$m^2\ s^{-1}$]

C is the solute concentration in water [mol m^{-3}]

x and z are the spatial coordinates [-]

Q is the flow discharge [$m^3\ s^{-1}$]

D_h is the diffusion coefficient in the hyporheic zone [$m^2\ s^{-1}$]

C_h is the concentration of chemical diffuses in hyporheic zone [mol m^{-3}]

A is the main channel flow area [m^2]

α is the hyporheic zone exchange coefficient [s^{-1}]

L is the wetted perimeter [m]

6.6.3. Water temperature and heat transport

6.6.3.1. Water temperature

Before we describe equations which govern heat transport in streams, the source of the heat should be discussed first.

The temperature of water in surface streams varies both temporally (diurnal, seasonal) and spatially. Water temperature is generally close to the groundwater temperature at the spring and increases thereafter with distance. The increase of water temperature with distance is not linear; it is grater for relatively small streams, reaching the order of 0.6°C per km (Caissie, 2006).

The temperature of rivers is a result of various heat inputs and outputs under specific hydraulic and meteorological conditions (Gu & Li, 2002). There are many factors which induce temperature of surface stream (river). They can be generally classified into four groups: atmospheric conditions, topography, stream discharge and streambed. The most important factors are usually atmospheric conditions. They cause heat exchange, which takes place at the water surface. Such atmospheric conditions are solar radiation, temperature, humidity and wind speed. Solar radiation is the dominant component of the total energy flux, followed by the net long-wave radiation and the evaporative heat flux. Atmosphere exchanges heat with water by conduction and movement of latent and sensible heat (Caissie, 2006; Burkholder et al., 2008). River temperatures are relatively highly sensitive also to instream flow rate, upstream inflow temperature, channel geometry and morphometry (Gu & Li, 2002).

For these reasons, water temperature varies both with a diurnal and annual cycle (Fig. 6.67). The diurnal cycle corresponds to daily minimum in the early morning and daily maximum in late afternoon. Diurnal variations are more expressed in larger streams, which are less dominated by recharge of groundwater and are more exposed to meteorological conditions. The highest diurnal variations are characteristic for wide and shallow rivers (Caissie, 2006).

The annual cycle reflects in sinusoidical shape of variation. Water temperature increases from winter toward summer, when it reaches peak value. Then it decrease in autumn, reaching the lowest temperature in the winter (Fig. 6.67).

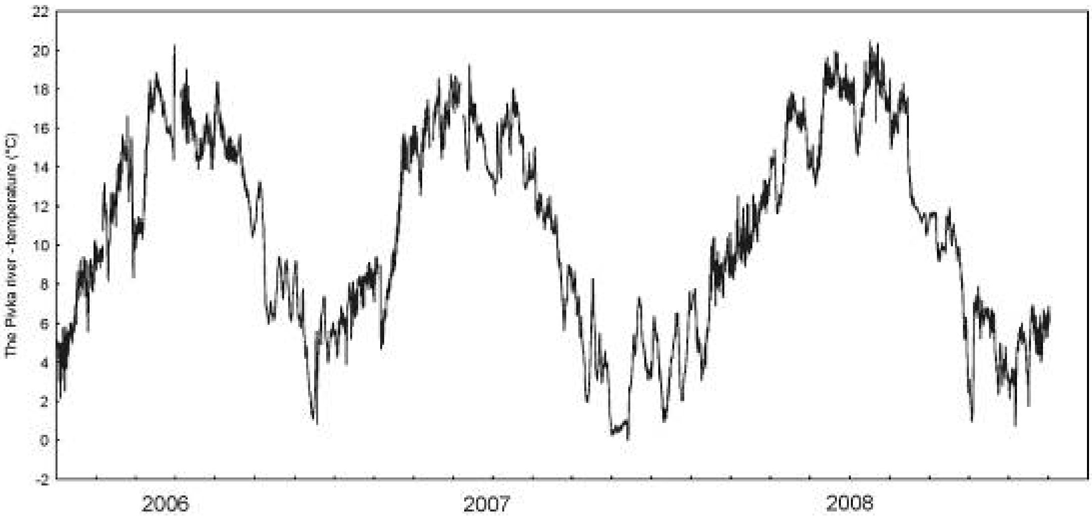

Figure 6.67: Diurnal and annual cycle of the Pivka River in time period March 2006 – December 2008. Measuring interval was shorter in year 2008 (10 min) than in 2006 and 2007 (15 min).

In contrast to surface streams, the temperature of underground water tends to be relatively constant on the daily scale (Baskaran et al., 2009). Hence, also the temperature of advective inflow from underground water to surface stream leaves its imprint on reach of surface stream, until after a certain travel time (distance) the heat exchange with the atmosphere has wiped out that memory (Sinokrot & Stefan, 1993).

There are also some internal drivers, which do not remove heat from the river channel; they only redistribute it temporally and spatially. Such are bed conduction and hyporheic exchange. Hyporheic exchange, where surface water enters the shallow subsurface (channel bed, banks or morphological features) and then re-emerges back into the main channel plays an important role in the thermal dynamics of some streams (Figs. 6.68 and 6.69). While advection via water flow dominates heat transfer in river, conduction controls heat exchange with sediments along hyporheic flow pathways. River water and heat can be retained for periods of time, before they are released back into the river. The hyporheic zone influences the thermal regime of rivers as it buffers, stores and releases advected heat over a range of timescales with some time lag. Hence, emergent hyporheic temperature is usually different to the temperature of main stream. However mixing does not cool or warm a river, but it dampens diurnal temperature variations of the river by decreasing maximum and increasing minimum temperatures (De Smedt, 2007; Burkholder et al., 2008).

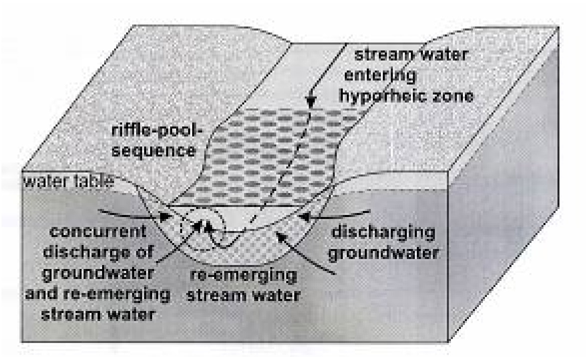

Figure 6.68: Flow exchange between surface water and ground water through the hyporheic zone. Water is partly stored in hyporheic zone; hence heat is buffered before it is released back (from Kalbus et al., 2006).

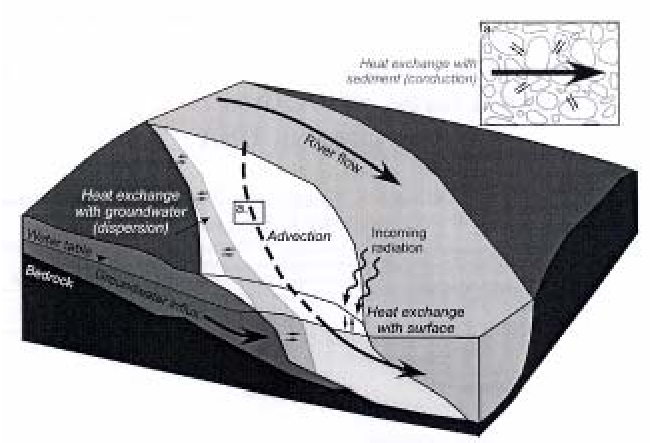

Figure 6.69: Thermal processes in hyporheic zone (white). Advection transports heat via fluid flow (large black arrows), conduction transfers heat between sediment and hyporheic water (small black arrows), a combination of conduction and dispersion occurs as hyporheic waters interact with groundwater and incoming solar radiation indirectly warms hyporheic water via conduction and transfer of latent heat (from Burkholder et al., 2008).

6.6.3.2. Heat transport in streams

Energy transport equation for calculating water temperature of open channel streams was represented by Sinokrot and Stefan (1993). Equation solves one-dimensional heat advection-dispersion equation and includes the heat exchange with the atmosphere. But atmospheric factors do not have any significance at all in the underground, more important is again exchange with hyporheic zone. Moreover underground flows exchange heat also with surrounding rock (walls).

For surface flows with open channel and constant cross-section, the ***heat advection-dispersion transport equation*** can be written in the same way as mass advection-dispersion equation (Sinokrot & Stefan, 1993; Socolofsky & Jirka, 2004):

$$A\frac{dC}{dt} = AD\frac{d^2C}{dx^2} - Q\frac{dC}{dx} + Exchange$$

But *Exchange* is different; it occurs as evaporation, radiation, conductive heat flux and diffusion heat flux entering the hyporheic zone. Conductive and diffusion heat fluxes are predominant in underground streams. Hence, conductive heat flux into the matrix and diffusion heat flux entering hyporheic zone may be written as (Mohrlok & Sauter, 1999):

$$Exchange = \lambda A \nabla T + \alpha(T_h - T)$$

where,

λ is the heat conductivity [°C /m]

A is the interfacial area [m^2]

∇T is the temperature gradient at the river bed

α is the hyporheic zone exchange coefficient [s^{-1}]

T_h is the temperature of water in hyporheic zone [°C]

T is the temperature of river [°C]

Longitudinal dispersion is negligible in thermally well-mixed streams. The cause is in the high velocity of flow and in the low longitudinal temperature gradients along the stream reaches (Sinokrot & Stefan, 1993; Gu & Li 2002). Hence, the heat advection-dispersion transport equation can be limited to ***advection*** and hyporheic, matrix heat exchange in a river such as the underground Pivka River.

6.7. ASSESING TRANSIT TIMES AND VELOCITIES OF UNDERGROUND FLOW IN POSTOJNSKA JAMA SYSTEM BASED ON HEAT AND MASS TRANSPORT

6.7.1. About water flow velocity and water transit time

Transit time is a time required for ground water to flow from one point to another (Perrin, 2003). It depends on the flow path and flow velocity.

All rivers have characteristic velocity profiles. The velocity of water flow is lowest near to the 'walls' of the channel (shorter arrows), at the river bed and the banks; and the fastest at the surface and middle of the channel (longest arrows) (Fig. 6.70). This is valid for an ideal, perfectly straight channel. In reality the highest velocity is somewhere just beneath the water's surface, and to one side of the centre-line of the channel because of turbulence, channel roughness and asymmetrical cross-profile (http://cronodon.com/files/River_Processes_1.pdf).

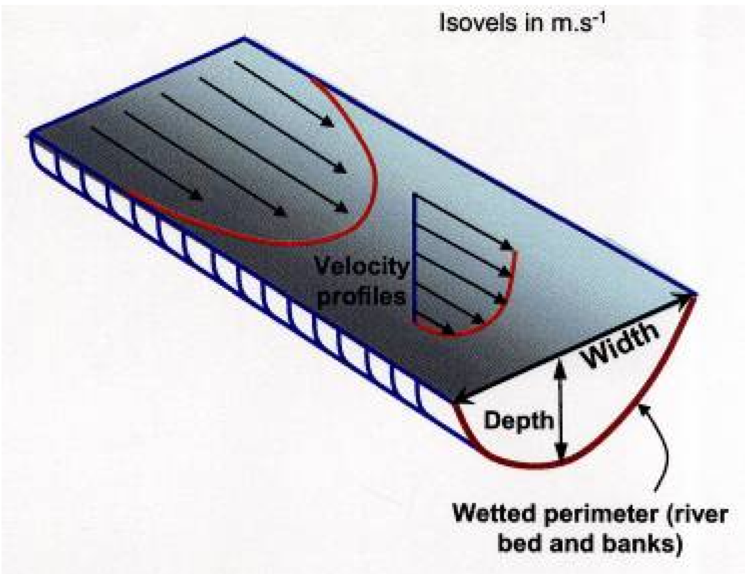

Figure 6.70: A portion of a river channel illustrating the velocity profiles. (http://cronodon.com/files/River_Processes_1.pdf)

Consequently, average stream velocity is primarily a function of the stream area, morphology and slope. Average velocity of flow in open surface channels can be estimated by Chezy - Manning's formula (Gierke, 2002; Schulze et al., 2005):

$$v = \frac{1}{n} \cdot R^{2/3} \cdot S^{1/2}$$

where v is the flow velocity, n is the roughness of river bed or conduit, R is the hydraulic radius and S is the slope or hydraulic gradient of the conduit.

As can be seen from Manning's formula, velocity of water flow is directly controlled by three parameters: hydraulic gradient, hydraulic radius and Manning's roughness coefficient (Raeisi et al., 2007). Hydraulic radius varies due to stage dynamics of the stream. Hydraulic radius depends on the shape of the channel or conduit cross-section and on the actual water level (discharge of the stream). For a rectangle riverbed, it can be calculated as a function of river depth (D) and width (W) (Schultze et al., 2005):

$$R = \frac{D \cdot W}{2D + W} \text{ [m]}$$

Stream velocity (and consequently water transit) varies with discharge. The relation between mean stream velocity (v) and discharge (Q) for surface streams can be assumed by the following equation (Jobson, 1996):

$$v = K * Q^a$$

where K is a constant and a is exponent with typical value around 0.34. Constant K and exponent a must be defined for each river reach.

6.7.2. How to asses transit time or velocity of concentrate water flows in karst

Parameters, which should be known to calculate flow velocity from Manning's formula, are difficult or almost impossible to obtain in underground systems (caves). Variation of these parameters can be significant even along relatively short underground reaches. For this reason, other relatively simple methods were applied to estimate transit time and consequently also velocity of underground flow.

Temperature of water as a natural tracer was applied to estimate groundwater velocity (Baskaran et al., 2009) and a tracer test was done for the same purpose.

- Transit time (*t*), which water needs to traverse distance between neighboring stations in Postojnska Jama system, was observed due to the phase shifts of temperature signals (Fig. 6.71) (Sket & Velkovrh, 1981; Stonestrom & Constantz, 2003; Birk et al., 2004). Temperature signal travels with water flow by advection and dispersion, but advection is the governing process (Sinokrot & Stefan, 1993; Gu & Li 2002), as already discussed (in chapter No. 6.6.3 "Water temperature and heat transport").

We observed transitions of a few hundred signals within Postojnska Jama system, at all possible flow rates (less than 1 m^3/s and up to 30 m^3/s).

Based on our measurements, transit times (*t*) among stations are known (at various discharges), also distances (*L*) are roughly known, hence velocity of temperature signal (*v*) at each of six underground sub-reaches can be calculated as v=L/t. This velocity, which reflects velocity of advection front, is used as a proxy for velocity of water flow.

Only temperature pulses, which coincide with stable ("constant") flow rate along entire monitored system (i.e. between two the most distant stations) were applied to analysis. However, such are majority of temperature pulses, except those, which coincide with the rising limb of the hydrograph, rapid hydrodynamic respectively (see also next chapter No. 6.8). Such temperature pulses were excluded from our survey.

Hence it can be considered that transit time of a signal (flow velocity) at certain flow rate depends mainly on the length of the underground pathway between two stations, conduit morphology, topography and particularly amount of ponding caused by restrictions (Jobson, 1996).

- Velocity of underground flow was additionally estimated by injection of soluble artificial tracer into the underground Pivka River. Velocities can be calculated by analysing breakthrough curves. Velocities obtained by this method are characteristic for certain discharge only, which occurs during the tracing. Velocity of water flow based on mass transport was compared with velocity of water flow based on heat transport.

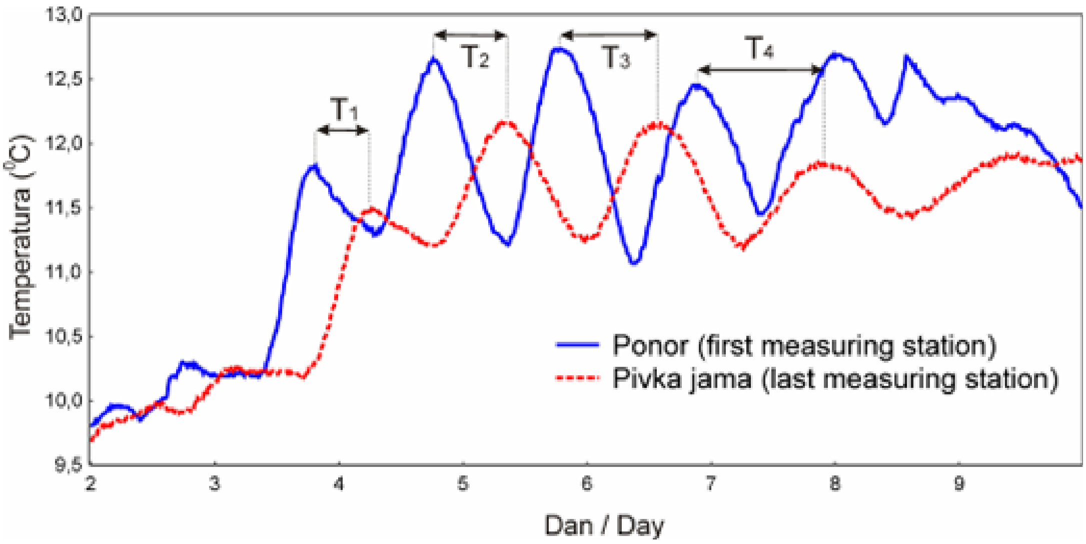

Figure 6.71: Phase shifts of maxima (or minima) are equal to transit time of temperature signal, which moves with water from one location to another.

6.7.3. Results

System with seven monitoring stations could be divided into six sub-reaches, we decided for division to five sub-reaches. Length of the sub-reach between Martel's chamber (fifth station) and Magdalena Jama (sixth station) is very short (approximately 250 m) and was therefore incorporated in another sub-reach together with Magdalena Jama (sixth station) and Pivka Jama (seventh station). The lengths of five sub-reaches ranging from 500 to 1100 m, which is an adequate length to study transit times of temperature signal at 10 minutes measuring interval.

The five sub-reaches were later reduced into three main reaches by combining. These three main reaches have characteristic hydraulical and hydrodynamical patterns. Their lengths are approximately the same.

Five sub-reaches

Relation between transit time of temperature signal and flow rate is exponential, but at relatively low flow rates only - from minimal discharge to around 5 m^3/s or 10 m^3/s (Fig. 6.72). Transit time decreases linearly from flow rates higher than about 8 m^3/s. However this linear decrease is very gentle and becomes almost negligible at the highest measured flow rates of the Pivka River.

As can be seen from Fig. 6.73, determined velocities of temperature signal (flow velocity) in five sub-reaches show a decreasing trend in downstream direction of the underground system. Velocities are on average relatively high in two of the most upstream sub-reaches, i.e. among stations 1-2-3 (Fig. 6.3 in chapter No. 6.). Further downstream velocities on average drop because the flow is obstructed by different hydraulic restrictions (Fig. 6.73, Tab. 6).

The standard deviation of measured transit time and calculated velocity of temperature signal in the most upstream sub-reaches ponor – Tartar and Tartar – Otoška Jama is high, hence also the error of these two parameters may be high (Tab. 6). The reason is the large sampling interval. Velocities, which are higher than 20 m/min, are problematic at chosen sampling interval (10 minutes). The highest velocities (Tab. 6; the upper quartile of velocities) can be even underestimated in sub-reaches ponor – Tartar and Tartar – Otoška Jama, due to high error. The slower the velocities are, the lower is standard deviation and error.

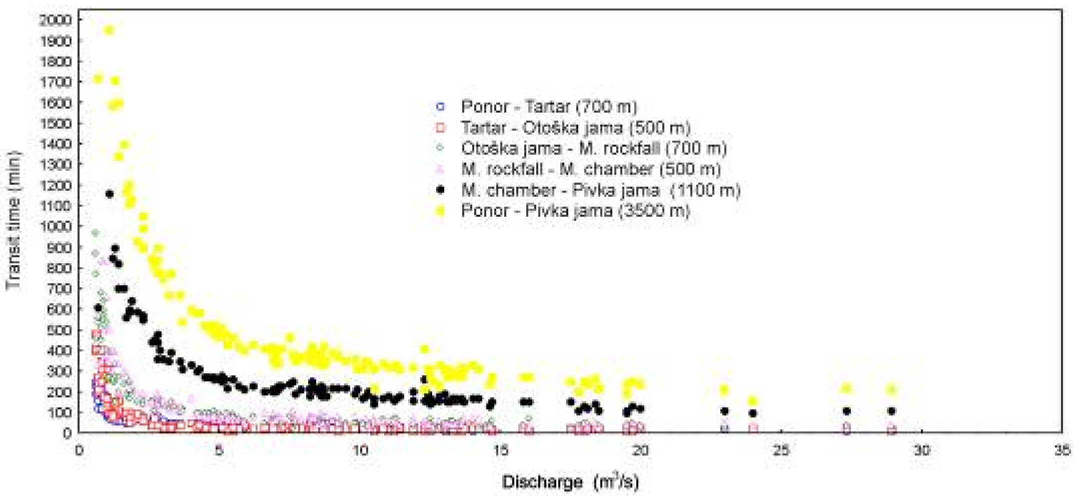

Figure 6.72: Relation between the discharge and transit time of temperature signal for 5 different stream sub-reaches in the system of Postojnska Jama. Also relation between the discharge and total transit time of temperature signals (time which signal needs to traverse from the ponor to the most downstream station in Pivka Jama) is depicted (yellow markers).

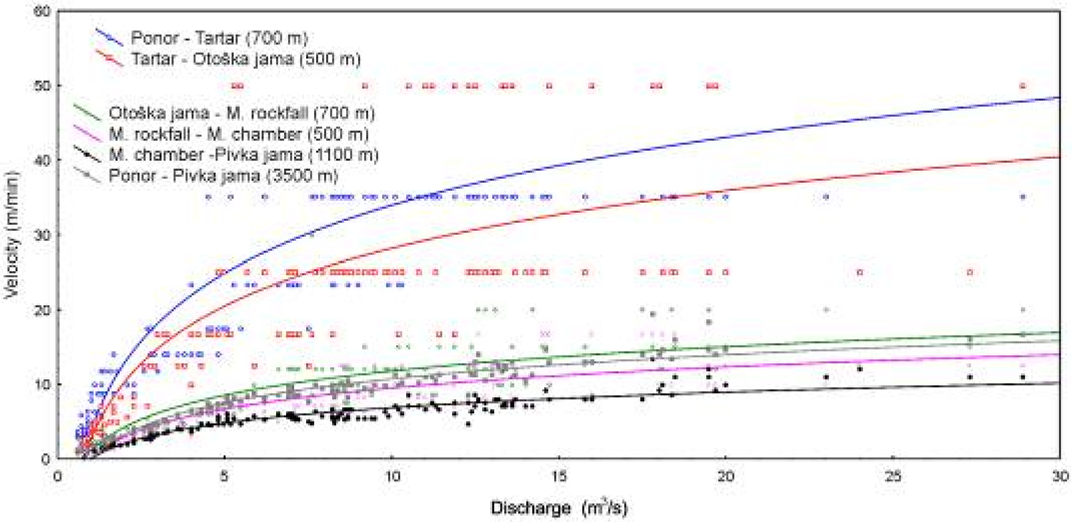

Figure 6.73: Mean velocities of temperature signal between neighboring stations, as a proxy of velocity of underground water flow at variable flow rate. The best fitting is also depicted.

Table 6: Basic statistics of velocities of thermal signal, determined among neighboring stations at all possible flow rates.

Station	Ponor-Tartar	Tartar-Otoška	Otoška-rock-fall	M. rock-fall-M. chamber	M. chamber-Pivka	Ponor-Pivka
Length (m)	700	500	700	500	1100	3500
MEAN (m/min)	25.2	20.9	8.8	7.6	5.9	9.3
MEDIAN (m/min)	23.3	25.0	8.6	7.1	5.7	9.5
SD	16.1	14.5	5.5	4.2	2.4	3.6
No. OF CASES	153.0	150.0	149.0	138.0	128.0	113.0
MIN (m/min)	2.8	1.0	0.6	0.6	1.0	1.8
MAX (m/min)	70.0	50.0	30.0	16.7	13.3	19.4
Lower quartile (m/min)	11.7	8.3	4.0	4.5	4.6	7.4
Upper quartile (m/min)	35.0	25.0	12.0	10.0	7.1	11.3

Three main reaches

According to obtained transit times of temperature signals and calculated mean flow velocities, which were all determined at a broad range of flow rates, the analysed system of the underground Pivka can be roughly divided into three main reaches. The division is based on measured transit times and consequently calculated flow velocities in five sub-reaches. Moreover, division is corroborated by characteristics of underground hydrodynamic (hydraulic), which was directly observed "in situ".

Section between ponor and third station in Otoška Jama forms the first stream reach, section between Otoška Jama and fifth station in Martel's chamber forms the second reach and the third reach is between Martel's chamber and the final seventh station in Pivka Jama (Fig. 6.3 in chapter No. 6).

Transit times of temperature signals and calculated mean flow velocities of water within these three stream reaches were determined at different flow rates. Graphical results and basic statistics are represented in Figs. 6.74 and 6.75 and in Tab. 7. The lengths of all three determined reaches are approximately similar (1100-1200 m), so transit times and velocities of temperature signals can be directly compared and differences argued by hydraulic characteristics of underground drainage in certain stream reach.

Transit time of the temperature signal is expectedly the lowest in the first and the highest in the third (last) reach of the underground Pivka (Fig. 6.74). There is a large contrast between calculated mean flow velocity in the first (the most upstream) and the second reach. Mean velocity in the second reach is more than three times lower (on average) than in the first reach (Fig. 6.75). Difference of calculated mean velocity in second and third reaches is relatively low, but it is still statistically significant. Mean flow velocity in the third reach is therefore the lowest.

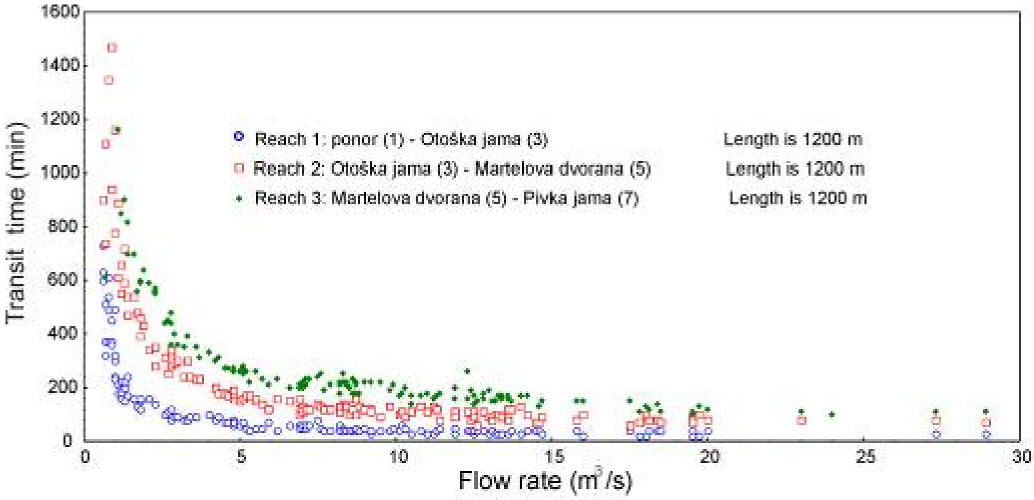

Figure 6.74: Relation between discharge and transit time of temperature signal for three stream reaches in the system of Postojnska Jama.

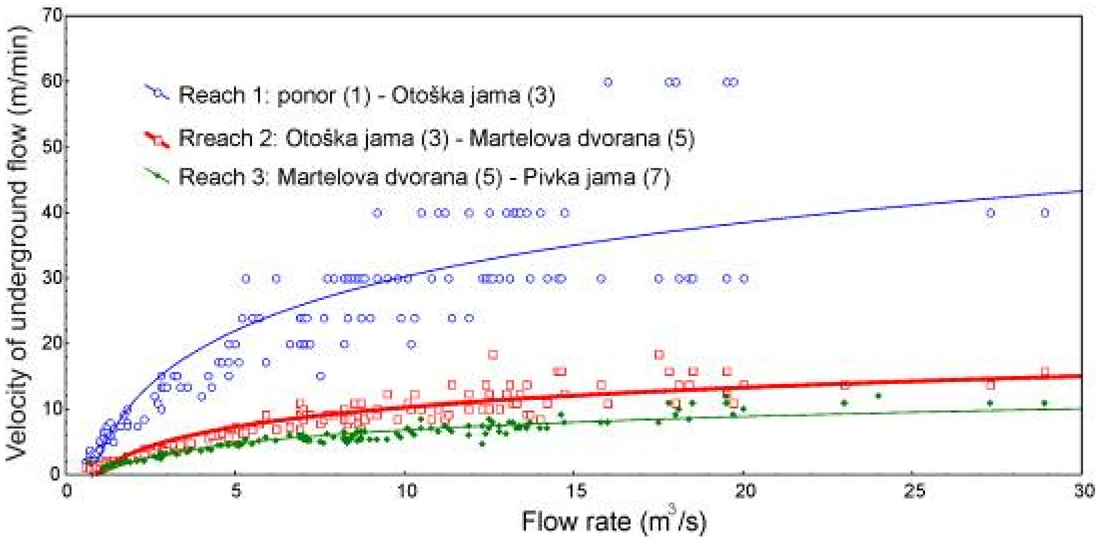

Figure 6.75: Mean velocities of temperature signal within three underground reaches, as a proxy of velocity of underground water flow, at variable flow rate. The best fitting is also depicted. Length of all three reaches is approximately the same 1200 m.

Table 7: Basic statistics of flow velocities based on the analysis of temperature signal, for three main underground reaches, at all possible flow rates. Length of all three reaches is approximately the same, it is 1200 m.

Section	1-3	3-5	5-7
MEAN (m/min)	22.1	8.0	5.8
MEDIAN (m/min)	24.0	8.5	5.7
SD	13.7	4.2	2.4
No. OF CASES	150.0	136.0	131.0
MIN (m/min)	1.6	0.7	1.0
MAX (m/min)	60.0	18.3	12.0
_25th% (m/min)	10.0	4.5	4.4
_75th% (m/min)	30.0	11.0	7.1

- Underground stream reach 1: Calculated mean advective velocity is highest between the ponor and Otoška Jama (stream reach between stations 1-2-3) (Fig. 6.75 and Fig. 6.3 in chapter No. 6). Underground water flow may be considered as an alternation of gentle steep channels and pool channels (at least at low and some moderate flow rates, such as up to 5 m^3/s). Length of steps and pools generally do not exceed a few tens of metres in the reach discussed (Fig. 6.13 in chapter No. 6.4). There are no hydraulic restrictions, except some narrow passages which may alter open channel flow to full pipe flow, but presumably at the highest discharges only. The length of such narrows is not more than few tens of metres. The mean hydraulic gradient between ponor (1) and Otoška Jama (3) is relatively high: around 0.005 at base flow (Fig. 6.14 in chapter No. 6.4). For all these reasons, underground water drains generally unrestricted and velocities of water flow are relatively high.

- Underground stream reach 2: Mean flow velocity drops significantly in the next stream reach between Otoška Jama (station No. 3) and Martelova dvorana (station No. 5) (Tab. 7). Conduits have similar geometry as in upstream reach, but several breakdowns appear in the second stream reach. Breakdowns represent important restrictions, as they cause ponding. Consequently conduits can be temporally flooded for hundred or more metres backwards. Hence long underground lakes occur in this reach. Most of these breakdowns behave not only as dams, but also as weirs with water spilling over them.

Hydraulic gradient is minimal along such permanently flooded conduits, underground lakes respectively. Several underground lakes with lengths of around 100 m and up to 200 m or 300 m (estimation) appear in this reach. Underground lakes are divided by steep channels, which are not affected by ponding, at least at base flow. However, conditions should change during floods. The total length of such steep channels is small, compared with pools. The mean hydraulic gradient along the second reach is similar to that along first one (on average) (Fig. 6.14 in chapter No. 6.4), but locally it is almost negligible, such as along underground lakes.

Drainage through long pools (lakes) is relatively slow even at the higher flow rates. Full pipe flow may occur at much longer distance (at the highest flow rates), than in the upstream reach.

- Underground stream reach No. 3: Mean flow velocity, calculated from transit times of temperature pulses, is on average the lowest in this reach, between stations 5 (in Martel's chamber) and 7 (phreatic loop at the end of Pivka Jama) (Figs. 6.75 and Fig. 6.3 in chapter No. 6). Anyway, we should stress that this reach has the most extreme and opposite hydrodynamical properties and it would certainly be better to divide it to two parts.

The first part stretches from Martel's chamber to inflow into Pivka Jama, incorporating Magdalena Jama mainly. Water flow is distributed among several channels, at least between Martel's chamber and Magdalena Jama. A relatively higher portion of water is in contact with surrounding rock in comparison with upstream reaches 1 and 2. Section between Magdalena Jama and Pivka Jama was inaccessible for us, due to its morphology. Therefore we have to rely on data from literature only. The 300 m long pool (underground lake) divided by three phreatic loops appear there. Length of phreatic loops is 33, 60 and 80 m and they are up to 15 m deep (Fig. 6.76) (Krivic & Praprotnik, 1975). Steep channels do not occur, hence mean hydraulic gradient is minimal. Full pipe flow takes place for a much longer distance than in upstream reaches 1 and 2. Distribution of water flow to possible lateral conduits is not certain here.

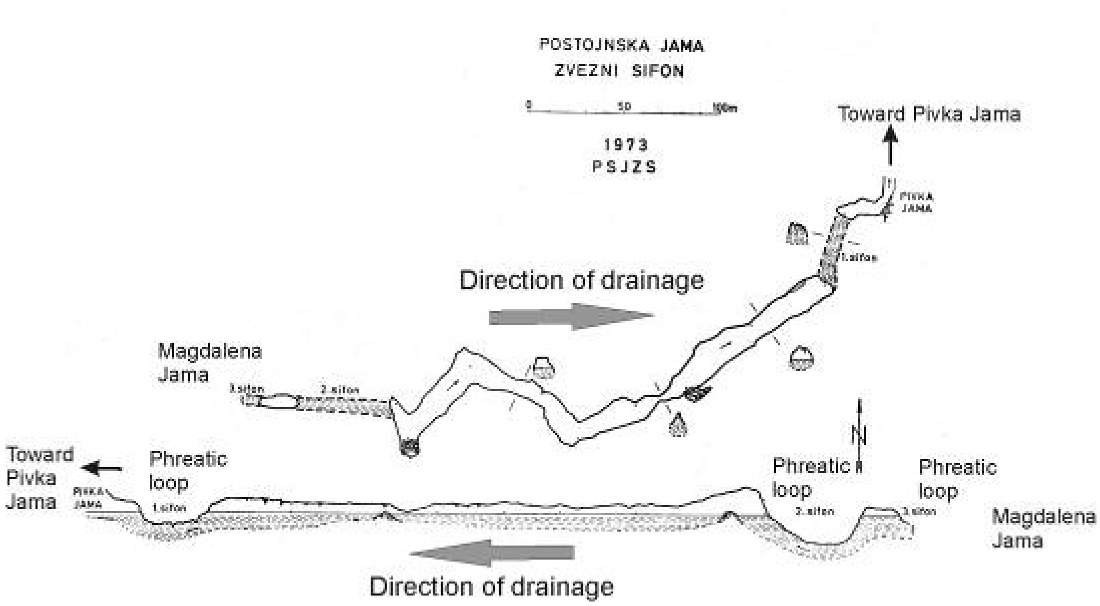

Figure 6.76: Ground plan and longitudinal sketch of an underground reach between Magdalena Jama and Pivka Jama. Note that two sketches are inversely orientated. There are three phreatic loops in this reach, one of which has not been physically researched yet (adapted from Krivic & Praprotnik, 1975).

The properties of underground drainage change completely in Pivka Jama. Water flow acts as a torrential flow in this part of the system with cascade-riffle channels. Mean hydraulic gradient is locally the highest there - 0.03 (Habič, 1985) or higher, and velocities of water flow are presumably the fastest in the entire system. Full pipe flow conditions almost never occur in Pivka Jama, due to large dimensions of the conduits. One breakdown blocks the drainage of water in Pivka Jama, but water penetrates through it relatively unretained.

Hence velocity in this third underground stream reach is a combination of slow drainage along the longest underground lake in system (this lake in Magdalena Jama is divided by several phreatic loops, total length is around 500-600 m) and rapid drainage through Pivka Jama (length around 600 m). Anyway, slow drainage along underground lake highly diminishes mean flow velocity between Martel's chamber (station 5) and outflow from Pivka Jama (station 7).

Mean hydraulic gradient in the third reach is not representative information, due to the described characteristics, anyway it is around 0.018 (Fig. 6.14 in chapter No. 6.4).

Ponor-Planinska Jama

Transit time, which water particles need to traverse the reach between the ponor and phreatic loop of Pivka Jama, is approximately half time lower, than transit time of water between phreatic loop of Pivka Jama and Planinska Jama, according to our available data (Fig. 6.77). Lengths of both reaches are presumably similar, hence the different transit times should be attributed to hydraulic processes. In the downstream reach, underground drainage is presumably under the influence of more numerous hydraulic restrictions, mean hydraulic gradient is slightly lower (around 0.007) (24 m / 3500 m) and wetted perimeter is on average presumably higher in comparison with the reach between the ponor and Pivka Jama (hydraulic gradient is 0.009 there). Downstream reach, with longer transit time, was only partly researched by divers; hence characteristics of underground drainage are mainly unknown.

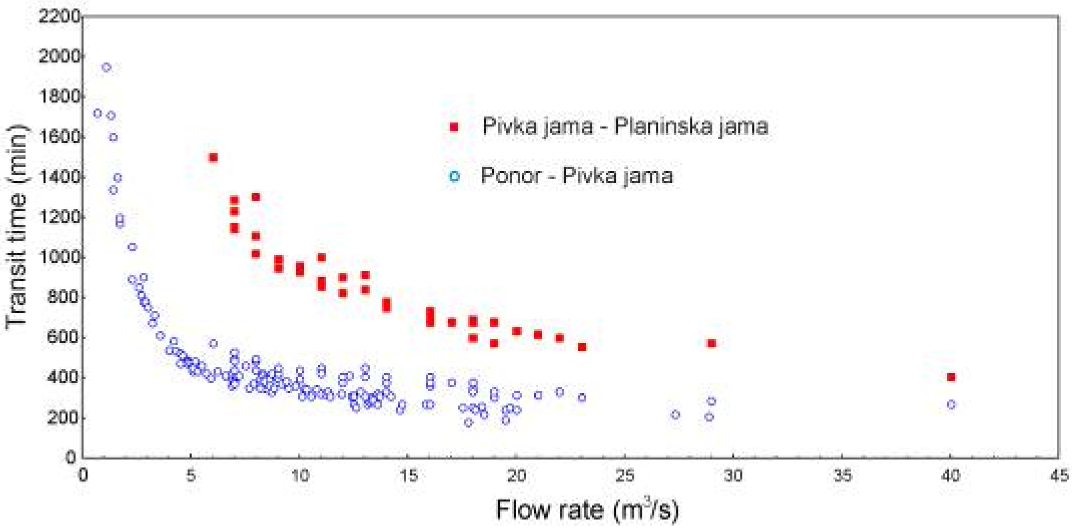

Figure 6.77: Relation discharge – transit time of thermal signal for two reaches of approximately similar length (3500 m – estimation). Transit times in reach Pivka Jama – Planinska Jama are for a factor of two higher than in upstream reach ponor – Pivka Jama.

Transit time of water between ponor and Planinska Jama was already studied by Sket and Velkovrh (1981) with the same method. Discharge should be higher than 4 m^3/s, otherwise diurnal variations are dampened in Planinska Jama and transit times can not be assessed. Temperature signal needed around 40-56 hours (2400-3360 min) to traverse the distance between Pivka Jama and Planinska Jama at discharge 4 m^3/s. Transit time reduced to 4 hours (240 min) at discharge 39 m^3/s (Sket & Velkovrh, 1981). This transit time is underestimated according to our data (Fig. 6.77); we measured around 400 min at similar discharge 40 m^3/s.

6.7.4. Discussion

Differences in assumed mean velocities of the water flow, which were determined for five sub-reaches (among six stations) in the underground system, can be only roughly explained by variation of conduit morphology, topography and occurrence of hydraulic restrictions, which alter hydraulic gradient by ponding.

Based on hydraulic and hydrodynamic characteristics of water flow, the system was divided into three main reaches of similar length (around 1200 m). It was clearly observed that mean transit times of temperature signals within three successive underground reaches differ significantly, even if they are all of approximately the same length.

Flow velocities are on average highest between stations, where underground drainage takes place through single conduit (without significant divergence) and this conduit is not restricted by breakdowns or other significant hydraulic barriers. The underground reach between three upstream stations (reach No. 1, between ponor and Otoška Jama) has such characteristics.

Local hydraulic gradient in front of hydraulic restrictions (such as breakdowns) is diminished, as they cause ponding. Consequently also flow velocity is diminished on average (underground reach No. 2).

Wetted perimeter presumably does not differ significantly in two upstream underground reaches (ponor – Otoška Jama and Otoška Jama – Martel's chamber), while it can increase greatly in third, the most downstream reach (in Magdalena Jama).

Flow velocity is on average the lowest between Magdalena Jama and Pivka Jama (reach No. 3). Hydraulic gradient is minimal along Magdalena Jama (300 m) (Fig. 6.76). Also flow diverges into many lateral conduits; hence relatively higher portion of water is in contact with conduit (bed of underground river, walls), i.e. that wetted perimeter is greater. The wetted perimeter refers to the extent to which water is in contact with its channel (Fig. 6.78). The greater the wetted perimeter, the higher is the friction between the water and the banks, the bed of the channel, and the slower is the velocity of river flow (http://library.thinkquest.org/28022/velocity/index.html).

Hence we assume that wetted perimeter has important influence on drop of flow velocity in reach No. 3. Moreover, full pipe flow presumably occurs for a long distance (hundred metres or more) in this reach (Krivic & Praprotnik, 1975). Mean velocity of water flow decreases in the transition to full pipe flow, as wetted perimeter increases (Raesi et al., 2007).
Total transit time of temperature signal between ponor and final station in Pivka Jama is a sum of all local transit times along the system. Hence total transit time or mean flow velocity is affected by all the mentioned hydraulic processes between ponor and Pivka Jama.

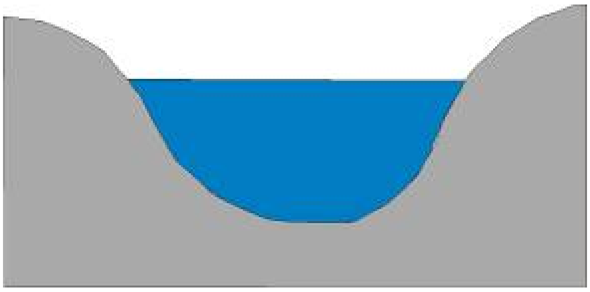

Figure 6.78: Wetted perimeter is calculated by adding the length and breadth of the channel in contact with water.

To verify these statements, we can make a test with Manning's equation (in chapter 6.7.1.). Significance of variability of Manning's roughness coefficient, hydraulic gradient and wetted perimeter (cross-section of the conduit) to affect velocity of water flow may be studied. We found out that the velocity of underground water flow (transit time respectively) is the most sensitive to changes of roughness coefficient and to abrupt changes of hydraulic gradient (abrupt changes of hydraulic gradient occur in the Postojnska Jama system). However, changes in velocity of underground drainage cannot be really argued by variability of roughness coefficient. For this variability is totally unknown.
Abrupt variations of diameter of cross-section affect wetted perimeter and consequently flow velocity. The reason is friction, as mentioned.

6.7.5. Comparison of velocities based on two different methods: analysis of tracer cloud and phase shifts of temperature signal

6.7.5.1. Introduction

Worthington (2007) made a comparison of ground water velocities and travel times, which were based on artificial and natural tracers. He found that natural tracers give times, which are much greater than estimates from artificial tracers (typically one hundred times longer). The reason is in multiple porosity elements in a carbonate aquifer. Different tracers measure different aspect of the porosity. The artificial tracers give the velocities of the fastest component of flow through aquifer (conduit flow), while natural tracers give the average age of the groundwater, including both rapid flow component (through conduits) and slow flow component (through the matrix and fractures). However, there is an exception, when all the flow takes place along a conduit from a ponor to a spring. Such conditions occur in Postojnska Jama system. In such a case, there is no significant mixing between water particles (of different ages, or different temperature). Consequently flow from ponor to spring follows simple advective piston-flow model (Worthington, 2007).

A tracing test was performed at certain hydrological conditions. Sulphorhodamine G, which is a water soluble tracer, was injected to the Pivka River in front of the ponor (Fig. 6.79). Tracing test was done during base flow conditions (slow recession respectively). Hence water conditions were stable during transition of tracer cloud through the underground system; flow rate was 2 m^3/s. Transition of tracer cloud was recorded at three locations. It was measured in Otoška Jama, in Magdalena Jama and in Pivka Jama, at exact locations as temperature signal of the underground Pivka River (Fig. 6.3 in chapter 6). Mean velocity of underground flow among discussed stations was calculated due to the analysis of tracer clouds (breakthrough curves). Calculated velocities of water flow, based on propagation of water soluble tracer, were compared with velocities of temperature signal, but at exact flow rate 2 m^3/s only. Comparison is limited to three stations only. Transition of tracer was not recorded at all seven locations in the underground as temperature signal; reason is the lack of equipment.

Figure 6.79: Solution of Sulphorhodamine G was injected into the Pivka River from the bridge just front of the ponor (photo: J. Turk).

6.7.5.2. Analysis of breakthrough curve and application of QTRACER2 program

Interpretation of breakthrough curve in open channel streams is usually based on analytical solution of a one-dimensional transport equation in which the source term is not considered.

The ***mass of tracer*** (M_r) to pass a cross-section is computed (Jobson, 1996) as:

$$M_r = \int_{T_l}^{T_t} \int_0^W C_v * q * dwdt \qquad (1)$$

$$M_r = \int_{T_l}^{T_t} \int_0^W C_v(w) \cdot q(w) \cdot dwdt$$

where w is the total width of the river, C_v is the vertically averaged tracer concentration and q is discharge per unit width. Both C_v and q are given at time t and distance w from one bank.

After the mixing is complete in the cross-section, the equation is transformed (Jobson, 1996) to:

$$M_r = \int_{T_l}^{T_t} C * Q * dt \qquad (2)$$

where C is tracer concentration and it is uniform in the cross-section and Q is the total discharge in the cross-section at time t.

On the basis of breakthrough curve, which is recorded at one or more locations, mean residence time of tracer and mean tracer velocity between measuring locations can be determined.

Mean residence time of tracer was determined as the length of time required for the gravity mass of the centroid of the tracer to traverse the length between two stations in the underground system (Fig. 6.80) (Field, 2002).
Mean tracer residence time for impulse releases is calculated by following equation in QTRACER2 program:

$$t = \frac{\int_0^\infty t * C(t) * Q(t) dt}{\int_0^\infty C(t) * Q(t) dt} \qquad (3)$$

where t is a time, C is a tracer concentration and Q is a flow rate.

The ***mean tracer velocity*** can be directly calculated from mean tracer residence time. In such a case, it is determined as a measure of the flow rate of the centroid of the tracer mass. Tracer was injected impulsively; hence mean tracer velocity can be calculated by following equation (Field, 2002):

$$v = \frac{\int_0^\infty (x_s / t) * C(t) * Q(t) dt}{\int_0^\infty C(t) * Q(t) dt} \qquad (4)$$

where x_s is a sinuous tracer migration distance.

The concentration centroid of the tracer cloud provides a good approximation of the mean flow transit time and consequently mean flow velocity at certain flow rate. The mean transit time of the tracer is higher than the time of maximum concentration, because breakthrough curve is usually asymmetric with recession limb relatively less steep than rising limb. Reason is in different processes such as dispersion, storage and transport processes (Benischke et al., 2007).
Benischke et al. (2007) proposed an alternative method to estimate the mean flow velocity at a half recovered tracer mass (a time at breakthrough curve when 50 % of the recovered tracer has passed).

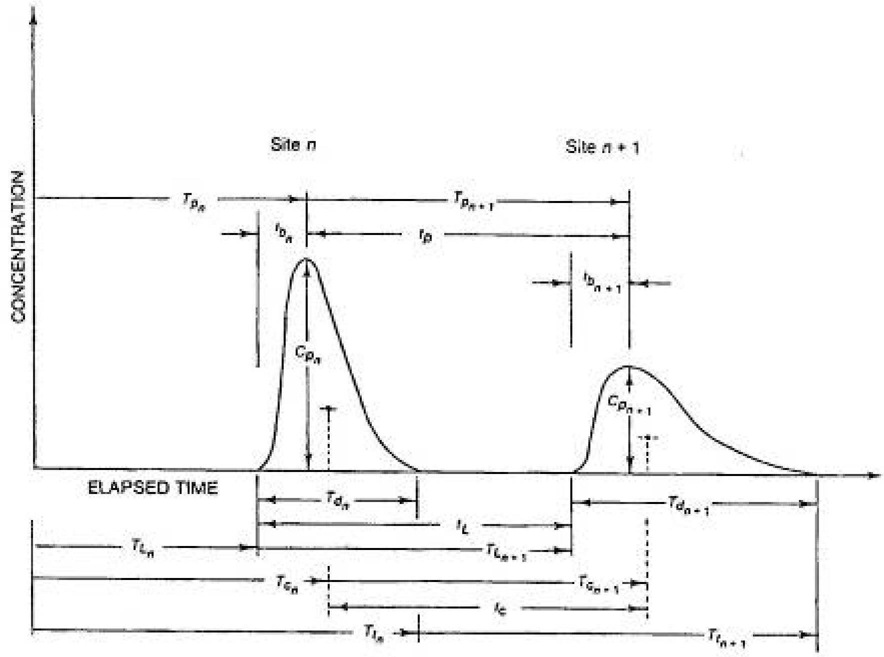

Figure 6.80: Sketch of a breakthrough curve along a selected tracer streamline. T_c represents the mean resident time of a tracer between two locations (from Field, 2002).

Skewness is a measure of the lateral asymmetry of the breakthrough curve and the **kurtosis** is a measure of the peakness of the same curve. For impulse and short-pulse releases, skewness (γ_t) may be determined from following equations (Field, 2002):

$$\gamma_t = \frac{\int_0^\infty (t-\bar{t})^3 Q(t)C(t)dt}{\sigma_t^3 \int_0^\infty Q(t)C(t)dt} \qquad (5)$$

where σ_t is standard deviation for mean residence time.

And kurtosis (κ_t) may be determined from following equations (Field, 2002):

$$\kappa_t = \frac{\int_0^\infty (t-\bar{t})^4 Q(t)C(t)dt}{\sigma_t^4 \int_0^\infty Q(t)C(t)dt} \qquad (6)$$

A symmetrical curve results in a ***skewness coefficient*** equal to zero. Positive number for the skewness indicates that the breakthrough curve is weighted to the right. It means that breakthrough curve recedes more gently than it rises and reflects both longitudinal dispersion and dead zone effects.

Higher the ***kurtosis coefficient***, the sharpest is the peak of the breakthrough curve and vice versa.

Skewness and Kurtosis are used by QTRACER2 only for comparison of dimensionless breakthrough curves generated from multiple tracer tests conducted from the same injection points to the same recovery locations (Field, 2002). However, we use them for comparison of the same breakthrough curve, but at three different locations in the underground system. The shape of the curve is changing during the propagation downstream.

Peclet number (*Pe*) is a dimensionless number that indicates the relative importance of mechanical dispersion and diffusion in comparison with advection in mass transport. It is a ratio between the time taken by fluid particles to traverse distance (*L*) by dispersion and diffusion alone ($t_{dispersion}$) and the time taken to travel the same distance (*L*) by advection ($t_{advection}$) at average velocity (*v*) (Field, 2002; Anwar, 2008):

$$Pe = \frac{t_{dispersion}}{t_{advection}} = \frac{L^2/D_m}{L/v} = \frac{uL}{D_m}$$

where *Dm* is molecular diffusion (L^2/T)

Peclet numbers below 0.4 indicate dispersion (diffusion) control, between 0.4 − 6.0 suggests that dispersion (diffusion) and advection are in transition and thus approximately equal to each other, while Peclet numbers higher than 6.0 indicates advection control. In most non-porous media instances of solute transport such as in karst conduits, Peclet numbers are many times greater than 6.0 (Field, 2002).

6.7.5.3. Results and discussion

Breakthrough curves, recorded in Otoška Jama (third station), Magdalena Jama (sixth station) and Pivka Jama (final seventh station) are represented in Fig. 6.81.

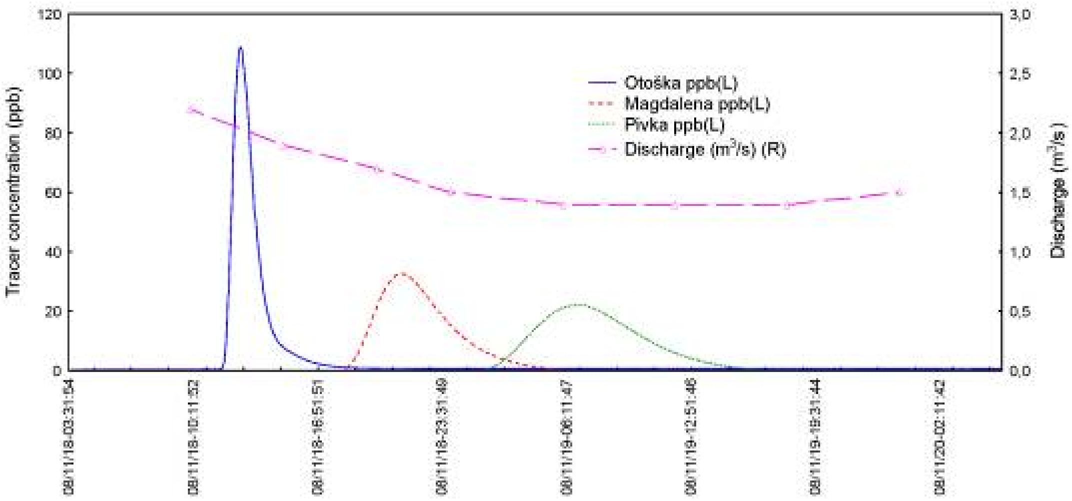

Figure 6.81: Discharge of the Pivka River and breakthrough curves for three locations within Postojnska Jama system. Transit time and velocity of tracer were calculated due to the occurrence and shape of breakthrough curves.

Several parameters can be calculated by analysing breakthrough curves, as was discussed. QTRACER2 program was applied (Field, 2002) to calculate mean tracer velocity and other parameters in Table 8.

QTRACER2 program uses equations 3 and 4 to calculate **mean tracer resident time** and **mean tracer velocity**. **Recovery percent** of injected tracer is calculated by equation 2.

The **longitudinal dispersion coefficient** is a function of scale. **Dispersivity** is in average the lowest along the shortest reach (ponor – Otoška Jama), while it is similarly higher along other two reaches (Tab. 8). It is logically, as dispersivity values increase as a tracer moves away from the source (Schwartz & Zhang, 2003). Dispersion and diffusion are much intensive downstream from Otoška Jama (third station), than between ponor and Otoška Jama also according to **skewness** and **kurtosis coefficients** (Tab. 8). Skewness and kurtosis coefficients are high in Otoška Jama and significantly lower in Magdalena and Pivka Jama.

Table 8: Parameters and statistics, based on transition of tracer cloud through three sections of the underground system.

	Ponor – Otoška Jama	Ponor – Magdalena	Ponor – Pivka Jama
Estimated length [m]	1210	2880	3850
r	-0.9862	-0.9888	-0.9852
Mean tracer resident time [hrs]	3.224	12.303	21.606
Standard dev. of mean trac. res. time	64.4	120.1	161.2
Mean tracer velocity [m/h]	375.34	234.08	178.19
Standard deviation for tracer velocity [m/hr]	99.844	37.235	21.949
Dispersion coefficient [m^2/s]	1.712	1.452	1.064
Longitudinal dispersivity [m]	16.4	22.3	21.5
Peclet number	73.68	128.98	179.11
Percent recovery of tracer injected	99.24	73.76	66.71
Skewness coefficient	2.737	0.7884	0.5581
Kurtosis coefficient	11.53	0.4684	0.0008

The **Peclet number** is high at all three monitored locations (Tab. 8), which indicates that underground flow is strongly advection controlled in comparison with dispersion and diffusion. Anyway, dispersion and diffusion are also important processes for mass transport in Postojnska Jama system.

33.29 % of tracer was lost between ponor and Pivka Jama, while losses of tracer were minor upstream from Otoška Jama. Almost the same losses (33.8 %) of tracer in Pivka Jama were determined also by tracer test in 1974, when 1500 kg of NaCl, diluted in 8000 litres of water, was injected to the Pivka River in front of the ponor (Avdagić et al., 1976). This tracer test was performed at similar water conditions to ours: the discharge of the Pivka River was similar, but more variable (in range 0.7 m^3/s – 3 m^3/s) in year 1974.

Velocity of tracer transition and flow velocity, based on transition of temperature pulse, were compared at exact discharge - 2 m^3/s. Both velocities give some approximation of flow velocity. We would like to evaluate representativity of such approximations.

Mean tracer velocities along underground system were calculated by QTRACER2 program, which use equation (4). Mean velocity of tracer between ponor (first station) and Otoška Jama (third station) was calculated to 375 m/h, between ponor and Magdalena Jama (sixth station) was 234 m/h and between ponor and Pivka Jama (seventh station) was 178 m/h (Tab. 9).

Lengths of these three reaches are not exactly the same as in chapter 6.7.3. QTRACER2 program corrects distance from input to output with certain sinuosity factor; hence distances are slightly higher (Tab. 9). These distances were applied for both approaches (velocity of tracer cloud and velocity of temperature signal), while comparing them.

Transit time of water flow, which is based on phase shifts of diurnal temperature maxima or minima of water, is known for each specific flow rate. Transit time of temperature pulse to traverse distance between two the most remote stations (ponor and Pivka Jama) at discharge 2 m^3/s is around 1000 min (± 100 min), as can be seen from the Fig. 6.72. Consequently, mean velocity can be calculated, as was discussed (Fig. 6.73). Relation between flow velocities and discharges is depicted in the Fig. 6.82.

Mean flow velocity (calculated from phase shift of temperature signal) at flow rate 2 m^3/s for reach between the ponor and Otoška Jama is approximately 12.2 m/min (732 m/h), for reach between the ponor and Magdalena Jama is approximately 5.4 m/min (324 m/h) and for the reach between the ponor and the most downstream location at Pivka Jama is approximately 3.75 m/min (225 m/h) (read from Fig. 6.82, at flow rate 2 m^3/s).

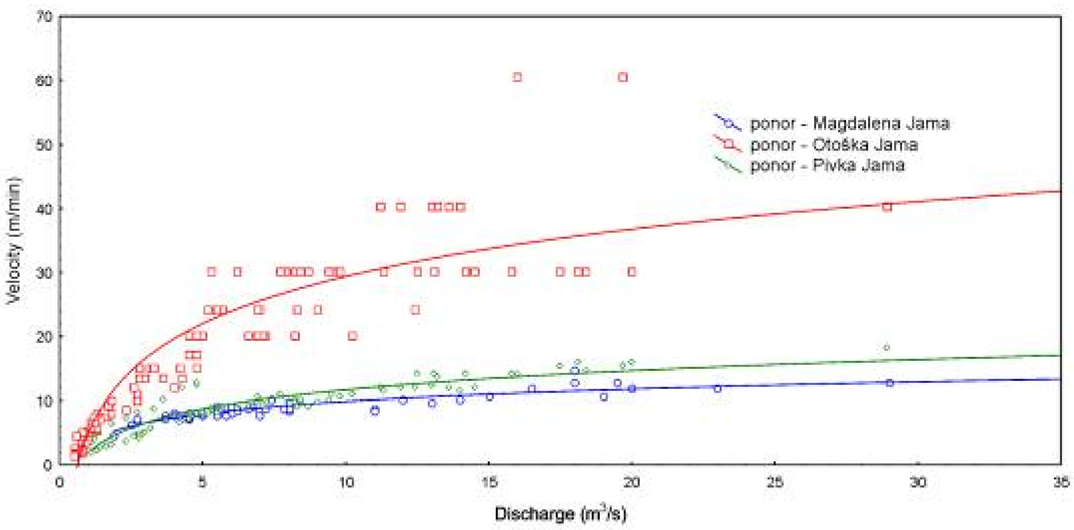

Figure 6.82: Flow velocity varies with discharge. We are interested in velocity at flow rate 2 m^3/s. The best logarithmic fitting was used to estimate velocity at certain flow rate.

Table 9. Comparison of velocities, based on two different methods (mass and temperature transport) at flow rate 2 m^3/s. These velocities serve us as an approximation of velocity of water flow.

	Ponor – Otoška Jama	Ponor – Magdalena Jama	Ponor – Pivka Jama
Length [m]	1210	2880	3850
Mean tracer velocity (m/h)	375	234	178
Maximum tracer velocity (m/h)	741	350	245
Mean velocity of water flow (based on phase shifts of temperature signal) (m/h)	732	324	225

6.7.5.4. Conclusion

Both applied methods indicate diminution of mean velocities of water flow with distance from the ponor (Tab. 9). However, mean tracer velocities show relatively low similarity to mean velocity of temperature signal. The mean tracer velocities are lower than velocity of the thermal signal measured at the same flow rate. Reason for differences should be in certain processes, which govern the transition of two different tracers (artificial, soluble in one side and natural in another side). Artificial, soluble tracer spreads and travels along the river channel or conduit in different manner, than the temperature signal. Both transports, mass and thermal, are advective controlled (see chapter 6.6). However, distribution of soluble and nonreactive Sulphorodamine G downstream is relatively higher affected also by diffusion and dispersion processes (Field, 2002; Benischke et al., 2007; Dogwiler et al., 2007) than distribution of temperature signal. Moreover, these two processes should be even unimportant for downstream distribution of temperature signal. Tracer artificially injected to the stream alters composition of natural water enormously. The coefficient of mechanical dispersion is high, due to high gradient. In contrast, surface water, which enters karst massif, represents relatively low thermal deviation for underground water and surrounding bedrock. There is much lower temperature gradient along the reach of underground stream, than concentration gradient caused by anthropogenic injection of water soluble tracer into the stream (see and compare "Exchange equations" in chapters 6.6.2 and 6.6.3.2). Hence, the coefficient of mechanical dispersion is relatively low for temperature signal.

Because of different intensity of physical processes, which control the transition of two different tracers (mass and thermal signal), determined transit times and velocities can differ significantly at equal flow rate conditions.

The difference in mean velocity of the tracer and velocity of the temperature signal is the highest in the most upstream reach (No. 1) of the underground system, where determined velocities differ almost for the factor of two. But the error can be high at both applied methods, as also standard deviation is high. Factor of difference is approximately 1.5 for both longer reaches (ponor – Magdalena Jama and ponor – Pivka Jama) and such difference is probably more representative. Mean velocities are much lower there and also standard deviation diminishes with length of underground reaches (Tab. 8).

Process, which influences on first arrival of the tracer, is attributed to pure advection. Maximum determined velocity of tracer (first arrival of the tracer), shows statistically significant similarity with velocity of thermal signal (Tab. 9). This proves that advection should greatly govern the transition of temperature signal along the system, while dispersion should be minor or even negligible.

6.7.6. Propagation of flood pulses through Postojnska Jama system

Propagation of flood pulse is considered as hydraulic response of the aquifer, which is different as physico-chemical response (temperature, electrical conductivity). The increase in hydraulic pressure due to recharge is almost instantaneously transmitted through phreatic conduits toward the spring. On the contrary, the fluid physico-chemical properties alter later, when the actual recharge water arrives at certain point of the aquifer or at the spring. Time lag between the hydraulic and physico-chemical responses corresponds to the travel time of the infiltrating water through the conduit system (Birk et al., 2004).

We made an attempt to compare transit times of temperature signals with the transfer times of flood pulses in Postojnska Jama system. However, we realize that such comparison is problematic for Postojnska Jama system.

First, we can not compare time delays of peaks of flood pulses, measured at various locations in the system. Already Preka & Preka-Lipold (1976) found that increase of water level between the ponor and Pivka Jama is often synchronous. Similar results were discovered by our study. Peak (crest) value of the flood pulse is mainly a consequence of geometry of the underground system. Water stagnates in some parts and crest of the flood pulse is distorted.

Much more adequate method would be to compare time delays of inflection point, which represents transition from base flow (or slow recession) to rising limb in the hydrograph (Fig. 6.83). Such comparison would give a relatively clear answer how does flood pulse travel along the system? But we found out that it is very problematic to determine this inflection point in hydrographs. It may be determined only roughly, with accuracy ± one hour or two hours, but such accuracy is too low for our research. The system of Postojnska Jama is relatively short (around 3.5 km) and certain point on hydrograph transverses it in a few hours at flood conditions.

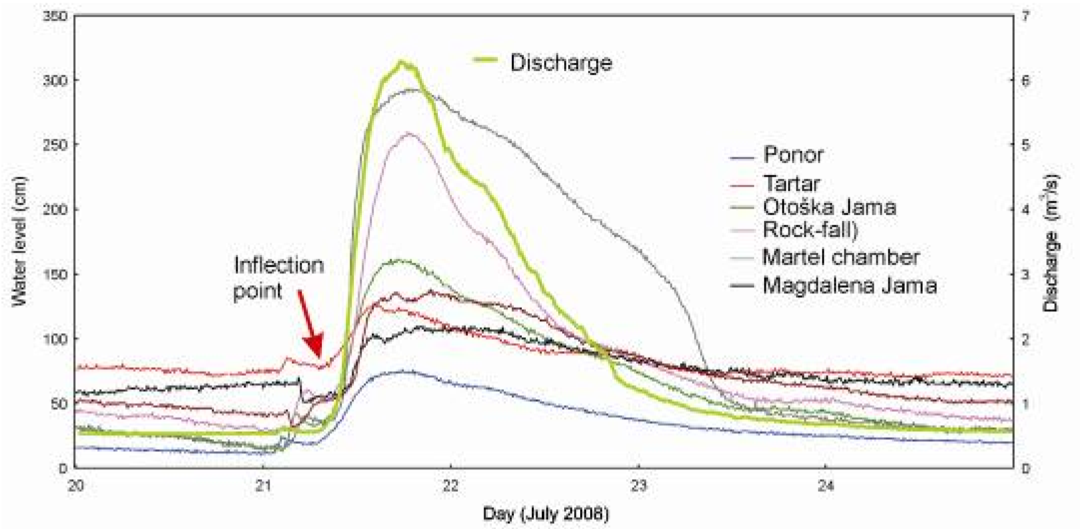

Figure 6.83: Hydrograph represents flood pulse recorded at various locations in Postojnska Jama system in July 2008. Crest of the flood pulse is highly distorted at some locations, due to the geometry of conduits. Arrow shows inflection point from base flow to rising limb for Tartar. It is problematic to determine this inflection point with high temporal accuracy.

6.8. TEMPERATURE OF THE PIVKA RIVER AT THE PONOR AND UNDERGROUND

6.8.1. Introduction

Temperature characteristics of natural streams and heat transport were discussed in chapter No. 6.6.3. As we will see later, the Pivka River represents important thermal disturbance for karst massif. The temperature of the surface Pivka River is relatively high in warmer part of the year, reaching up to 20°C in summer and close to freezing in winter. The heat transfer between the river and surrounding occurs in both directions. Water is either cooled or heated underground.

We were interested in equilibrium temperature, which represents limit between cooling and heating. Moreover, are changes in water temperature linear along pathway of underground drainage, or they depend on hydrodynamic and geomorphology of conduits also?

We tried to find some answers to these questions by means of statistical analysis of water temperature at all monitoring stations.

6.8.2. Mean year temperature of the surface and of the underground Pivka River

Temperature at the ponor was compared with temperature at the most downstream station in Pivka Jama. Data from year 2007 (Fig. 6.84) show that mean year temperature of the water at the ponor was 10.4°C and 9.7°C in Pivka Jama (3.5 km downstream from the ponor). Difference of 0.7°C is statistically significant for the year 2007 (Fig. 6.85).

While in year 2008, mean year temperature of the water at the ponor was 10.08°C and for 0.43°C lower in Pivka Jama (9.65°C) (Figs. 6.86 and 6.87).

It seems that the underground Pivka River loses relatively more heat than it gains it from the rock mass. However, heat exchange is a product of discharge and temperature variation.

If discharge is large, then the rock temperature field can be greatly altered, but the water temperature at the outflow is relatively little changed from the temperature of the inflow. Bedrock is much more sensible to thermal exchange than water flow at high discharge. If discharge is small, the rock temperature field is little altered, but the temperature of water may change significantly in the underground. Water flow at low discharge is relatively slow and it is more sensitive to thermal changes, for two reasons. It has more time available for thermal exchange with the bedrock. At the same time low discharge means also small volume of water (Badino, 2005).

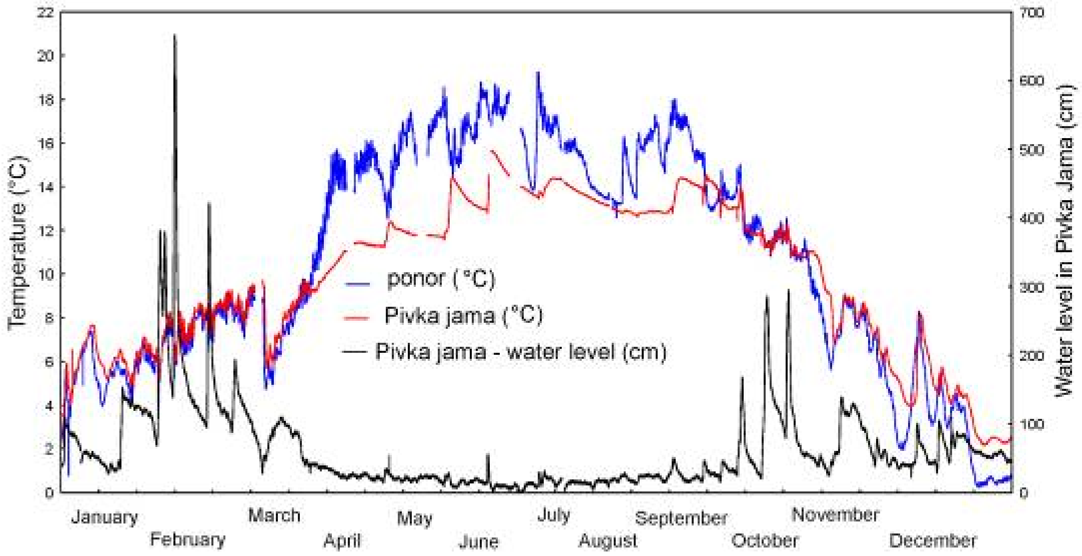

Figure 6.84: Temperature of the Pivka River at the ponor and 3.5 km downstream in Pivka Jama. Data are from year 2007. Some data are missing, hence curves are discontinuous. Discharge was not measured in this year, water level is plotted instead.

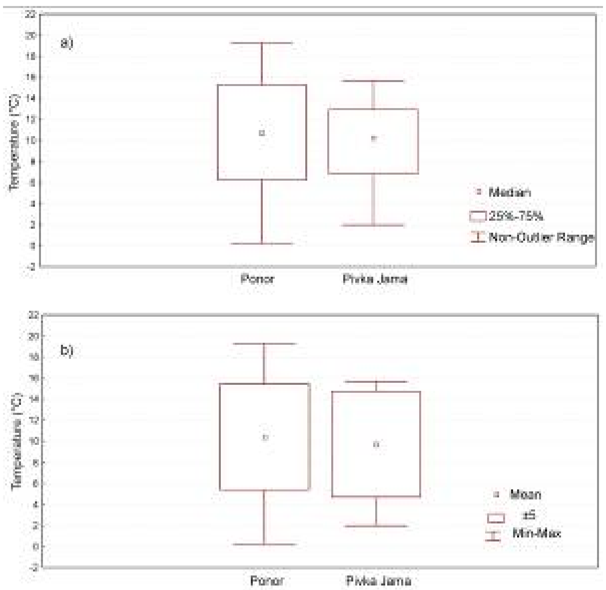

Figure 6.85: Comparison of the water temperature at the ponor and in Pivka Jama, 3.5 km downstream. Included are data from year 2007.

But discharge has no role in heat exchange, if temperature of the input water is equal to temperature of the underground environment (bedrock, sediment, air). The higher the deviation between water temperature at the ponor and mean annual temperature of the karst massif, the higher is the heat exchange (see also Fig. 6.94 in the continuation).

Reason, why the difference between mean year temperature of the Pivka River at the ponor and in Pivka Jama was higher in year 2007 than in year 2008, can be explained by different discharges. Only water level was measured in year 2007 and it cannot be reliably recalculated to discharge, hence direct comparison with year 2008 is not possible. However, it is sure that summer 2007 was much drier than 2008, while temperature of water at the ponor was similar in both summers. Consequently mean discharge of the Pivka River was relatively high in summer 2008 in comparison with summer 2007, when mean discharge was extremely low. There was more time for heat exchange in summer 2007 than in summer 2008.

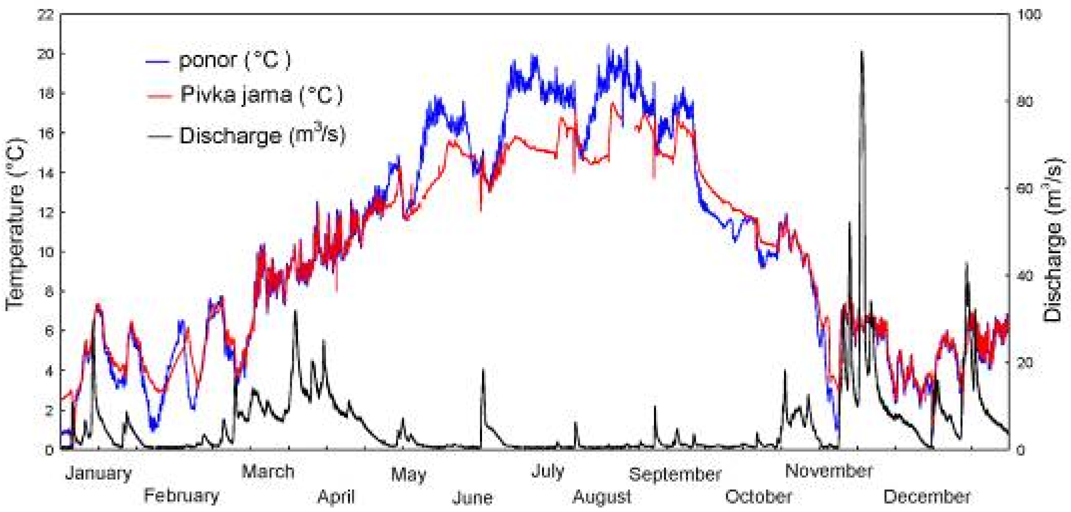

Figure 6.86: Temperature of the Pivka River at the ponor and 3.5 km downstream in Pivka Jama. Data are from year 2008. Discharge is also plotted.

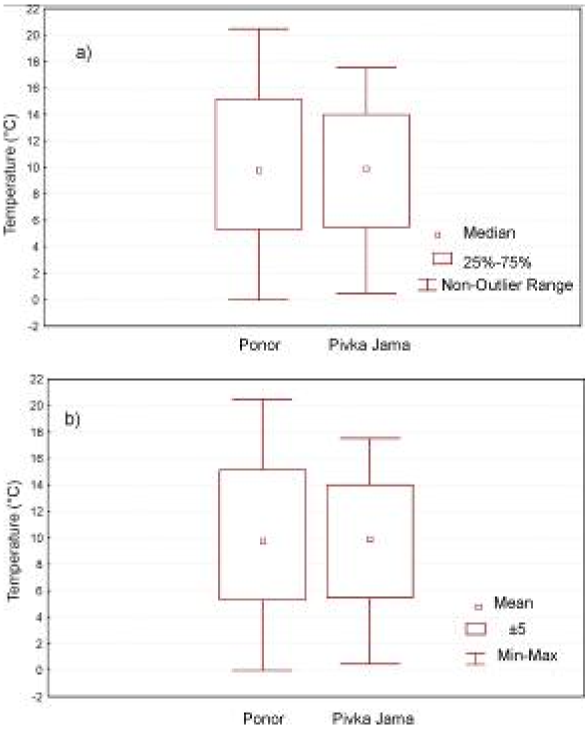

Figure 6.87: Comparison of the water temperature at the ponor and in Pivka Jama, 3.5 km downstream. Included are data from year 2008.

6.8.3. Study of temperature changes along underground pathway of the Pivka River

Thermal processes (cooling or heating) along six underground reaches were studied by analysing temperature of water at all seven monitoring stations. Periods with relatively stable discharge (slow recession respectively) were chosen for such temperature study. Discharge may be considered as spatially constant at all monitoring stations. However, note that this is not valid at flush events.

To directly compare the temperature values at different stations we have to account the time-lags between them. Therefore, all data from stations downstream from ponor should be shifted back to neutralize time lag. Data were shifted peak to peak and saddle to saddle, to obtain optimal correlation with the most upstream station (ponor) (Fig. 6.88). Despite this, some of data (between peak and saddle) may not fit exactly together, as also period of diurnal temperature variation alters downstream.

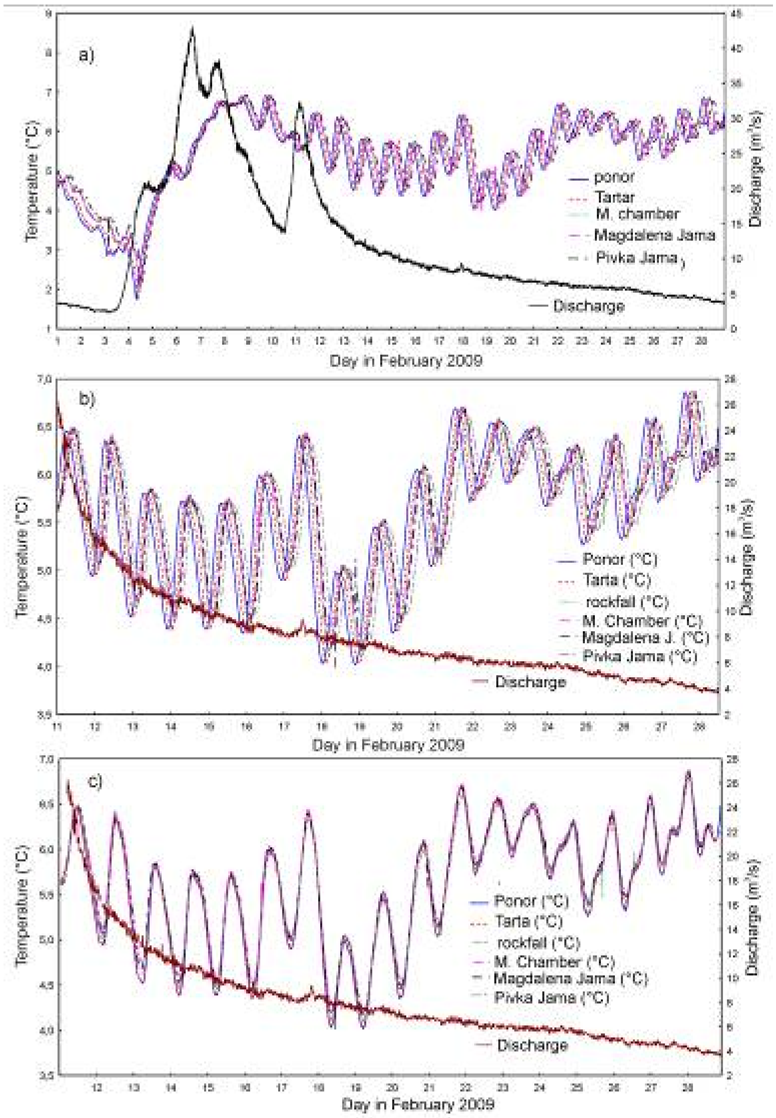

Figure 6.88 a: Temperature of the underground Pivka River and its discharge in February 2009.

b: Slow recession of the Pivka River. Temperature signal needs some time to traverse distance between stations, hence diurnal temperature maxima and minima are shifted.

c: temperature data from six stations were shifted backwards to cover with data at the ponor (data are correlated peak to peak and saddle to saddle).

Two periods of slow recession were chosen to study temperature changes along six underground reaches: March 19th – 21st 2008 (Fig. 6.89 a) and June 20th – 26th 2008 (Fig. 6.90 a). Water temperature of the Pivka River in March 2008 was generally cooler than cave temperature (bedrock and cave air) or near equilibrium with cave surroundings. The Pivka was mainly heating underground or no temperature changes occured. Water temperature was warmer than cave temperature in June 2008; hence the Pivka was cooling underground.

We were interested in which of six underground reaches the temperature change is the highest regarding variable discharge. However, temperature changes are also a function of temperature of inflowing water and its deviation from cave temperature. A certain small range of discharge (0.5 m^3/s), was taken as a grouping variable. Decrease of discharge within such a small range takes usually not more than few hours. Hence temperature deviation of inflow regarding to cave temperature usually does not vary significant in such relatively short time interval. Temperature of water at various stations was a dependent variable (Figs. 6.89 b and 6.90 b).

Temperature changes seem similar along all underground reaches, according to Figs. 6.89 b and 6.90 b at certain range of discharge (during slow recession). Relatively low change of temperature between Martel's chamber and Magdalena Jama should be attributed to short length – 250 m between these two stations. Transit time of water is relatively low there due to short distance.

Nevertheless, our results exhibit only slight variations of the rate of temperature change along the underground system. At least we would expect that temperature changes would be generally higher in reaches where velocity of water drainage is slower (between Magdalena Jama and Pivka Jama for example – see previous chapter No. 6.7). The applied method has some disadvantages, which could be a reason for such non logic.

Accuracy of data logger is 0.1°C. But changes of water temperature between ponor and the most downstream station in Pivka Jama are low. Mean temperature change between two the most remote monitored sites (ponor and Pivka Jama) was 0.216°C and between ponor and neighbor Tartar station was 0.115°C in period March – July 2008 (Tab. 10). Accuracy of data logger is too low for such small temperature differences. This also increases the error. Study of temperature changes along underground pathway is therefore strongly limited.

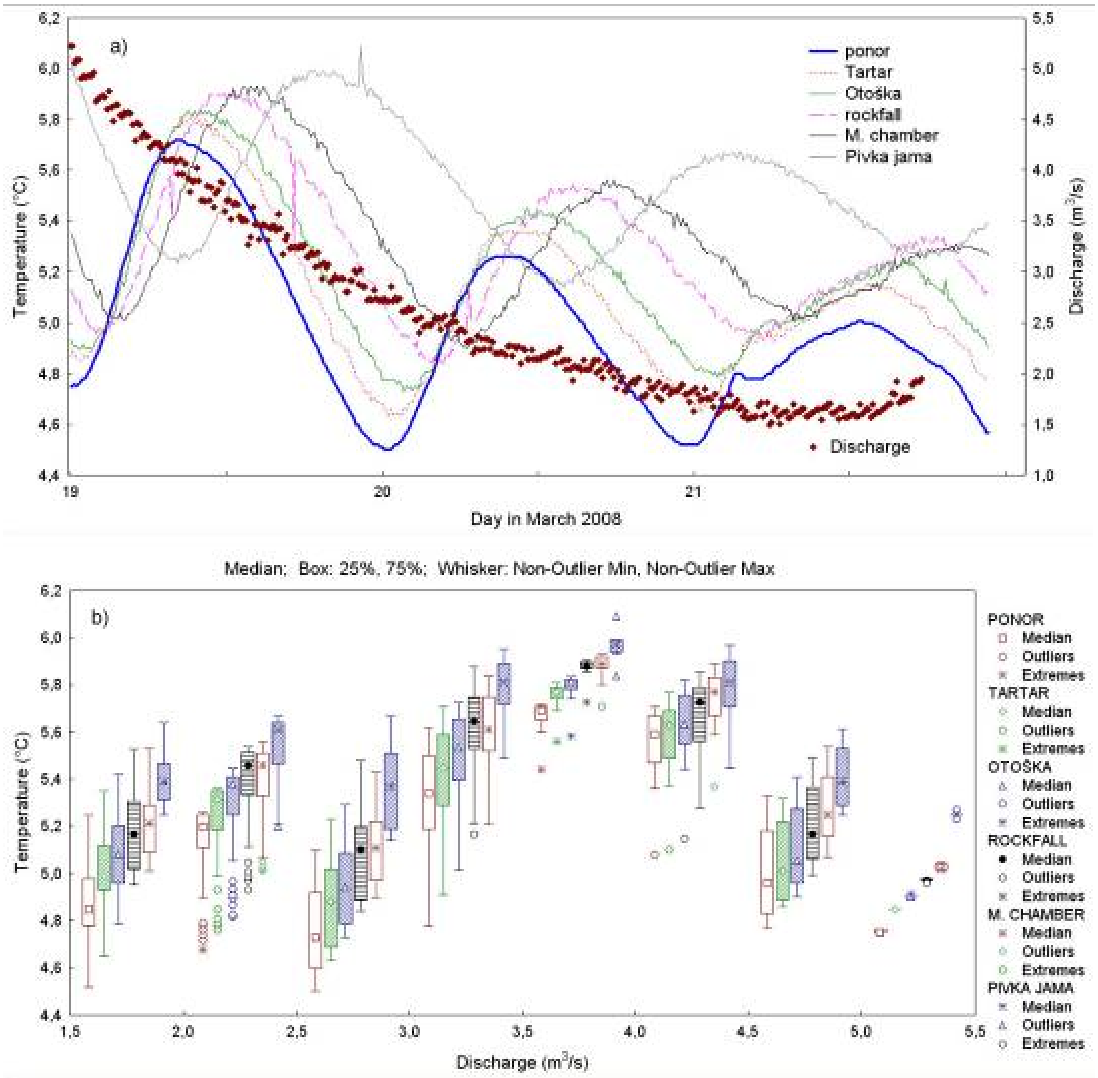

Figure 6.89 a: Transition of temperature signal through underground system during slow recession (March 19th – 21st, 2008).

b: Box-Whisker graph representing temperature characteristics of the Pivka River at six monitoring stations, in period between March 19th and 21st, 2008. Water was not monitored in Magdalena Jama in this period. Discharge represents a grouping variable (grouping interval is 0.5 m^3/s), while temperature of water at various stations is dependent variable. 50 % of data is included in a box (with median inside it), while upper quartile (25 % of data) and lower quartile (also 25 % of data) are shown as whiskers.

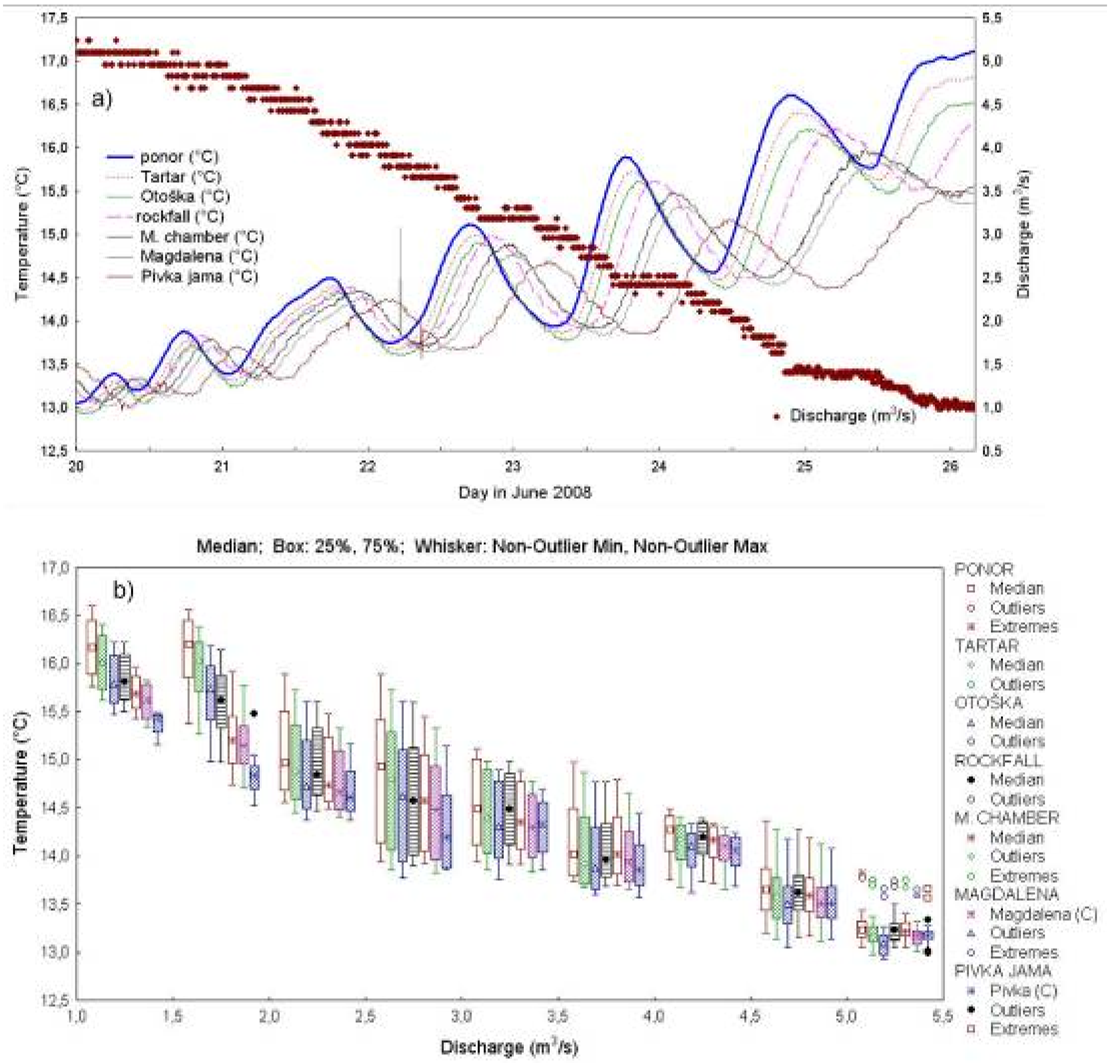

Figure 6.90 a: Transition of temperature signal through underground system during slow recession (June 20th – 26th, 2008).

b: Box-Whisker graph representing temperature characteristics of the Pivka River at seven monitoring stations, in period between June 20th and 26th, 2008. Discharge represents a grouping variable (grouping interval is 0.5 m^3/s), while temperature of water at various stations is dependent variable. 50 % of data is included in a box (with median inside it), while upper quartile (25 % of data) and lower quartile (also 25 % of data) are shown as whiskers.

Table 10: To reduce the error, calculations of basic temperature statistics are exclusively based on diurnal maxima and minima temperatures of water. Maxima and minima were studied to define changes of temperature between neighboring stations. Basic statistics of temperature changes are represented for period March – July 2008.

Reach	Ponor – Tartar	Tartar – Otoška	Otoška – rock-fall	Rock-fall – M. chamber	M. chamber – Magdalena	Magdalena – Pivka Jama
MEAN (°C)	0.116	0.175	0.125	0.072	0.096	0.096
MEDIAN (°C)	0.07	0.07	0.08	0.03	0.09	0.06
SD	0.125	0.223	0.155	0.112	0.052	0.087
No. cases	228	227	214	171	33	24
Max. (°C)	0.72	1.05	1.4	0.68	0.33	0.33
_25th % case (°C)	0.02	0.03	0.05	0.01	0.07	0.03
_75th % case (°C)	0.17	0.25	0.11	0.07	0.10	0.13

The underground system was additionally divided to two parts of about the same length. The first underground reach is between ponor and Martel's chamber (station No. 5) and the second reach is between Martel's chamber and final station in Pivka Jama. Heating and cooling of water was observed along these two reaches. Exclusively diurnal maxima and minima of the Pivka River were applied to study heating or cooling. Temperature changes differ most at the lowest flow rates (Fig. 6.91). Temperature changes in a reach between Martel's chamber and Pivka Jama are higher than in the upstream reach at low flow rates. This result is in accordance with lower flow velocities in downstream reach, which was discussed in chapter 6.7.

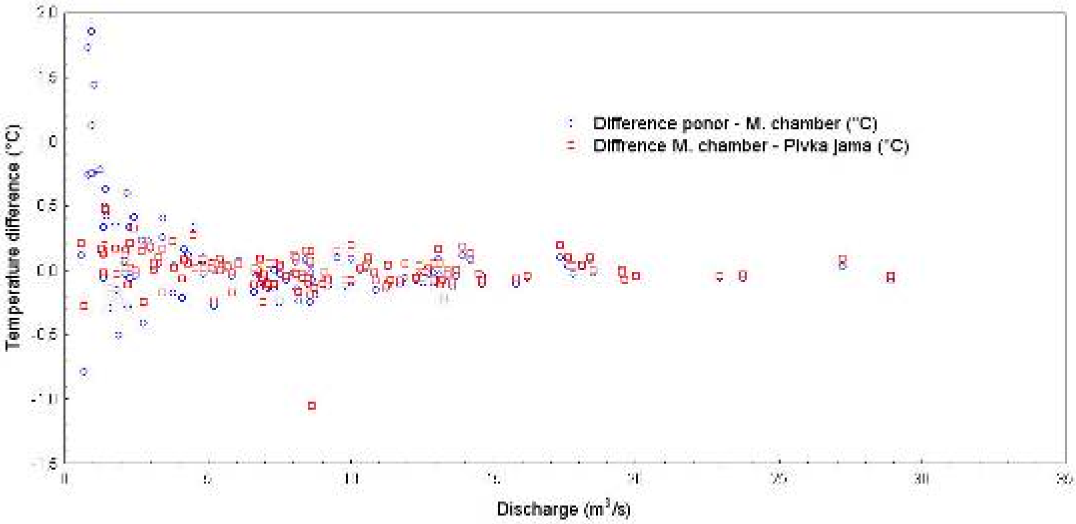

Figure 6.91: Temperature loss and gain along two underground reaches. Maxima and minima from period March – July 2008 were applied to draw this graph, see also Tab. 10.

6.8.4. Temperature equilibrium between underground water and karst massif

Advective and conductive processes, described in previous chapter (No. 6.6), tend to bring underground water into **thermal equilibrium** with the surrounding (Dogwiler & Wicks, 2005). Heat fluxes in the underground are mainly referred to exchanges between underground water on the one hand and surrounding rock (walls), hyporheic zone (sediments at the bed of the underground river) on the other hand. Equilibrium may be achieved as the atmosphere is usually relatively stable in the underground. Temperature of underground air may fluctuate significantly only if it circulates in underground system. Air circulation is usually driven by pressure differences between different entrances (so called chimney effect). Volumetric air flow should be 400 times higher than that of water, to play a dominant role in heat exchange (Luetscher & Jeannin, 2004a; Luetscher & Jeannin, 2004b). Such conditions never occur in Postojnska Jama.

Only water which stays in underground system sufficiently long time, is fully equilibrated to an underground ambient. It gains a temperature which is reflection of mean annual temperature. The length of time which is required for establishment of thermal equilibrium, depends not only on residence time, but also on thermal gradients between the surface and underground streams, flow volumes and geometry of the conduits (Dogwiler & Wicks, 2005).

However, the residence time of water which enters the aquifer as sinking stream and flows along the conduits is usually short. Thermal equilibrium is rarely achieved between the allogenic water and the surrounding bedrock (sediments) in such a case (Wicks, 1997).

The Pivka River approaches thermal equilibrium with surrounding media by dampening diurnal temperature variations in first phase. Finally its temperature becomes totally stable and flat (Fig. 6.92). Such a final scenario happens rarely in Postojnska Jama system, only when discharge decrease to minimum (around 0.1 – 0.5 m^3/s). Such low discharges usually occur in the summer time, after long drought and due to intensive evapotranspiration.

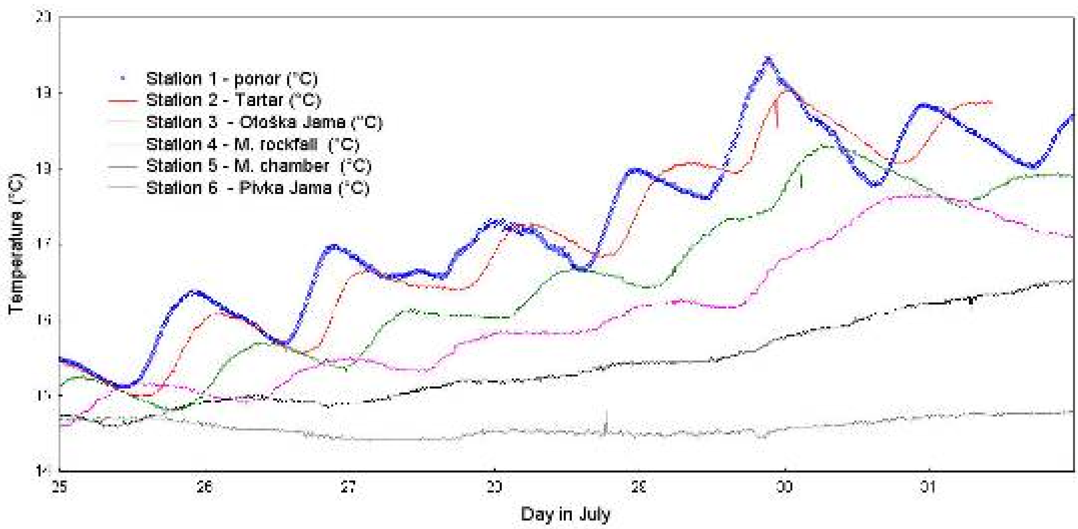

Figure 6.92: Dampening of diurnal temperature variations along the underground drainage can be observed at low discharges of the Pivka River. Finally, water temperature becomes constant, as it is equilibrated with surrounding media (rock massif).

We tried to determine the equilibrium temperature between water and karst massif for some meteorological and hydrological stable time period. **Methodology** is based on study of dampening of diurnal temperature variations.

We have to shift the signal recorded downstream from the ponor to the expected transit time of the signal (flow velocity). All the set of data between peak (maximum) and neighbour saddle (minimum) of each temperature pulse at the downstream station (Pivka Jama) was shifted and correlated with the upstream station (ponor) in the same way as in previous chapter 6.8.3 (see also Fig. 6.88 c). Other authors have usually correlated peak and saddle data only (Dogwiler et al., 2007). An advantage of our method is higher resolution, because more data is used to determine equilibrium temperature. Both methods give similar results. The disadvantage of our method is that some data do not fit well together and so may increase the error. These data are usually neglected.

Hypothetical equilibrium temperature was estimated by two methods. Both methods are based on simplified assumption that thermal exchange stops when equilibrium temperature between water, bedrock (including sediments) and air is established. Equilibrium temperature is calculated due to the difference between temperature of surface water, which enters the underground system through ponor, and temperature of water in Pivka Jama, which is 3.5 km downstream. This difference represents mean thermal exchange. Difference decreases (or increases) linearly and straight line approaches to zero difference. In such a case thermal exchange becomes zero and equilibrium temperature may be determined (Fig. 6.93) (Gabrovšek, 2006).

On the other hand, timely local equilibrium temperature may be determined without any calculations, but at specific conditions only. When maximum or minimum of diurnal temperature pulse, which enters the cave, has the temperature equal to equilibrium temperature, then the temperature of the diurnal minimum or maximum does not change at downstream measuring station. Maxima (or minima) are only timely shifted, without any temperature change (Fig. 6.94, see the last maximum). Timely locally equilibrium temperature may be determined in such a case.

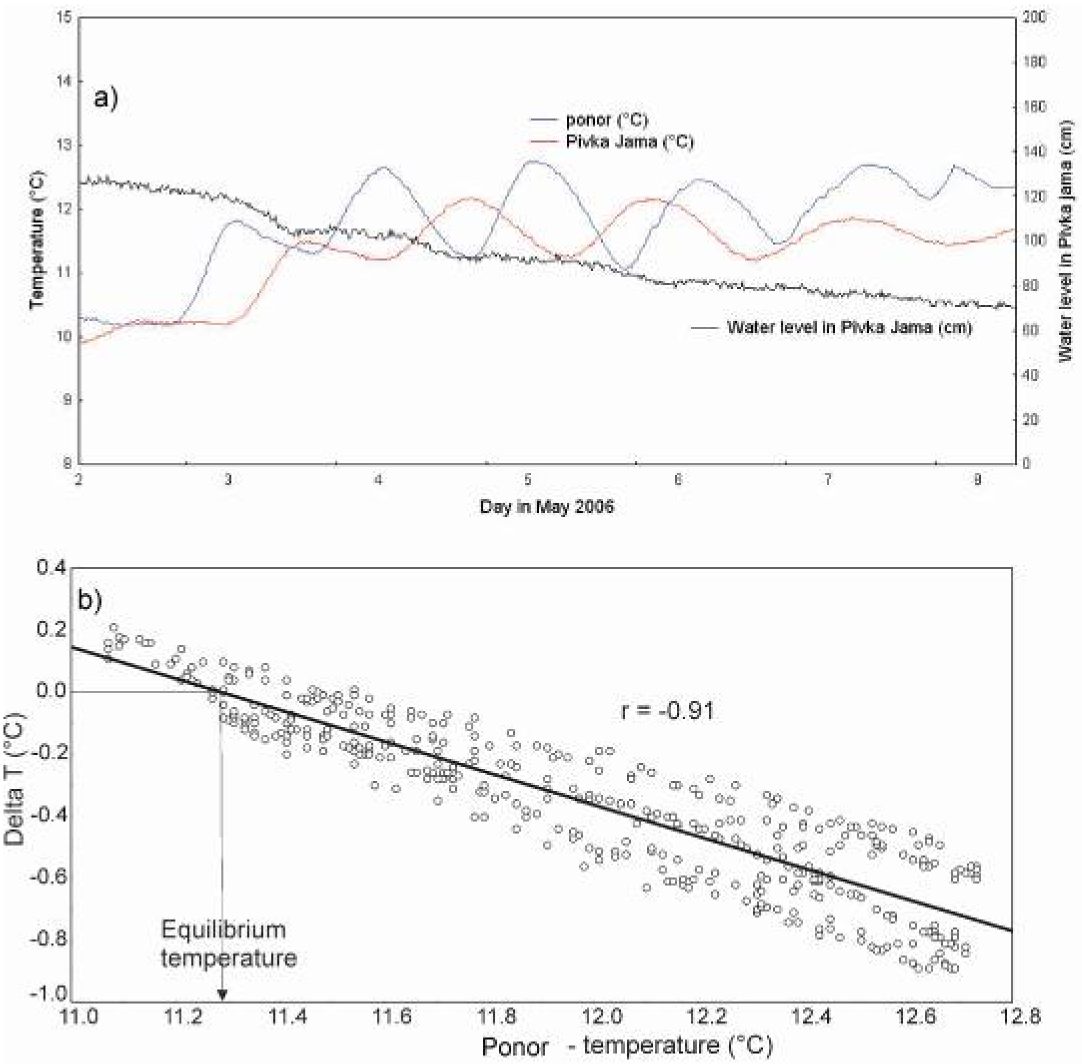

Figure 6.93 a and b: Determining equilibrium temperature for time period May 3rd - 7th, 2006 (a). Thermal exchange stops when equilibrium temperature between water and bedrock (including sediments) is established. Equilibrium temperature was determined due to the difference between temperature of water at the ponor and temperature of water in Pivka Jama, which is 3.5 km downstream from ponor. Difference decreases (or increases) linearly and when it becomes equal to zero, equilibrium temperature may be determined (b).

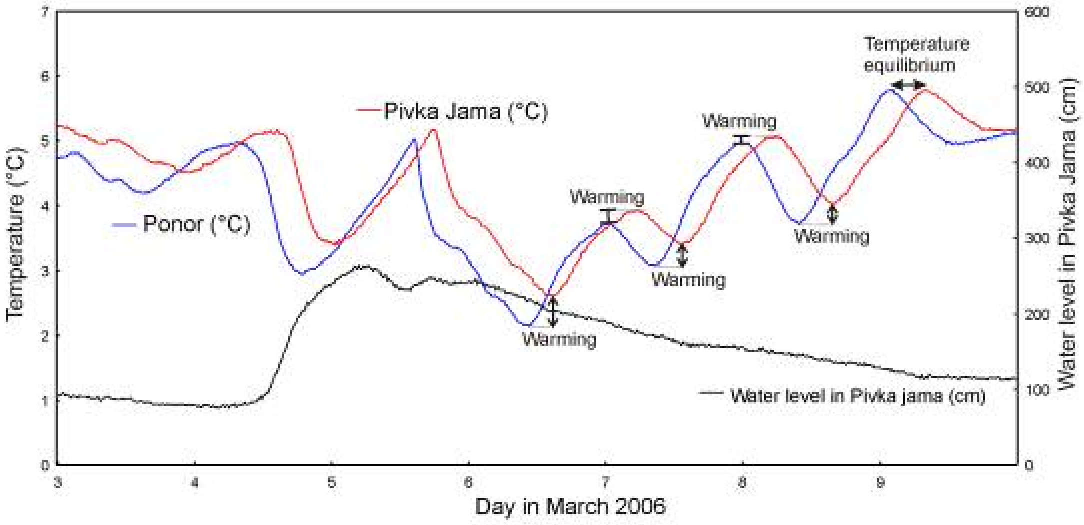

Figure 6.94: The temperature of the last diurnal maximum on March 9th did not change underground. Hence its temperature should be equal to the equilibrium temperature underground, as there was no heat exchange between water and surrounding (bedrock, sediments). Observe also the fact that the higher the deviation from temperature equilibrium, the higher is temperature change.

6.8.4.1. Conclusion

We tried to estimate the equilibrium temperature of Postojnska Jama system. Equilibrium temperature determined by our method varies with time and as expected is directly induced by discharge of the Pivka River and its temperature (the input). The Pivka River represents an important external factor, which may alter cave temperature. Hence, the equilibrium temperature in the four studied periods of the spring 2006 varied from 4°C - 7°C in March and up to 13°C in May and June (Tab. 11). Hence we did not determine real thermal equilibrium of Postojnska Jama system, but rather some provisional and fictive equilibrium, which establishes between water and certain layer of bedrock (hyporheic zone), which is in contact with water. Real equilibrium should be achieved between water and entire rock massif.

Retardation and heat exchange with hyporheic zone is assumably significant at relatively lower flow rates. At flow rates with magnitude around 10 m^3/s and more, this exchange becomes more or less negligible.

Rapid inputs of huge volumes of cool water, which usually coincide with the rising limb of the hydrograph, may represent important interruption for otherwise relatively stable underground environment (Figs. 6.95 and 6.96). Such rapid and cool inputs may diminish fictive thermal equilibrium to 4°C or even to lower temperature (Tab. 11). Flood pulses of the Pivka River are usually of short duration. Hence, thermal influence of such rapid, cool inputs is significant, but temporally short (a day or less). As soon as cool input flows out from the system, previous fictive equilibrium tends to reestablish again.

Table 11. Some basic statistical data of four treated time periods are shown. Mean air temperature was obtained from Environmental Agency at the Ministry of the Environment and Spatial Planning of Slovenia. Mean water temperature of certain time period was calculated as an average of all available data within such time period (measured every 15 minutes). Equilibrium temperature between water flow and bedrock (sediments) was estimated. It changes due to meteorological and hydrological conditions and is therefore considered as fictive. Discharge was not measured in this period, water transit time is represented instead of discharge.

	March 2nd to 21st	March 22nd to April 18th	April 25th to May 15th	May 30th to June 19th
Mean air temperature at the surface [°C]	0.3	7.7	11.7	14.0
Mean water temperature (ponor) [°C]	4.76	8.14	11.9	12.18
Mean water temperature (Pivka Jama) [°C]	5.01	8.17	11.31	11.55
Fictive equilibrium temperature - range [°C]	4 - 7	6.5 – 9.5	9 - 12	9 - 13
Water transit time - range [hours]	3 - 8	4 - 8	6 - 24	3 - 28

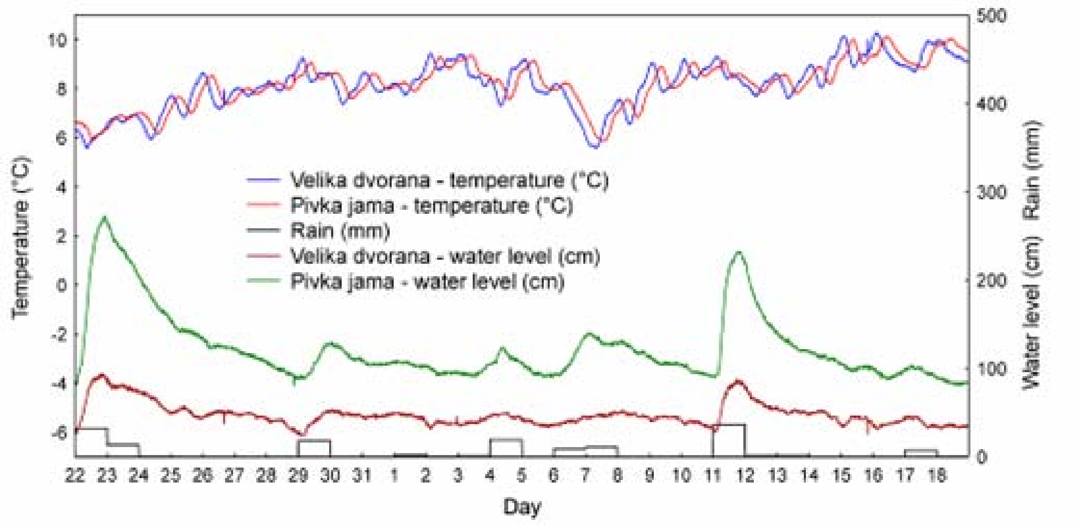

Figure 6.95: Temperature and water level characteristics between March 22nd and April 18th, 2006. Heavy rain results in inputs of flood and cool water, which alter thermal equilibrium significantly.

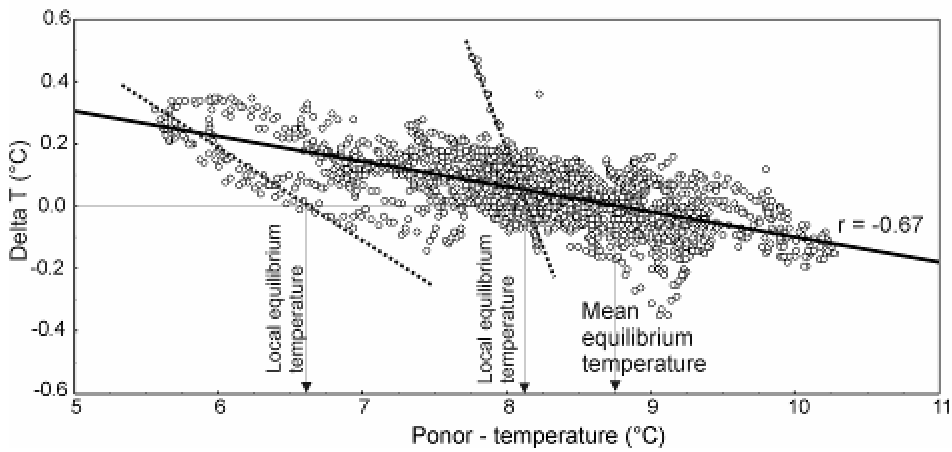

Figure 6.96: Mean equilibrium temperature in time period March 22nd to April 18th, 2006 would be 8.8°C, according to figure. But there were many flood pulses, which coincide also with significant drop of water temperature. Hence, several trends may be distinguished within the data. Trends should be divided and local (fictive) equilibrium temperatures should be determined for each trend separately.

Equilibrium temperature is unusually variable also during stable hydrological conditions. It is strongly induced by temperature of the Pivka River at the ponor (input temperature). The temperature of the surface Pivka River mainly depends on solar radiation and air temperature, as already discussed in previous chapters. If surface Pivka River warms for 1°C or 2°C, it undoubtedly affects fictive equilibrium temperature, which also rises. Drop of water temperature at the ponor for 1°C or 2°C consequently induces decline of fictive equilibrium temperature. Temperature of surface Pivka River may warm even to 20°C in front of the ponor, but at extremely low discharge and in the summer only. Anyway the highest fictive equilibrium temperature may reach 12°C or 13°C at most, which is surprisingly higher than mean annual temperature of Postojna (around 10°C in years 2006, 2007 and 2008). Hyporheic exchange can not explain this fact. But it may be possible that heat exchange, which takes place between water and bedrock by conduction, affects certain layer of wetted bedrock only. Hence, fictive equilibrium temperature can be much higher than the temperature of the entire rock mass. Transfer of heat by conduction from water to wetted bedrock should take place longer time, to establish real equilibrium with entire rock mass, which temperature is around 10°C. Before it happens, reverse heat transfer occurs (from bedrock to water), as temperature of the water at input alters seasonally and also daily, as was discussed.

These hypotheses may serve as an idea to elucidate some indistinctness. Thermal characteristics of the Postojnska Jama system were studied only briefly; they remain partly unsolved so far. This is a challenge for future task, which will base on a numerical model. Such model is already in progress.

7. REGIONAL SCALE STUDY OF KARST AQUIFER

7.1. Study area: aquifer between Planinsko polje and Ljubljanica springs

The monitoring was done at 6 points between the Cerknica Lake and Planinsko polje in the south and the springs of Ljubljanica river at Vrhnika (the rim of Ljubljansko barje basin) in the north (Fig. 7.1).

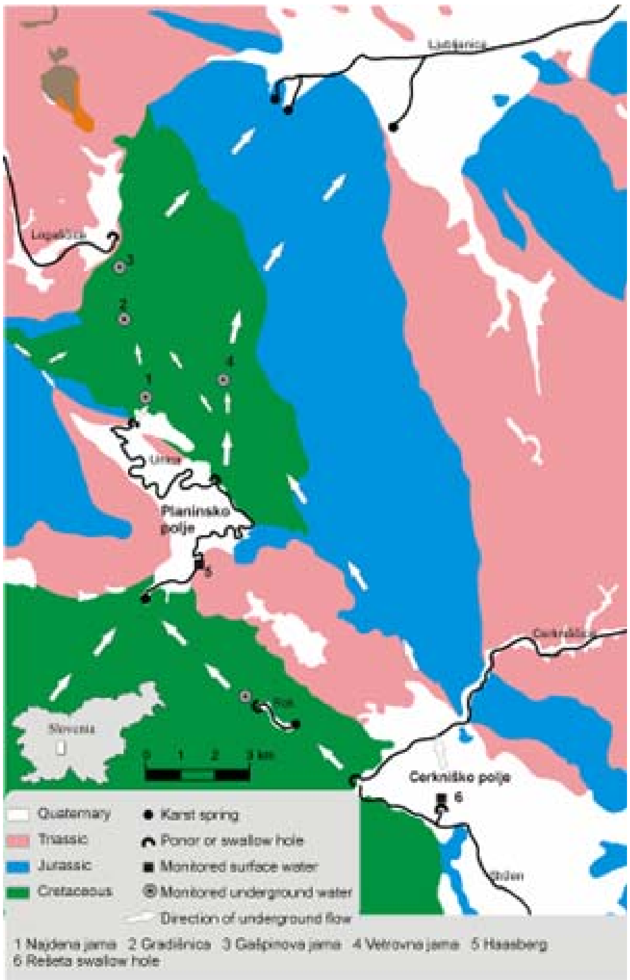

Figure 7.1: Geological map of studied area with measuring stations. The arrows indicate supposed underground flow.

The region between Planinsko polje and Ljubljanica springs represents important karst aquifer, where waters from entire drainage basin of Ljubljanica springs collect and finally emerge at Vrhnika. Water enters the aquifer mainly from the Planinsko polje, which otherwise represents an overflow. Waters locally emerge at the southern margin of the Planinsko polje and finally sink into the aquifer along northeastern margin of Planinsko polje. Some unknown (minor?) portion of water flows also below the polje, through relatively low permeable Triassic dolomite. Some portion of water arrives into aquifer (which stretches between Planinsko polje and Ljubljanica springs) also from Cerkniško polje (from the Cerknica lake). Both surface waters (on Planinsko and Cerkniško poljes) were monitored to determine recharge characteristics of aquifer researched on regional scale. Furthermore, underground water was monitored in four caves in Ravnik area. This area covers only southern part of discussed aquifer, but the majority of underground water drains through it (Gospodarič & Habič, 1976).

Ravnik area consists of high porous and well karstified Cretaceous rocks. Conduits and fissures transmit water generally towards north.

7.2. Measuring locations (stations)

As mentioned, underground flow was measured in four caves. Additionally two surface waters were monitored. These observation points are:

- The Unica River

The surface Unica River represents an overflow, which emerges at the contact between well permeable Createaceous limestone and relatively less permeable Triassic dolomite at the southern margin of the Planinsko polje (Fig. 7.1). However, some portion of water undoubtedly flows also through Triassic dolomite (below the polje), but its proportion should be minor.

Discharge of the Unica River and its temperature were measured at Haasberg in Planinsko polje (Fig. 7.1, monitored station No. 5). Environmental Agency at the Ministry of the Environment and Spatial Planning of Slovenia kindly provided us discharge curve, made for this special location. This location is very appropriate to measure total discharge of the Unica River, after it gets all important affluents. However, this location has also some disadvantages for our survey:

Discharge measured at Haasberg represents total discharge of the Unica River, which later loses water in different ponors disposed along the margin of Planinsko polje. We do not know how much sinks into each ponor. To measure discharge or swallow capacity of certain ponor is a special problem, which we did not deal with.

But the amount of water, which feeds the aquifer through a ponor or group of ponors, is not necessarily similar at two comparable flood inputs (comparable due to their magnitude).

The reason is in swallow activity of ponors, which can depend on many factors:

- For example it may be strongly influenced by transition of open channel flow to full pipe flow, which occurs in the conduit which connects ponor with karst underground (Bonacci, 1987).
- Swallow activity of ponors does not depend only on water level at the ponor area (discharge of surface stream respectively), but depends also on piezometric level of underground water in the karstic hinterland of the ponor. However, temporal and spatial variations of piezometric level can be enormous (Bonacci, 1982).

The location is not optimum from the water temperature point of view (temperature as a natural tracer). It is situated relatively close to the Unica spring (around 2.5 km) and almost 3 km far from first ponor at the eastern margin of the polje. Northern Pod stenami ponors, are even almost ten kilometres further downstream. Surface flow between the Unica spring and measuring station at Haasberg is relatively short, comparing with further surface flow towards the first and final ponors. Temperature of the Unica River may change during long and relatively slow flow along the polje. Especially amplitude of diurnal temperature variations may change (increase) significantly downstream from Haasberg. Anyway, comparison of temperature of the surface Unica River measured at Haasberg and temperature of underground water flow in selected caves can be roughly done and it is certain.

- The Cerknica Lake

Cerkniško polje is the biggest polje in kras of Notranjska region; it is seasonally flooded. Surface and also underground waters from hill sourounding collect in the polje, from where they recharge karst underground. The lake exists when inflow is higher or in balance with outflow (usually most of the year). Hence the Cerknica Lake represents an important reservoir of water, which feeds the karst aquifer NW of Planinsko polje and consequently Ljubljanica springs.

Data logger was put in the swallow hole at the bottom of the lake, in the area called Rešeta (Fig. 7.1, monitored station No. 6). Rešeta and Vodonos swallow holes are both located in polje's bottom, at the center of the polje. According to a tracing test

(Gospodarič & Habič, 1976), they drain water underground directly towards Ljubljanica springs in the north.

The lake has different temperature characteristics than surface streams. Its huge volume of water represents a large heat reservoir, similar to the sea, where temperature of the water few metres below the water table depends more on seasonal than short term (diurnal) temperature changes. Hence, lake water represents a relatively constant warm input in the summer. Similar it represents relatively constant cool input in the winter. Therefore water, which sinks through swallow holes located at the bottom of the lake, has significant temperature characteristics within some long time period. It may influence also on temperature of some Ljubljanica springs (Cunder & Cunder, 2000).

The hydraulic head above selected bottom swallow hole usually changes slowly in the Cerknica Lake, due to large lateral extent of the flat polje and low swallow capacity of bottom holes. Moreover, changes of hydraulic head are also low, due to activation of highly permeable marginal ponors at relatively higher floods. Total swallow capacity of all bottom holes is estimated to be approximately 6 m^3/s (Habič, 1987). Swallow capacity of marginal ponors is high (up to 45 m^3/s), but they mainly swallow high waters and contribute to Unica spring. Medium waters are drained through bottom swallow holes, which are fissure type, and only partly through some marginal ponors. Fluctuation of water level is relatively slow because of these reasons. Consequently also discharge through bottom swallow holes changes relatively slowly. Lake therefore represents relatively stable recharge for karst underground and springs of the Ljubljanica river, from both aspects thermal and quantitative (flow rate).

- Najdena Jama

Najdena Jama is situated in Logaški ravnik just near the northern margin of the Planinsko polje and it is formed in Cretaceous limestone (Fig. 7.1, monitored station No. 1). Najdena Jama is a very complex, anastomotic cave system, which is divided into several channels ending by breakdowns and overflows (Šušteršič, 1982).

Distance between northern ponor area (Pod stenami) and Najdena Jama is short. The nearest parts of Najdena Jama are only 150 m far from ponors at the northern margin of the polje. Connection between discussed ponors and Najdena Jama is undoubted, in spite of the fact that ponors are developed in collapsed and fissured tectonic zones, which are not accessible to human exploration. Hydraulic gradient between ponors and the nearest parts of Najdena Jama is 0.13 and it diminishes to 0.05 toward the central part of the cave (all at base flow conditions). The absolute elevation of water in Najdena Jama at the base flow differs for different locations in the cave (Šušteršič, 1982).

A data logger was fixed to a cave wall in a pool called Vipera Nera (Fig. 7.2), located around 700 m far from ponors. Pool Vipera Nera is around 405 m a. s. l. and it probably represents local level of water table.

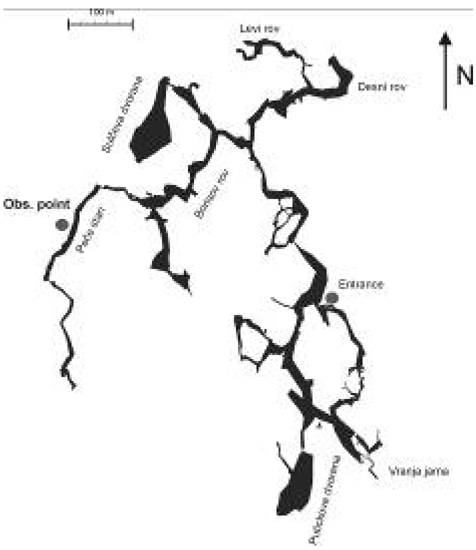

Figure 7.2: Ground plan of Najdena Jama with measuring location marked.

- Gradišnica

Gradišnica is known as a cave where the water level fluctuations are among highest in Slovene Dinaric karst.

Entrance to the Gradišnica cave is located approximately 2350 metres north from entrance to Najdena Jama, near Logatec (Fig. 7.1, monitored station No. 2). Morphology of Gradišnica is totally different then of other water caves in this area. Entrance is a large vertical shaft, with dimensions of 20 x 40 m (Marussig & Velkovrh, 1957). Cave ends with great chamber called Putikova dvorana, which is more than 200 m below the surface. Ground water flows into the chamber from south and out at the northern side, in direction towards Vrhnika. Measurements were taken in the southern, inflowing side (map of Gradišnica is in chapter 7.10).

Altitude of the water table at the base flow is 377 m a. s. l. (Nagode, 1997; Gams, 2004), 379 m according to some other references (Gospodarič & Habič, 1976). It is more than 20 m lower than in northern part of Najdena Jama, therefore hydraulic gradient between monitored locations in Najdena Jama and in downstream located Gradišnica is around 0.01 (at base flow conditions). It is known that the Gradišnica is hydrologicaly connected with Najdena Jama and consequently with the Unica River, which represents major input at floods (Gospodarič & Habič, 1976).

- Gašpinova Jama

Gašpinova Jama is the northernmost cave in drainage basin of Ljubljanica springs, where underground water can be observed at present 2009 (Fig. 7.1, monitored station No. 3). Entrance to the cave is located at the rim of the town Logatec with some conduits extending under the settlement.

Water conduits were discovered in 2002. Members of Logatec speleoclub dug along crack, till they broke through to epiphreatic conduits. Cave is 109 m deep and till now around 3500 m of conduits have been explored. Cave is very complex from hydrogeological point of view. Underground water appears at least at three different locations within the cave (at base flow). According to some assumptions (Vovk & Nagode, 2003), water comes in the cave from different origins. Underground water was monitored at the most upstream, southern location (Fig. 7.3).

Straight line distance between monitored locations in Gradišnica and Gašpinova Jama is relatively short, it is around 1500 m. The lowest water in Gašpinova Jama is around 3 to 5 metres lower than in upstream Gradišnica; at absolute height approximately 374 m (Volk, 2007). Hypothetical hydraulic gradient between both caves is therefore around 0.002 at base flow conditions.

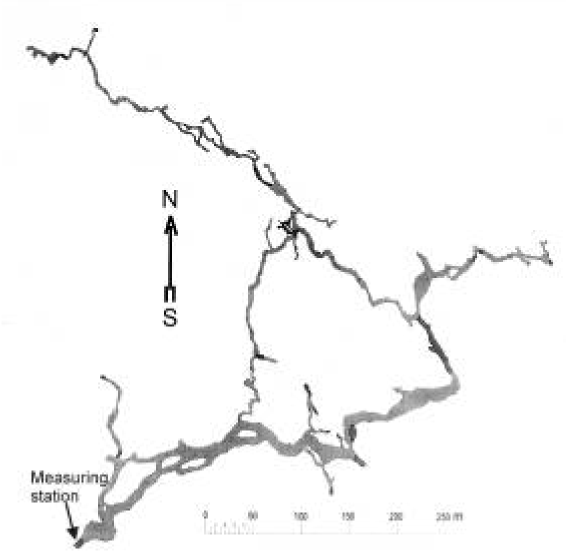

Figure 7.3: Ground plan of Gašpinova Jama, with measuring location marked.

- Vetrovna Jama

Epihreatic conduits in Vetrovna Jama (= windy cave) were discovered in 2004.

In contrast with other selected caves, Vetrovna Jama is situated in the south-eastern part of Ravnik (Fig. 7.1, monitored station No. 4), where different underground water flows suppose to interact (Krivic et al., 1976). Cave is situated in direct vicinity of the largest collapse doline in this area, Laška kukava. Outflow from the cave takes place directly below this collapse doline (Volk, 2007).

Cave is 110 m deep, total length of researched passages is around 500 m. Data logger was installed in a pool at the downstream part of the cave, which is already below the Laška kukava collapse doline (map of Vetrovna Jama is in chapter 7.7). Approximate altitude of data logger was 410 m (Volk, 2007). At the base flow, the hydraulic gradient between Planinsko polje and Vetrovna Jama is approximately 0.014.

7.3. Hydrogeological characteristics of Planinsko polje – Ljubljanica springs area

Waters, which recharge southern part of discussed aquifer, belong to different hydrological regions (according to Gospodarič & Habič, 1976, Fig. 4.3 in chapter Research area), but all of them are part of Ljubljanica drainage basin. There are a few sinking streams, which recharge the aquifer directly. The most important is the **Unica River**, which recharges the aquifer from south. **Hotenka** and **Logaščica**

Streams sink underground in Logaške Rovte and Logaško polje, north-west from researched area. At least eastern part (maybe also central?) of the aquifer is fed by underground water flow, which drains from the **Cerknica Lake**. Lake water disappears underground through a few ground swallow holes, with estimated capacity 6 m^3/s (Habič, 1987). Pathway of underground drainage is totally unknown so far, in spite of some assumptions (Krivic et al., 1976). Also **autogenic recharge** of discussed aquifer should not be neglected. Such is autogenic recharge from entire well permeable Ravnik area. Autogenic recharge from Hrušica Mt. in the west probably feeds the underground Unica and especially the underground Hotenka.

Drainage basin of the surface **Unica River** is relatively extensive (about 800 km^2) and karstic. Together with hinterland of Planinsko polje, it covers important part of drainage basin of Ljubljanica springs (Fig. 7.1 and 7.4) (Gams, 2004). Mean annual discharge of the Unica River is 26 m^3/s (Breznik, 1998). We assume that such mean input into aquifer may represent higher value than mean inputs of all other water flows together (Hotenka, Logaščica, leakage from the bottom of the Cerknica Lake, autogenic recharge and other unknown inputs). Mean discharge of the Ljubljanica at Vrhnika is very similar as mean discharge of the Unica River.

The Unica River sinks through many fissures and alluvial ponors (Čar, 1982) disposed along the margin of the Planinsko polje. Two groups of ponors may be roughly distinguished: **eastern group** and **northern group of ponors** (Šušteršič, 2002). The Unica River feeds eastern group of ponors permanently. These ponors are disposed along southeastern margin of the polje, between Haasberg and the Laze village (Fig. 7.4). Not all of them are active all the time, however they are capable transmiting all baseflow of the Unica River and flood water, when flow rate does not exceed around 20 m^3/s – 25 m^3/s.

At flow rates around 30 m^3/s and more, when the capacity of eastern ponors is exceeded, the surplus of flow continues toward northern margin of the polje, where finall northern group of ponors is situated (Fig. 7.4). Hence, this group of ponor is active only at relatively high flow rates of the Unica. Swallow capacity of all ponors in Planinsko polje can be exceeded during the highest floods and polje becomes flooded for days or even weeks.

Two discussed groups of ponors drain the majority of underground water through different conduit systems, before they presumably begin to interact with each other, somewhere in the "central" part of the aquifer. Water tracing showed that Milavcovi ključi and Ribce ponors (both belong to eastern group of ponors) drain water generally toward Lubija and Bistra springs (eastern springs of the Ljubljanica). While Pod stenami ponor (which belong to northern group) drains water generally to Hribščica, Mala Ljubljanica, Velika Ljubljanica and Lubija springs (western springs of the Ljubljanica) (Gopodarič & Habič, 1976).

Even different ponors of the same group may apply different geological structures to convey water within underground system. Hence, hydrodynamic within the aquifer can be strongly dependent on geological structure of the aquifer (Čar, 1982).

Drainage basins of the surface **Hotenka** and **Logaščica** Streams are relatively small (4 and 20 km^2) and non karstic in comparison with drainage basin of the Unica River. Both streams are confined on small area of Logaške rovte, which is built by relatively less permeable (karstified) Triassic dolomite (Gams, 2004).

We do not know exactly where the underground **Hotenka** joins with the underground Unica. Gospodarič and Habič (1976) assume that it happens somewhere under Ravnik area, therefore near Gradišnica or Gašpinova Jama. Gams (1974) assumed that springs near Grčarevec (at NW border of the polje) also get water from the underground Hotenka. The latter could use some other underground pathways at the high water conditions, due to spilling and flowing along Idria fault (Fig. 7.4). Discharge of the surface Hotenka is relative low; according to data from 1972-1975 it varies from 0.02 m^3/s to 4.1 m^3/s. According to some assumptions (Gospodarič & Habič, 1976), the underground flow of Hotenka receives also water from SE part of Hrušica Mountain.

The **Logaščica** sinks into Jačka ponor, located in the centre of Logaško polje. Part of the water leaks underground before the ponor. Discharge of the Logaščica Stream is in average little higher than discharge of the Hotenka Stream. The highest measured discharge in years 1972-1975 was 9.2 m^3/s (Gospodarič & Habič, 1976). Our observation point in Gašpinova Jama is located upstream from the points, where the Logaščica enters the cave. Hence we did not expect to record its influence.

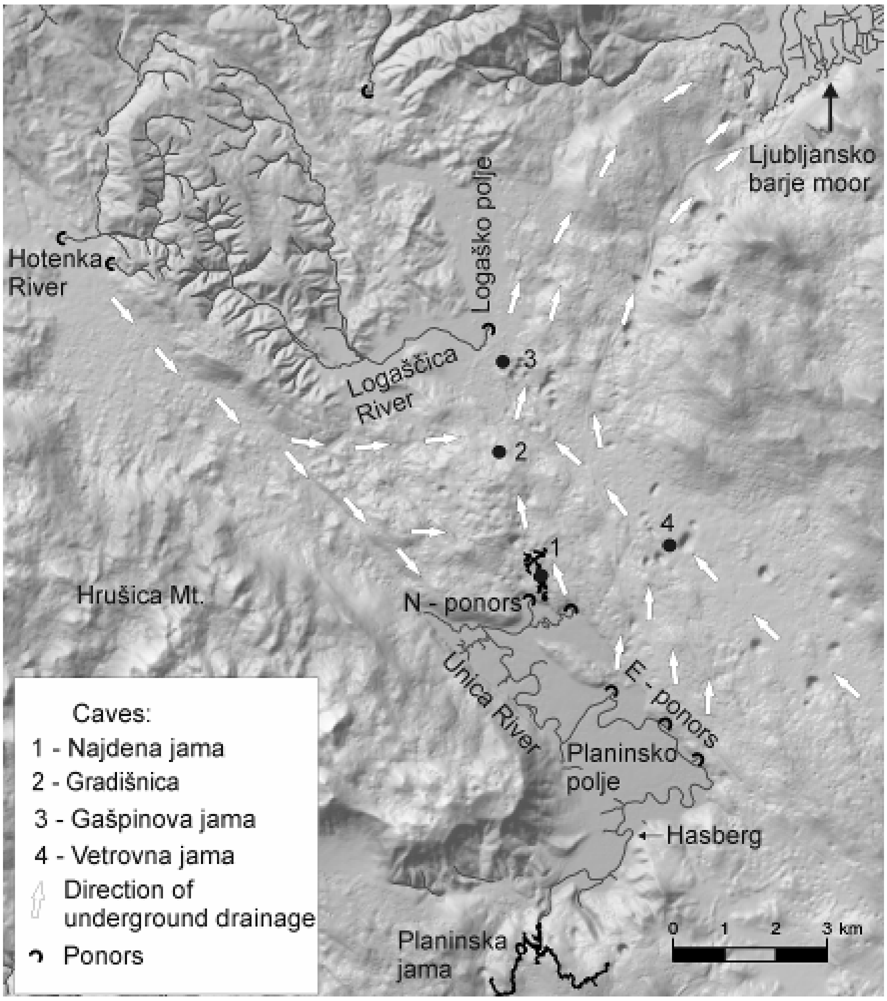

Figure 7.4: Map of Planinsko polje – Ljubljanica springs area, with marked main surface and underground streams

7.4. Overview of some preliminary researches in Ravnik area

Geological mapping of the Planinsko polje and ponors area was done by Čar (1982). He concluded that rocks are tectonically well fractured. Ponors on the margin of Planinsko polje are genetically associated with fault zones and bedding planes (dip and strike of strata). Pathways of underground water take place through bedding plane partings in stratified Cretaceous limestone or (mainly) through collapsed and fissured zones, which are directed toward NE.

Šušteršič (2002) tried to confirm the hypothesis about tectonically conditioned drainage of underground water within carbonate massif of Ravnik. He determined two directions of faults (NE-SW and NW-SE). Faults with up to more than 100 m wide fractured zones presumable represent hydrogeological barriers for underground water. Such barriers should have important role on underground drainage within the aquifer. The relatively straight string of collapsed dolines between Slaven dol and Voden dol is presumably associated with such fructered zone, according to Šušteršič et al. (2001). They named this fractured zone as Slavendol fault. Presumably it did not permit a formation of any larger lateral conduits, which would intersect the fault (Šušteršič et al., 2001). The Unica River, which sinks underground through eastern group of ponors (situated just east of Slavendol fault), should drain along the fault (i.e. in direction toward north) regarding to this hypothesis. Assumption of Šušteršič et al. (2001) can be partly confirmed with the location of the Logarček cave. This cave was formed east from Slavendol fault and its conduits extend parallel with fault zone.

First observations of water levels in caves were done in Najdena Jama and Gradišnica by Gospodarič and Habič (1976) in the frame of survey of combined tracing test in the Ljubljanica River catchment area (3rd International Symposium of Underground Water Tracing). Water levels were observed occasionally, during floods mainly. They first realized that both caves are hydraulically connected, as water level in Gradišnica increases in accordance with water level in Najdena Jama. It was also observed that maximal water levels in Najdena Jama reach the same absolute altitude as those in downstream Gradišnica. Hence hydraulic gradient between both caves is relatively high (0.01) at base flow and it diminishes rapidly during the floods.

Šušteršič (1982) described morphology and hydrology of Najdena Jama. His research focused on hydraulic characteristics of Planinsko polje – Najdena Jama system. He distinguished three hydrogeological conditions in the cave, due to height of water level in Najdena Jama. Low water level in the cave corresponds to totally dry polje. The Unica River sinks into eastern ponors and do not reach northern group of ponors. Underground water in Najdena Jama occurs in pools only, there is no streaming. Streaming occurs at middle water conditions, when the Unica River reaches northern group of ponors. Most of the cave passages are flooded at high water conditions. Šušteršič assumed that there are no important hydrogeological (hydraulical) restrictions between Najdena Jama and Gradišnica. Such restrictions or barriers appear downstream from Gradišnica, according to the hypothesis of Šušteršič (1982).

Hydrogeology of Gradišnica was studied also by already mentioned survey of Šušteršič (2002), when he tried to assume several main corridors of underground drainage in Ravnik by tectonic and by mapping of denuded cave features. It is known since 1976 (Gospodarič & Habič), that the northern group of ponors drains underground water toward Gradišnica. But Šušteršič assumed that the main water flow turns northeast before it reaches Gradišnica. Underground flow corridors are strongly influenced by direction of faults and their intersection. Gradišnica lies in the margin of the preferential flow corridor, which drains underground water coming from northern ponors. Šušteršič concluded that Gradišnica does not transmit large quantities of water, which drains from Planinsko polje.

7.5. Methodology and goals of regional survey

We would like to determine the significance of the Unica sinking River and of the Cerknica Lake to recharge underground system of Ravnik. Methods are based on the analysis of stage and temperature hydrographs at the described locations in the caves. These analyses also include flow/temperature hydrographs of the Unica River and stage/temperature hydrographs of the Cerknica Lake. Moreover, hydraulic and some other hydrogeologic characteristics of the aquifer are assumed by comparison of parameters measured at different caves within aquifer only.

Characteristics of dynamic of underground water among monitored caves may be defined by comparison of **stage hydrographs** among the caves. Hydrogeological significance and eventual peculiarities of any of monitored cave, in comparison with other caves can be also determined.

According to fluctuation of water level in monitored caves and relations among them, we may assume some hydraulic characteristics of the aquifer. Several questions may be answered, such as: "What is the water table in the aquifer, how does it fluctulate, what are hydraulic gradients?" "What are underground connections among ponors and caves located at the margin of the polje (Najdena Jama) and caves in the "inner" part of the aquifer (Gradišnica, Gašpinova Jama, Vetrovna Jama)?" "Is underground flow from aquifer's margin towards "central" part similar to a pipe system, i.e. through conduits which could be divided with some hydraulical restrictions?" "Or does flow split into many connected voids and is slowly

distributed along entire lateral extent of the aquifer?” Different water conditions should be taken into consideration, to answer such questions.
Moreover, detailed analysis of hydrographs may reveal some information about interaction of flood waters of different origin. For example, some inflection points on stage hydrograph may indicate interaction of two hydrographs, representing two important inflows of different surface origin (Bonacci, 1993).

We can determine possible water connection between surface stream (or ponor) and certain cave or connections between caves, by analysing the temperature hydrographs. Sinking river exhibits diurnal temperature variations, which occur at the surface due to solar radiation mainly. Variations are transmitted into the underground, where can be preserved for a relatively long distance within the conduit system. Therefore such water may be traced at different locations within the aquifer. Transit time and velocity of water between two monitored locations can be defined, for a specific flow rate.

In addition, precipitation data from Planinsko polje (station Planina) and other stations in the catchment area of the Unica River have been obtained from Environmental Agency at the Ministry of the Environment and Spatial Planning of Slovenia. All precipitation data have daily resolution only. The height of the flood pulses is indirectly associated with intensity and total amount of the rain. Influence of direct infiltration from surface into aquifer may be studied at certain conditions.

7.6. Boundary conditions

Methodology is based on one important boundary condition, which is water condition at Planinsko polje. It is directly associated with flow rate of the Unica River and swallow capacity of the ponors. Two groups of ponors can be roughly determined at Planinsko polje as mentioned. Eastern group of ponor is active at all water conditions (Fig. 7.4). They are capable of swallowing all low and the great majority of medium waters of the Unica River. Northern group of ponors (Fig. 7.4) are active periodically only, at relatively high water conditions in the polje.

Low flow rate of the Unica is up to 15 m^3/s. All flow of the Unica disappears through eastern ponors. Such conditions at the polje are **low water conditions**.

At higher flow rates up to 25 m^3/s or 30 m^3/s the most, part of the water passes eastern ponors and the Unica proceeds its pathway toward northern part of the polje. However, all surplus of the Unica, which passes eastern ponors, sinks underground along riverbed and riverbank, before it reaches final northern swallow holes, which remain dry. Such conditions are treated as **medium water conditions** at the polje.

At **high water conditions** at the polje, the Unica River recharges both, eastern and northern group of ponors. Flow rate of the Unica River should be higher than 30 m^3/s, swallow capacity of several of eastern ponors is exceeded (estimated to around 20 m^3/s according to Šušteršič, 2002), important part of the water spills toward northern ponors.

At **extreme high water conditions**, swallow capacity of all ponors in the polje is exceeded and polje is altered into lake. Swallow capacity of all ponors is estimated to 40 - 60 m^3/s, depending to height of the seasonal lake (Šušteršič, 2002). Hence flow rate of the Unica River should exceed 40 m^3/s, to begin the inundation of the polje.

Based on water conditions at the Planinsko polje and activity of certain group of ponors, the discussed system may be divided to four systems:

- System Planinsko polje – eastern group of ponors – Vetrovna Jama
- System Planinsko polje – northern group of ponors – Najdena Jama – Gradišnica
- System Planinsko polje – eastern group of ponors – Gradišnica
- System Gradišnica – Gašpinova Jama

7.7. System Planinsko polje – eastern group of ponors – Vetrovna Jama

Of all studied caves, Vetrovna Jama is the easternmost. It is situated 2.7 km NE from the eastern ponors at the margin of the Planinsko polje (Fig. 7.4). Hence, the cave can not be treated as a marginal one, as it belongs to the inner part of the aquifer, due to its location. According to some previous surveys (Gospodarič & Habič, 1976; Krivic et al. 1976), several ponors at the eastern rim (Laška žaga, Dolenje loke) drain water in direction toward Vetrovna Jama. This recharge is permanent. Vetrovna Jama is studied first, due to its location within influential area of eastern group of ponors. Based on geological mapping (Čar, 1982; Šušteršič, 2002) and tracing tests (Gospodarič & Habič, 1976), we assume that all other monitored caves belong preferentially to the influential area of northern group of ponors (Fig. 7.4), which are otherwise active periodically only.

Moreover, we may assume that underground flow, which drains from the Cerknica Lake, could also recharge Vetrovna Jama. Assumption is based on previous, above mentioned surveys and the location of the cave (Fig. 7.5). All cited surveys were performed before the Vetrovna Jama was discovered. The assumptions may be verified with our measurements.

The absolute altitude of the water table at the base flow conditions is the highest in Vetrovna Jama (410 m a. s. l.), compared with other three monitored caves. Hence it can certainly be concluded that Vetrovna Jama does not gain any water from the other three caves. However, water from Vetrovna Jama can theoretically drain toward Gradišnica and Gašpinova Jama, which are both located downstream, but NW from Vetrovna Jama. General direction of underground drainage is pointed toward north according to previous assumptions (Gospodarič & Habič, 1976; Krivic et al., 1976).

Measurements of hydrogeological parameters took place in two phases in Vetrovna Jama: May 2006 – January 2007 and April – December 2007 (Figs. 7.6 and 7.7).

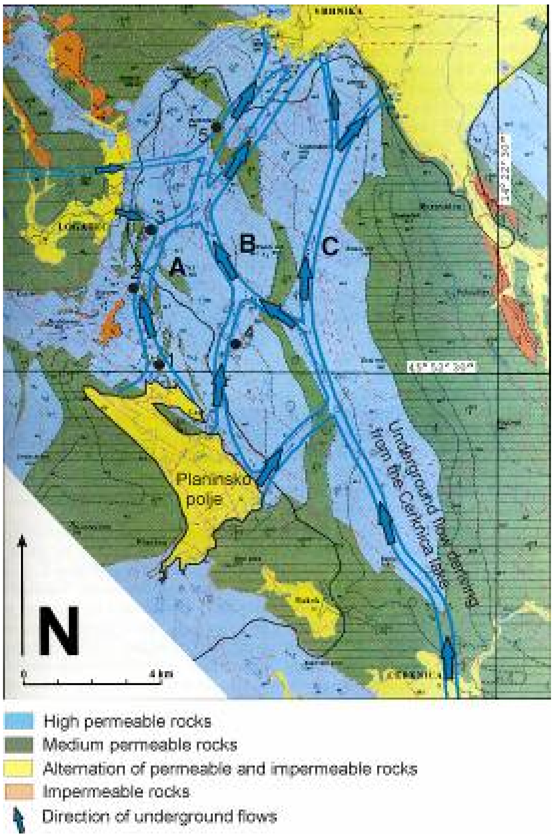

Figure 7.5: Hydrogeological map of the area. Vetrovna Jama is marked No. 4 (adapted from Krivic et al., 1976).

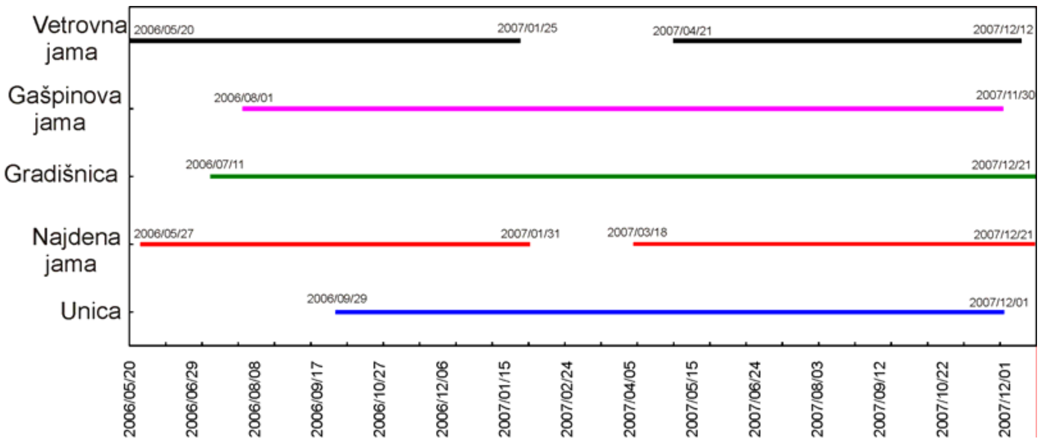

Figure 7.6: Monitoring periods in four selected caves.

Discharge, temperature of the Unica River and parameters in other three caves were measured simultaneously with parameters in Vetrovna Jama, with some exceptions (Fig. 7.6). The monitoring of the Cerknica Lake took place from May 2007 on.

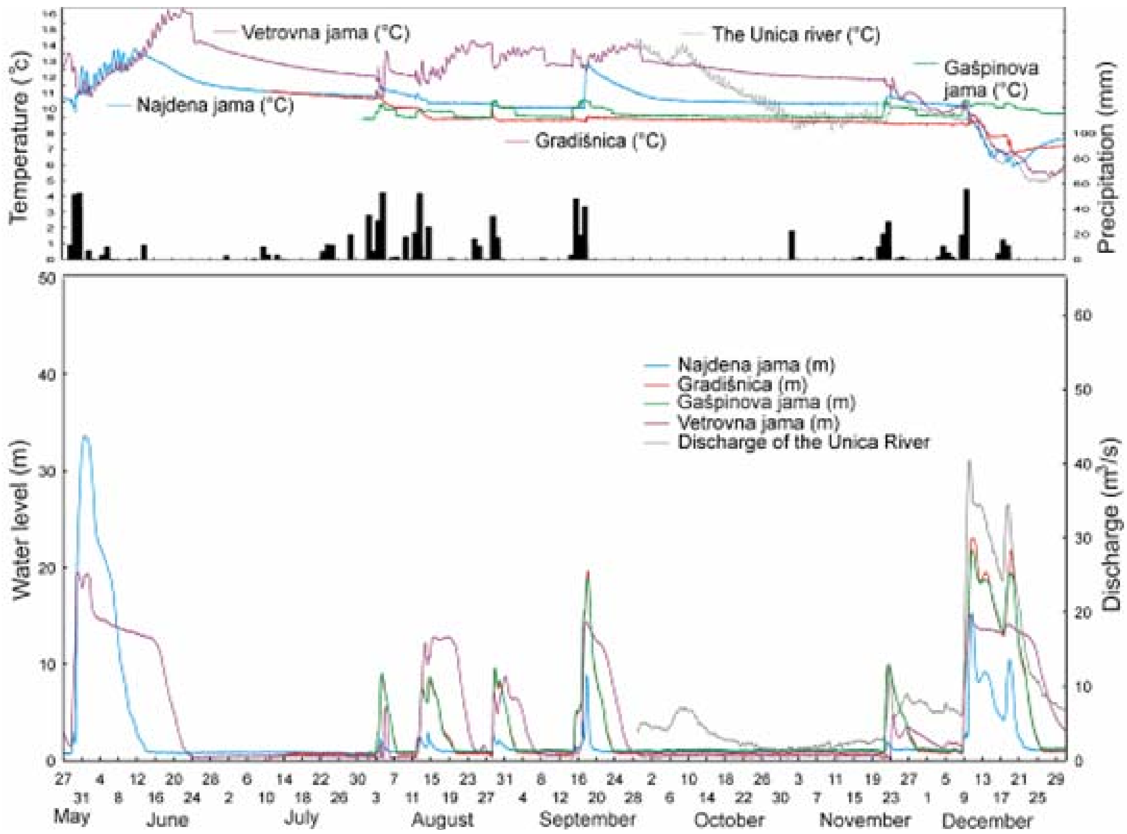

Figure 7.7a: Stage and temperature hydrographs of all four monitored caves and flow and temperature hydrographs of the Unica River for monitored part of the year 2006. Precipitation data are included.

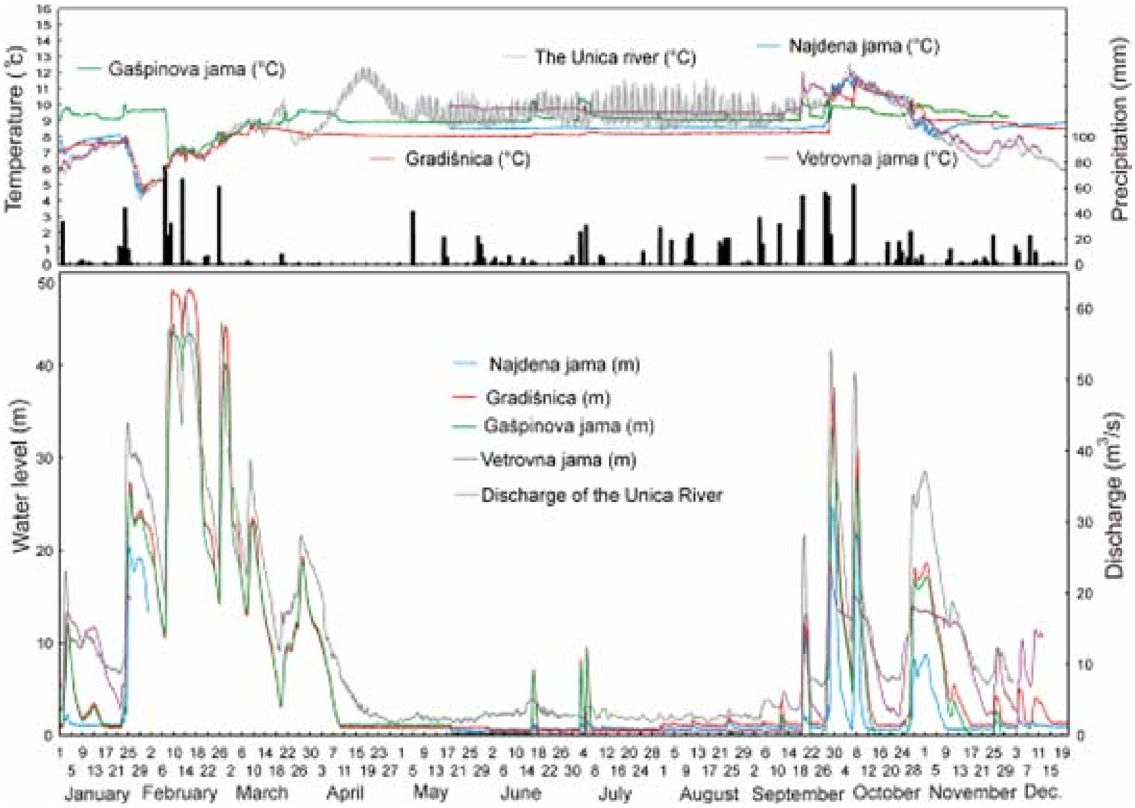

Figure 7.7b: Hydrographs of all four monitored caves and of the Unica River for the year 2007. Precipitation data are included.

7.7.1. Geological and geomorphological characteristics of surrounding of the Vetrovna Jama

Before we begin to interpret the hydrographs from the Vetrovna Jama, geological and geomorphological characteristics of its direct surrounding should be taken into account. The cave is encircled by deep and large collapse dolines at three sides (Fig. 7.4). Collapse dolines are a relatively frequent karst feature in Ravnik area. The largest collapse doline in this area is Laška kukava, which is situated in direct vicinity of the Vetrovna Jama (Fig. 7.8). Its depth is almost a hundred metres and its volume was estimated to 4.17 million cubic metres (Šušteršič, 2000b). Known downstream parts of Vetrovna Jama stretch directly below the Laška kukava. Hence outflow from the cave takes place below the collapse doline (Volk, 2007).

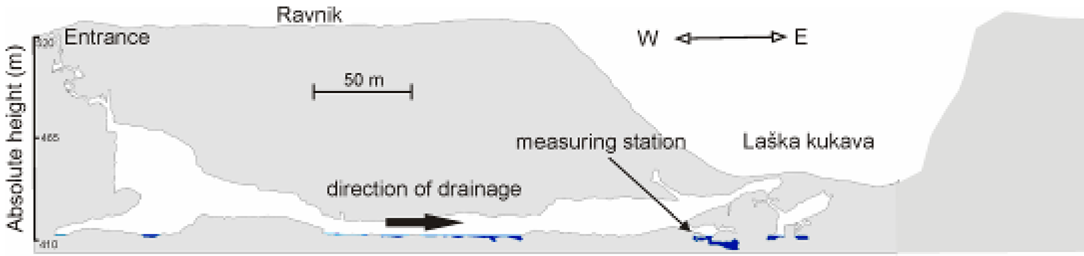

Figure 7.8: Sketch of longitudinal cross-section of Vetrovna Jama with measuring station marked. Author of the sketch is Miran Nagode, original was modified.

Genesis of collapse dolines in the area was primary interpreted with hydrogeological processes, with underground drainage respectively (Michler, 1954-1955). Recent findings indicate both hydrogeological and tectonic influence on formation of at least some of collapse dolines in this area - including those between Slaven dol and Voden dol (Šušteršič, 2002), which may affect the inflow to Vetrovna Jama. Collapse dolines are formed by the collapse of bedrock into underlying water caves (Palmer & Palmer, 2006) and by progressive removal of rock mass above active conduit system (Stepišnik, 2006). The intensity of breaking down is higher where the bottom of the collapse doline is relatively close to the conduit system (i.e. the thickness of ceiling is low). Mechanical stability of a rock, which can be already affected tectonically, is additionally diminished in such a case (Brenčič, 1993; Šebela, 1998). Bottom of the Laška kukava collapse doline is situated only a few metres above the ceiling of downstream part of Vetrovna Jama. It is probable, although not proven, that the rock-fall blocks the outflow from the cave, as the phreatic loop at the outflow has not been explored by divers. Several hydrogeological stages may be distinguished in a case, when a relatively large breakdown blocks the pathway of underground stream by filling conduits up to the ceiling: water tries to find a pathway through pores of collapse blocks in a first stage. Water gradually dissolves and erodes material (especially during flood events). In case of additional collapsing of rock material, water develops bypass routes, which avoid the breakdown (Šebela, 1998; Palmer & Palmer, 2006; Xuwen & Weihai, 2006).

To which stage outflow from Vetrovna Jama (below the Laška kukava collapse doline) belongs, is unknown, until the underground pool is researched.

7.7.2. Results from Vetrovna Jama

- **Recharge characteristics and peculiarities of Vetrovna Jama, based on hydrographs relations**

Relationship between discharge curve of the Unica River and the stage hydrograph in Vetrovna Jama can be generally considered as statistically significant (r=0.85) for the entire observation period (Fig. 7.7).

The water, which drains through the cave, belongs to the Unica. This is undoubtedly confirmed by diurnal temperature variations of water (Fig. 7.9). Such variations do not occur only during every flood input in Vetrovna Jama, but partly also during the base flow conditions.

Water connection of the Unica, sinking into eastern ponors at the Planinsko polje, with Vetrovna Jama was expected, according to previous hydrogeological knowledge of the area (Gospodarič & Habič, 1976; Krivic et al., 1976). Assumptions about water connections between bottom swallow holes of the Cerknica Lake and Vetrovna Jama were on the contrary relatively less reliable. This connection can not be confirmed by our measurements. Temperature comparison of Cerknica Lake with water in Vetrovna Jama does not give any clear indication, even if temperature hydrographs shows some similarities. However, such similarities can be also a consequence of regional climatic conditions. Comparison of stage hydrographs is even more problematic (Fig. 7.9).

As our research did not give clear answer about water connections between the Cerknica Lake and Vetrovna Jama, final answer remains unsolved. However, if connections exist, recharge from the lake should be minor in comparison with recharge of the Unica River in Vetrovna Jama.

Comparison of stage hydrograph of Vetrovna Jama with stage hydrographs from other monitored caves (Fig. 7.7) shows relatively low correlation. Coefficient of linear regression between Vetrovna Jama and Gradišnica (or Gašpinova Jama) is 0.75, while between Vetrovna Jama and Najdena Jama is 0.58 only. On the contrary, water level in Najdena Jama is in significant relation with water level in Gradišnica or Gašpinova Jama (r=0.90 and 0.89). Recession of underground water in these three caves is in good accordance with the recession of discharge of the Unica River. Vetrovna Jama is exception among monitored caves, because recession is significant slow on exactly defined levels where the recession does not follow the recession of discharge curve of the Unica River. This is characteristic of Vetrovna Jama.

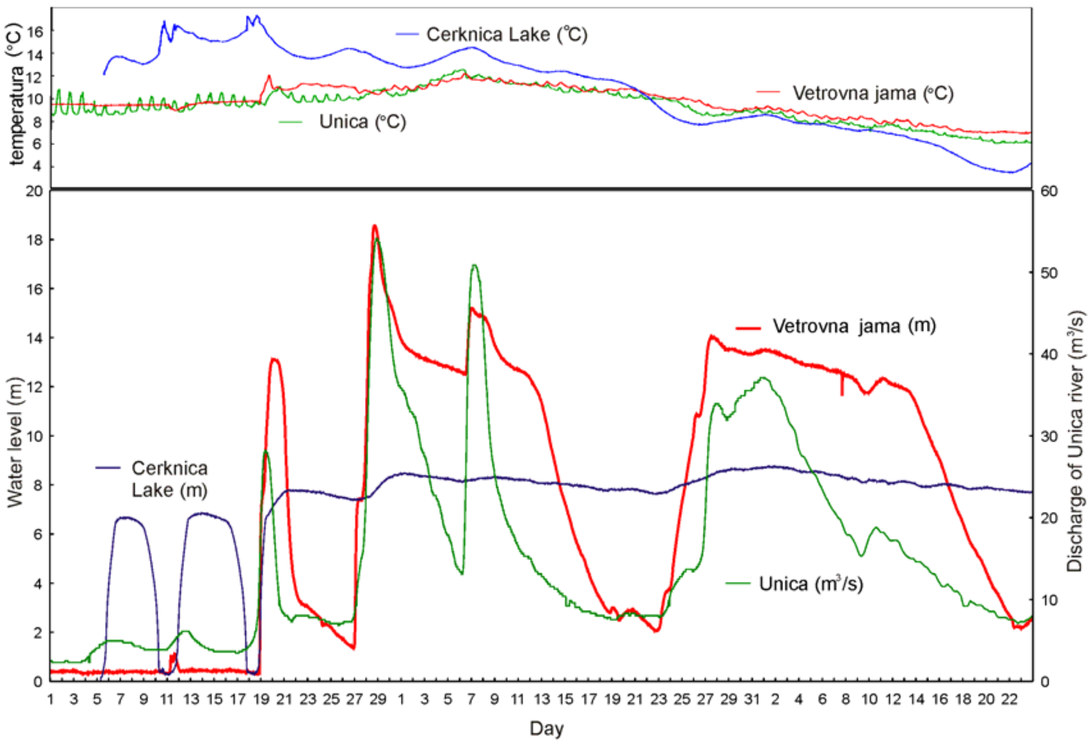

Figure 7.9: Hydrographs of the Cerknica Lake, the Unica River and the Vetrovna Jama in period between September 1st and December 24th, 2007.

- **Basic hydraulic characteristics of Vetrovna Jama based on relation between flow hydrograph of the Unica River and stage hydrograph of the Vetrovna Jama**

To interpret the hydraulic characteristics of the area of Vetrovna Jama, transition of different flood pulses have been analysed.

The pulses were divided into two groups, based on their magnitude (flow rate):

- We consider high flood pulses when the discharge of Unica is above 30 m^3/s. All six high flood pulses recorded in Vetrovna Jama reveal similar pattern. Transition of high flood pulses through Vetrovna Jama is considerably delayed compared to other monitored caves in the area. Recession of water level is relatively slow in the stage interval between 15 m and 12 m. Examples from December 2006 and from the end of September - October 2007 are shown in Figs. 7.10 and 7.11.

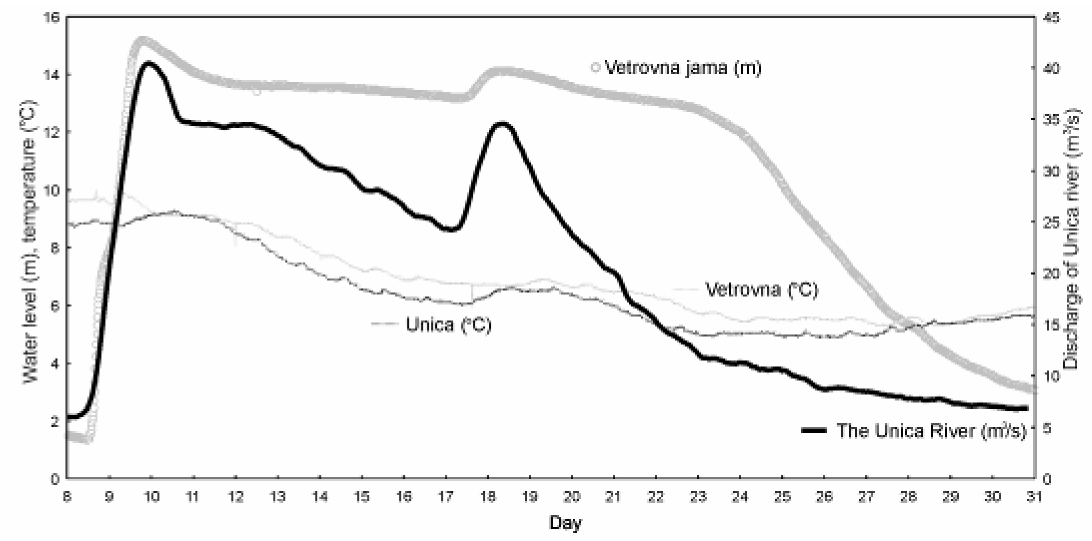

Figure 7.10: Comparison of flow hydrograph (the Unica River at Haasberg) with stage hydrograph of the Vetrovna Jama in period between December 8th – 31st, 2006. Thin dotted lines represent temperature hydrographs.

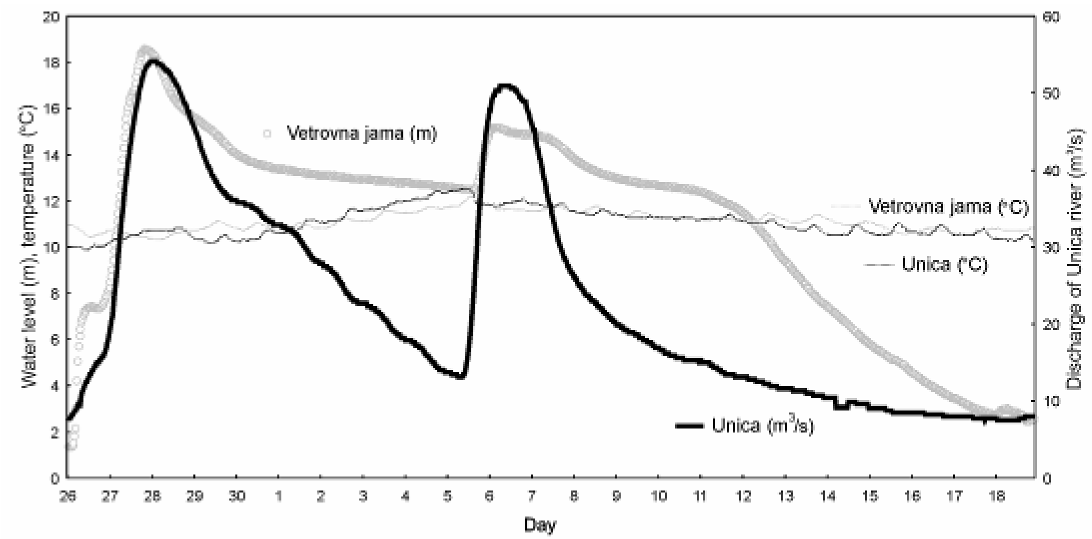

Figure 7.11: Comparison of flow hydrograph (the Unica River at Haasberg) with stage hydrograph of the Vetrovna Jama in period between September 26th – October 18th, 2007. Thin dotted lines represent temperature hydrographs.

- We consider small flood pulses when the discharge of the Unica River fluctuates between 5 m^3/s and 25 m^3/s or maximal up to 30 m^3/s. Small flood pulses may have different dynamics; they either pass the cave without significant distortion (see example from September 19th – 22nd, Fig. 7.12) or they may be considerably delayed in the cave (see example from January 1st - 16th, Fig. 7.13).

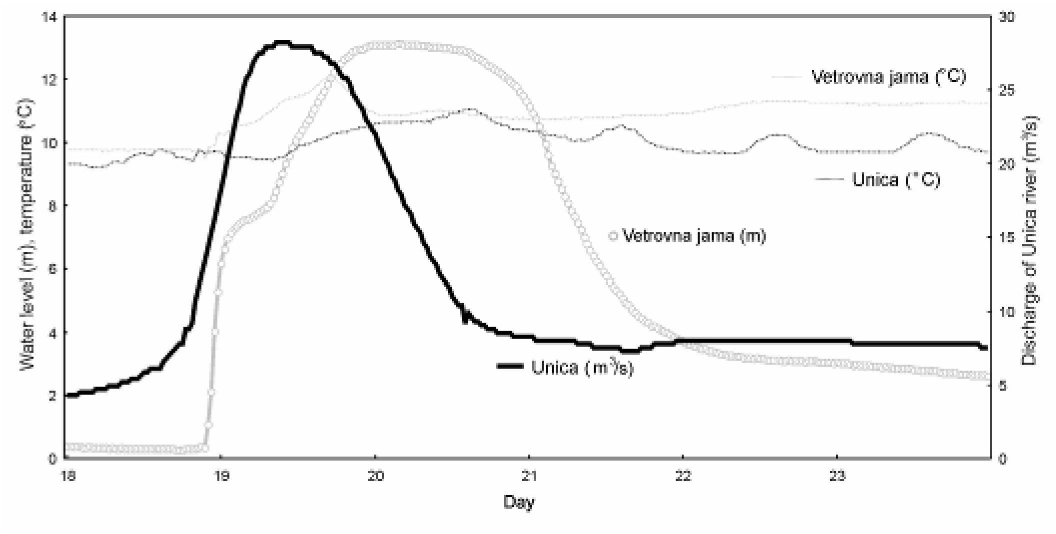

Figure 7.12: Comparison of flow hydrograph (the Unica River at Haasberg) with stage hydrograph of the Vetrovna Jama in period between September 18th – 23rd, 2007. Temperature hydrographs are also represented.

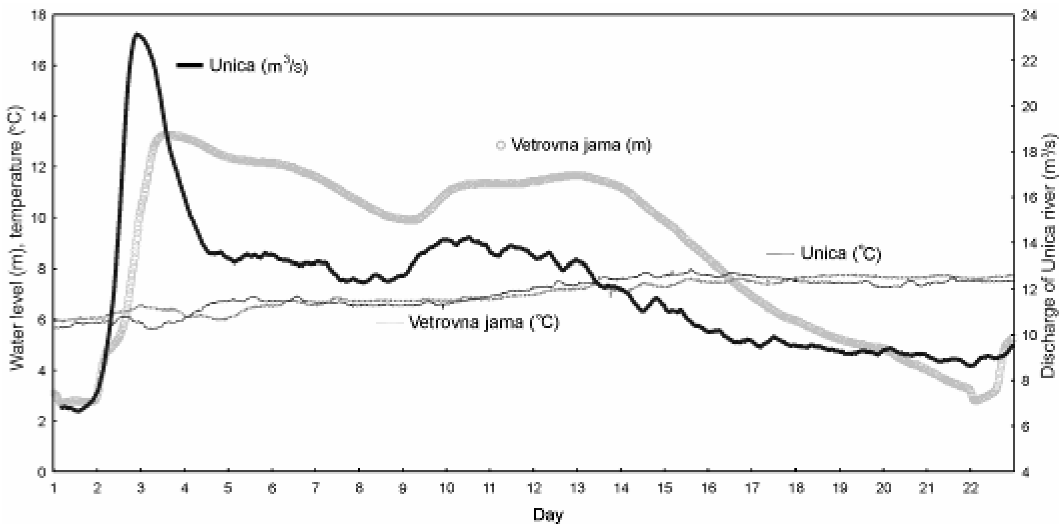

Figure 7.13: Comparison of flow hydrograph (the Unica River at Haasberg) with stage hydrograph of the Vetrovna Jama in period between January 1st – 22nd, 2007. Temperature hydrographs are also represented.

Diagram (Fig. 7.14) represents filling and emptying of Vetrovna Jama with flood water. It shows relationship between total discharge of the Unica in the polje and water level in the cave for certain flood pulse from December 2006 (Fig. 7.10).

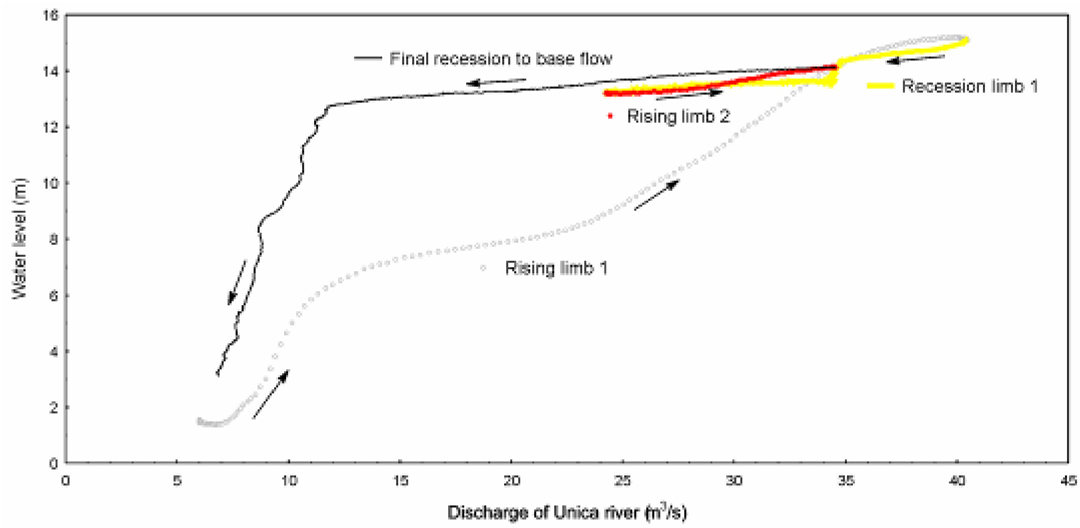

Figure 7.14: Relation between discharge of the Unica River measured at Haasberg and water level in Vetrovna Jama for period between December 9th and 31st, 2006.

As can be seen from the Figures 7.10 to 7.13, increase of water level is relatively fast in Vetrovna Jama (around 10 m/day), during the flood input. Some examples are interesting, as slow phase of recession was interrupted by a new flood pulse (Figs. 7.10 and 7.11). Recession in Vetrovna Jama takes place in two clearly distinguished phases. Water level decreases relatively slowly down to the stage 13 m or 12 m, with the rate 0.08 m/day to 0.33 m/day. Later on, it decreases with the rate between 1 m/day to 2 m/day (Fig. 7.10 – after December 24th, Fig. 7.11 – after October 12th and Fig. 7.13 – after January 14th), when it becomes comparable to recession of underground water in the other three monitored caves.

7.7.3 Discussion

- **Example of propagation of small flood pulse from Planinsko polje to Vetrovna Jama**

Analysis of hydrograph, which represents flood pulse from November 2006 (Fig. 7.15), offers some basic information about hydrodynamic of underground water between eastern ponors and Vetrovna Jama. It is a typical example of small flood pulse, which passes Vetrovna Jama without any significant distortion. Comparison of discharge curve of the Unica River with curve of water level in Vetrovna Jama shows very good accordance, in spite of the fact that correlation coefficient is not so high (r=0.81). Reason for relatively low coefficient is in phase shift of two curves; delay varies with flow rate.

There is some time delay between flood pulse recorded at Haasberg (a few km upstream from eastern ponors) and the one recorded in Vetrovna Jama. Delay should be attributed to both surface flow between Haasberg and ponors (around 5 km) and underground flow between ponors and the cave (straight line distance 2.7 km). According to temperature hydrographs, we believe that rise of water level (after November 23rd) was not caused by direct flood inflow of the Unica. Increase of water level at a spring or in a downstream part of the aquifer may be caused by displaced water, which has the same chemical composition as base flow. Flood water of surface origin usually reaches spring at the crest of the hydrograph, or only during the recession (Raesi et al., 2007). Similar characteristics may be observed on November hydrograph from Vetrovna Jama (Figs. 7.15 and 7.16). Direct flood flow of the Unica River entered the Vetrovna Jama just prior the crest of the hydrograph (see arrow in Fig. 7.16) at November 2006 flood event. This assumption is based on temperature characteristics of the underground water in Vetrovna Jama. Flood pulse, which entered karst underground, displaced underground water first. It was water which might be caught in large pools or epiphreatic loops. However, such hydrogeological process is characteristic especially for aquifers with well developed conduit porosity. And this aquifer undoubtedly is.

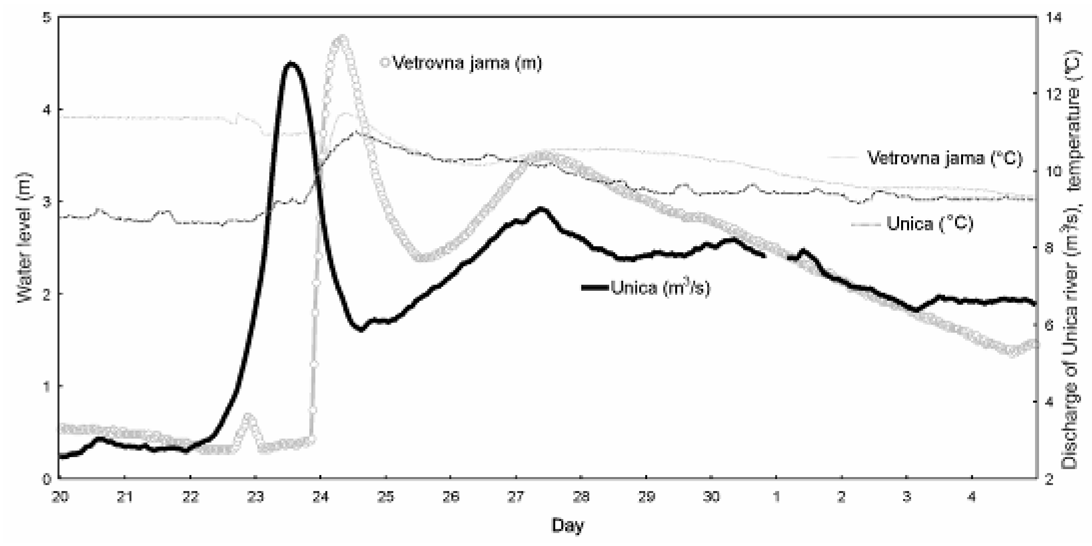

Figure 15: Comparison of flow hydrograph (the Unica River at Haasberg) with stage hydrograph of the Vetrovna Jama in period between November 20th – December 4th, 2006. Also temperature hydrographs are represented.

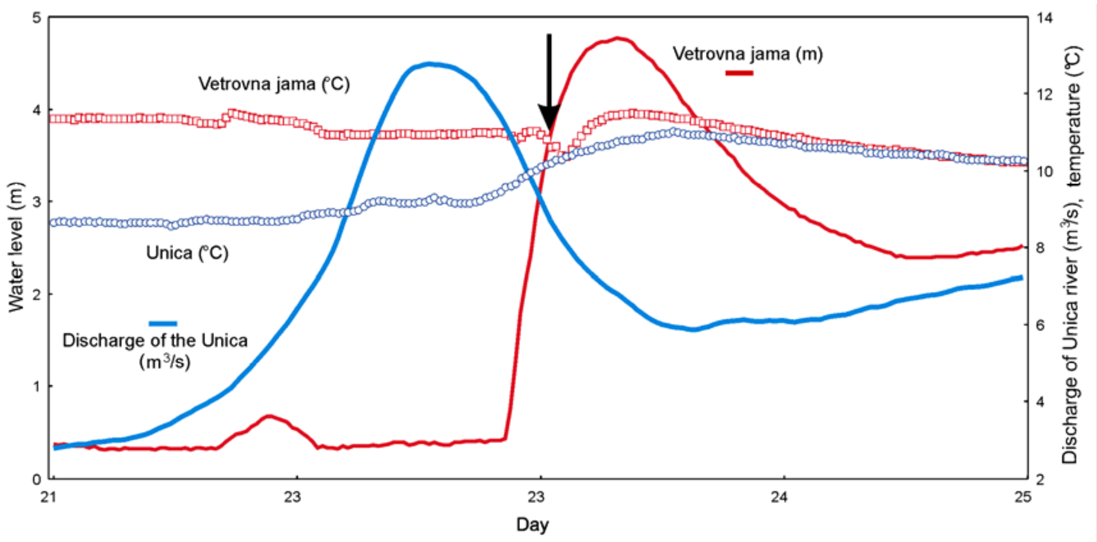

Figure 16: Detail of the November flood pulse. Arrow shows a point on rising limb, where the flood water of the Unica River penetrates to the Vetrovna Jama. Assumption is based on temperature characteristics of underground water. Temperature changes at the time of breakthrough.

➢ **Regional placement and local hydrogeological study**

Regional study of Vetrovna Jama within the discussed aquifer is based on comparison of hygrograph from Vetrovna Jama with hydrographs obtained in other monitored caves. Hydraulic response of Vetrovna Jama to flood pulses is considerably different to hydraulic response of monitored caves situated west and NW from Vetrovna Jama. Hence we may assume that the water, which enters aquifer through eastern ponors, flows preliminary toward north (Fig. 7.17) and does not have important hydraulic effect to other studied caves, situated in the NE. Reason for such directions of underground flow is attributed to hydrogeological barrier. Šušteršič (2002) claims that Slavendol fault prevents water to drain toward NE. For further explanation see chapter "System Planinsko polje – eastern group of ponors – Gradišnica".

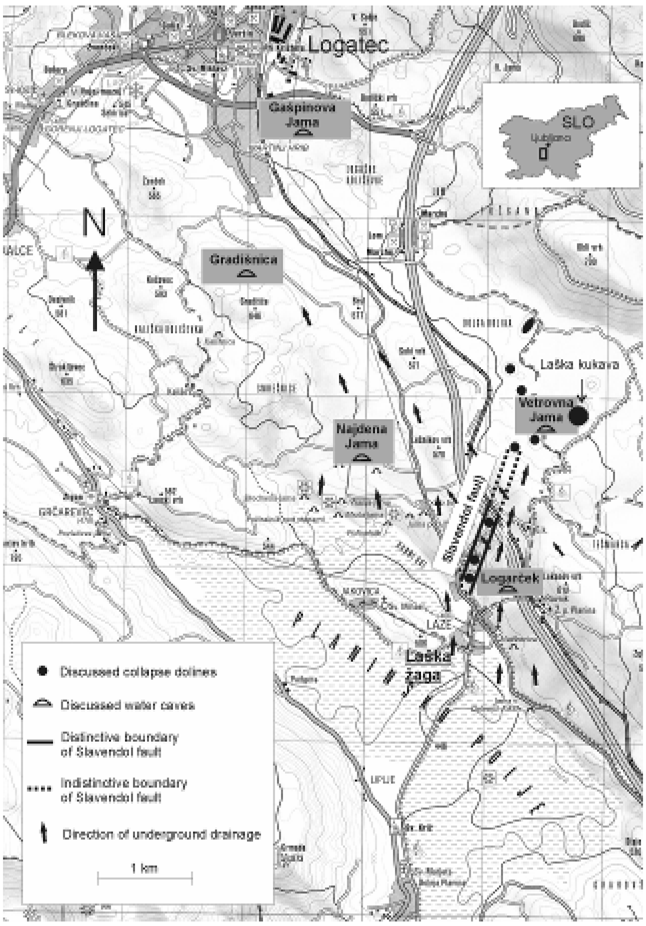

Figure 7.17: Geographical map of studied area. Discussed caves, collapse dolines, presumable direction of underground drainage and Slavendol fault, which

presumably represents low permeable hydrogeological structure (or barrier) are marked.

On local scale, Vetrovna Jama shows an important particularity, as already discussed. It reflects during transition of all relatively high flood pulses through the cave. Transition of high flood pulses through Vetrovna Jama is presumably distorted by hydrogeological restriction located downstream from Vetrovna Jama. Consequently, flood water is retained in the cave. Local hydrogeological (hydraulic) restriction presumably appears in direct vicinity of the cave. There is a great possibility, that outflow from the cave is confined by a rock-fall, which can block the conduit from the bottom to the ceiling.

Rising limbs on hydrographs from the Vetrovna Jama are relatively uniform. However, some inflection points may be often observed. Inflection points appear on hydrographs, where the rate of increase of water level relatively diminishes. It was observed several times that rising limbs can become relatively less steep at some certain levels, in two cases between 7 m - 8 m and in three cases between 5 m - 6 m. Such segments with relatively gentle rising limb can not be correlated with discharge curve of the Unica River as main feeder (Fig. 7.10 – December 8th, Fig. 7.11 – September 26th, Fig. 7.12 – September 19th and Fig. 7.13 – January 2nd). Reason could be attributed to occurrence of some relatively large reservoirs at certain levels. Filling of such reservoirs can be relatively slower at certain recharge conditions. Other reasons could be morphology of the Vetrovna Jama or occurrence of more permeable geological structures at certain altitude. However slower process of filling reservoirs at certain levels can not be always observed on the hydrograph, due to low resolution of hydrograph.

There is also another explanation, that the swallow capacity of ponors may be exceeded, which results in a “step” on rising limb. “Step” is short, due to activation of additional ponors, which occurs during rapid increase of water level in the riverbed of the Unica.

Water level in Vetrovna Jama reaches peak value usually a few hours prior the surface Unica River (Figs. 7.10 and 7.11). This fact only supports the assumption that maximal swallow capacity of eastern ponors is exceeded at certain segments on the hydrograph.

More complex than filling the Vetrovna Jama is its emptying. Latter takes place in two or sometimes three phases, depending on the maximal rise of water level. Water level recesses significantly slower in Vetrovna Jama as in other monitored caves west from it, as can be seen from hydrographs (Fig. 7.7). Outflow from the Vetrovna Jama is not much higher as inflow during slow stage of recession. Inflow is presumable relatively steady, i.e. that it should decrease much slower as discharge of the Unica at the surface. Inflow to the underground can be steady only if it is controlled by maximal swallow capacity of ponors, which are active at specific water conditions. Total swallow capacity of eastern ponors is estimated to be around 20 m^3/s (Breznik, 1998), hence such is supposed also relatively steady inflow to Vetrovna Jama during slow phase of recession.

When the stage drops to about 13 m, the recession accelerates considerably. This transition normally occurs when the discharge of Unica decreases to about 13 m^3/s. (Fig. 7.10 – December 23rd, Fig. 7.11 – October 12th and Fig. 7.13 – January 14th). Inflow into Vetrovna Jama should decrease enough, that outflow through a restriction (breakdown under Laška kukava collapse doline, see Fig. 7.8) is able to transmit all the inflowing water from this point of recession on. But decrease of inflows into Vetrovna Jama should be significant at this point. Reasons for significant decrease of the inflow could be in the structure of the conduit system (anastomotic structure) and splitting the flow into many conduits, which generally avoid Vetrovna Jama and area affected by collapse dolines. Or more probably, important ponor may drain out, causing rapid and high diminish of direct inflow into the cave. However inflow into Vetrovna Jama does not dry up totally during final, fast recession. Temperature characteristics of the Unica River may be observed in the cave also at the time of final recession.

So far, we find two hypotheses to explain characteristic hydraulic response of Vetrovna Jama.

One hypothesis is that inflow to the Vetrovna jama is governed by limited swallow capacity of ponors, which is exceeded at every relatively high flood pulse of the Unica (with magnitude above 15 m^3/s). To satisfy this hypothesis, there is no need that the outflow from the cave is restricted by relatively low permeable rock-fall.

Another hypothesis is based both, on limited inflow to the Vetrovna Jama and restricted outflow from the cave. Also lateral conduits should exist to explain hydraulic response of Vetrovna jama in this second hypothesis.

Both hypotheses may be reliable, they are argued by following facts:

- Only two of six recorded high flood pulses caused increase of water level above relative height of 15 m in Vetrovna Jama (to 18.5 and 19.5 m more exactly, see Fig. 7.7). Increase of water level ceased at relative height 14-15 m in the rest of four cases, even if the magnitude of flood pulses was different at the polje. It looks like that capability to exceed relative height of 15 m is relatively rare in Vetrovna Jama.

Such fact can be explained by steady inflow to the cave (according to the first hypothesis, swallow capacity of ponors is exceeded, at flow rate of the Unica above 15 m^3/s).

According to second hypothesis, swallow capacity of all eastern ponors is never totally exceeded, when discharge of the Unica spans from minimal to around 40 m^3/s. But some portion of underground water should diverge from main conduit (oriented S – N) to the west and it should happen upstream from Vetrovna Jama. Such lateral flow should avoid Vetrovna Jama and therefore would have no influence on water level in Vetrovna Jama. But to enable characteristic hydraulic response of Vetrovna jama (water level in Vetrovna Jama "stabilizes" on relative height 12 m - 15 m) with this second hypothesis, very important fact should be realized. The majority of lateral draining should take place at certain absolute height only (Fig. 7.18). As such presumable lateral conduit or well permeable horizon takes over all surplus of inflowing water, inflow to the Vetrovna jama is steady, regardless of the magnitude of input through eastern ponors (it is only for inputs with magnitude approximately in range 20 m^3/s - 40 m^3/s).

- However, water level in Vetrovna Jama can rise above relative height 15 m, at extreme high water conditions in the polje, when flow rate of the Unica River exceeds 50 m^3/s. Such events were observed two times only during our measurement (Figs. 7.7 and 7.9 see flood pulses between May 31st – June 2nd 2006 and between September 27th – 28th 2007). Maximal recorded height of water level in Vetrovna Jama was 19.5 m. When water level in the polje increases significantly, additional ponors activate.

According to first hypothesis, inflow to the cave increased with such activation of additional ponors. Also stage hydrograph responses with increase of water level above plateau of relative height 15 m, which otherwise coincides with steady inflow. Also according to the second hypothesis, inflow to the underground is higher. But capacity of presumable lateral conveyers (or well permeable horizon along Slavendol fault) is limited and may be exceeded also. Consequently, surplus of inflow does not spill over Slavendol fault toward NW but it drains through main conduit (directed S – N) directly toward Vetrovna Jama, where water level increases additionally (above relatively height 15 m).

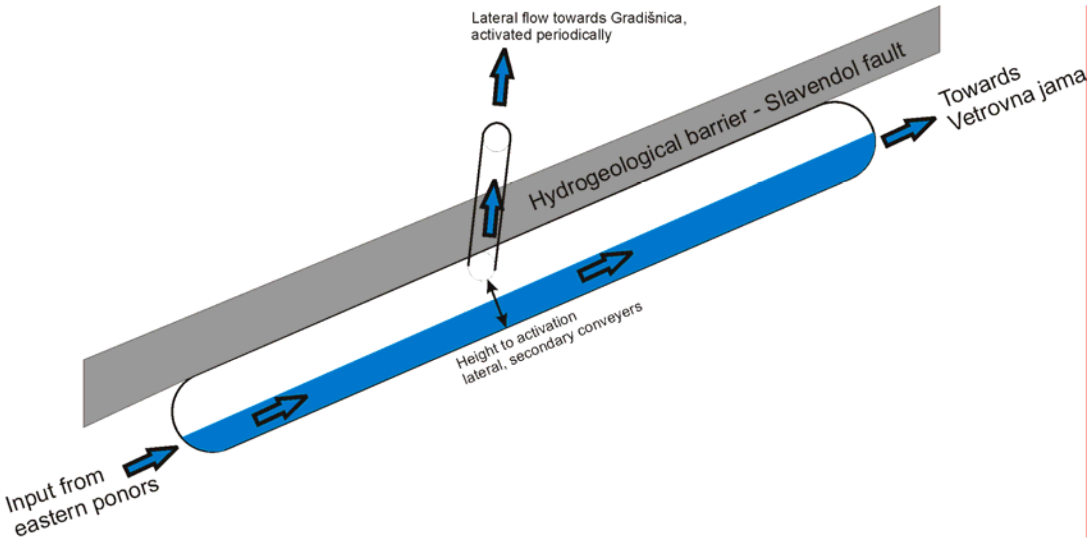

Figure 7.18: Water, which recharges eastern ponors, flows along low permeable Slavendol fault toward Vetrovna Jama in the north. However, some lateral conduits or some relatively well permeable horizon may exist, as some portion of water may theoretically penetrate through Slavendol fault toward NW (Gradišnica respectively). These secondary, lateral conveyers activate at relatively higher water conditions in the aquifer only.

7.8. System Planinsko polje – northern group of ponors – Najdena Jama – Gradišnica

Of all four monitored caves, only Najdena Jama is situated in direct vicinity of the margin of the Planinsko polje (near Pod stenami northern ponors respectively). Northern ponors are hydraulically connected with Najdena Jama and also Gradišnica downstream from Najdena Jama, as was already discovered by Gospodarič & Habič (1976) (Fig. 7.4).

Najdena Jama is recharged by the Unica River periodically only, at high and extreme high water conditions in the Planinsko polje, when capacity of eastern ponors becomes exceeded. Frequency of such conditions is relatively low, they occur usually in the autumn and spring. The Unica usually does not reach northern ponors and neither Najdena Jama consequently (Fig. 7.7).

Parameters of underground water in Najdena jama and Gradišnica were synchronically monitored in two periods, from July 2006 till January 2007 and from May till December 2007. Flow rate and temperature of the Unica River were measured from September 2006 on (Fig. 7.6).

7.8.1. Results

- **Small flood pulses, corresponding to low and medium water conditions in the Planinsko polje**

Almost all of sixteen recorded and analysed small flood pulses in **Najdena Jama** have similar characteristics. Water table in Najdena Jama generally fluctuates for around two metres. Response of the hydrograph to every storm event is sudden and very distinctive (Figs. 7.19, 7.20 and 7.21). Hydrographs have usually relatively sharp peaks, due to relatively rapid increase of water level from base flow to peak and relatively fast recession in first phase. Precipitation data have daily resolution only; therefore we may only assume that small flood pulses directly correspond to duration and intensity of the rainfall. Also the time lag between onset of the storm event and the point of transition from base flow to rising limb in the hydrograph may not be studied because of the same reason.

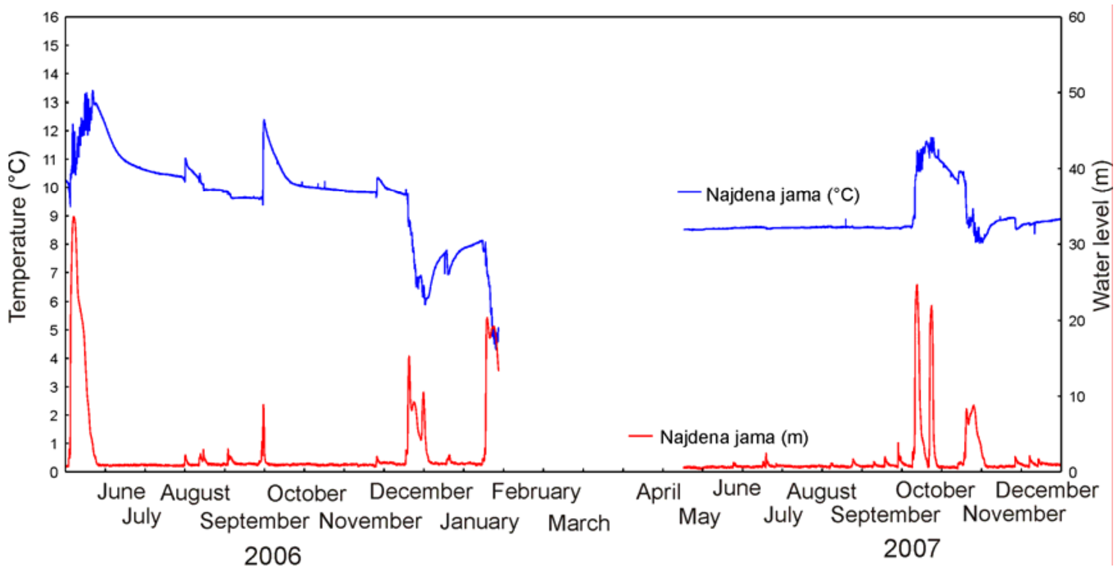

Figure 7.19: Hydrograph of Najdena Jama. Cave was monitored in period May 2006 – December 2007, with a break between February and April 2007. Seven high flood pulses (higher than 8 m) were recorded and several small ones (around one to three metres).

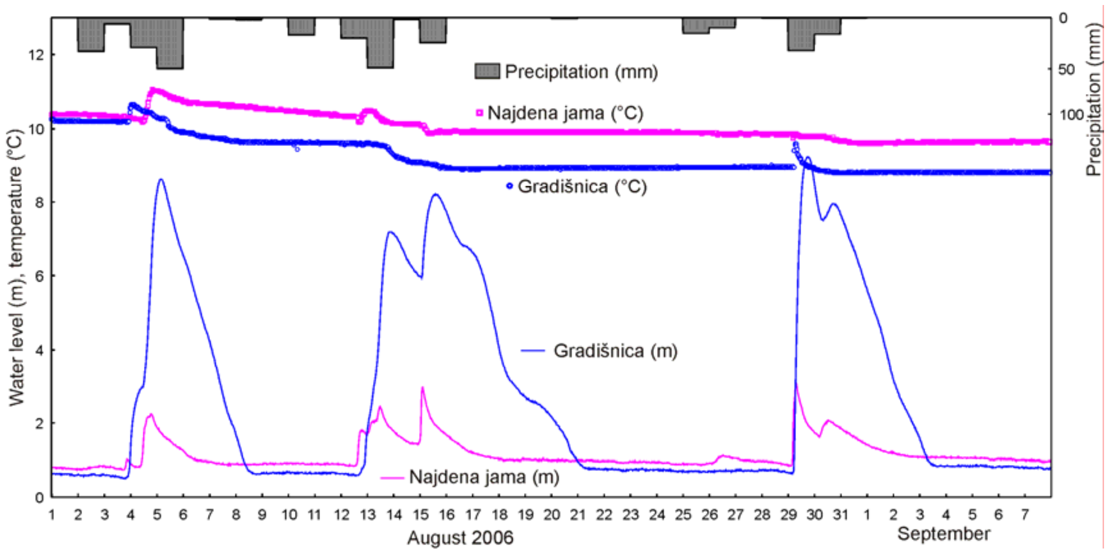

Figure 7.20: Hydrographs from Najdena Jama and Gradišnica in August 2006. Three small flood pulses were recorded; two of them have also secondary peak.

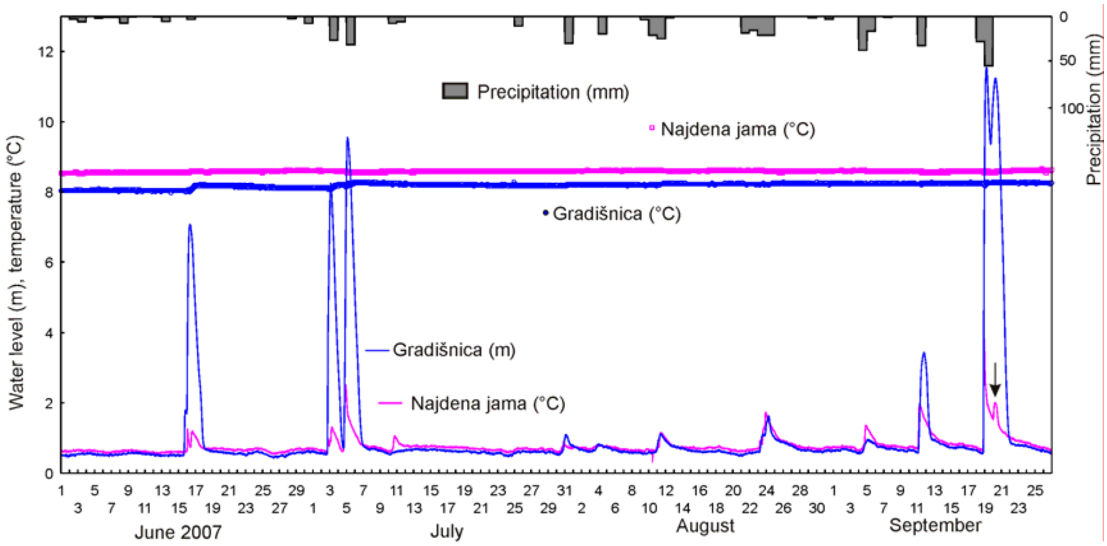

Figure 7.21: Hydrographs from Najdena Jama and Gradišnica in summer 2007. Several small flood pulses were recorded. Secondary peak of the last represented flood pulse from Najdena Jama (marked with arrow) is relatively gentle in comparison with other peaks (see also next figure).

Peaks (whether primary or secondary) are usually directly associated with the intensity of precipitation (Figs. 7.20 and 7.21). However, two secondary peaks (January 2nd 2007 and September 20th 2007 – Fig. 7.22 peak marked with arrow No. 2) occur more than a day after a storm event, moreover they have also different shape. All peaks, which coincide with storm event are characteristically sharp (for example Fig. 7.22, peak marked with arrow No. 1), while two discussed, delayed peaks are rounded (for example Fig. 7.22, peak marked with arrow No. 2). Rounded peak is otherwise characteristic for crests of flood pulses of the Unica River (see green crest of green curve in Fig. 7.22). As will be detailed argued in Discussion (7.8.2), we assume that the Unica River may recharge Najdena Jama also independent of northern ponors, but this recharge is slight regarding to magnitude of such pulses in Najdena Jama.

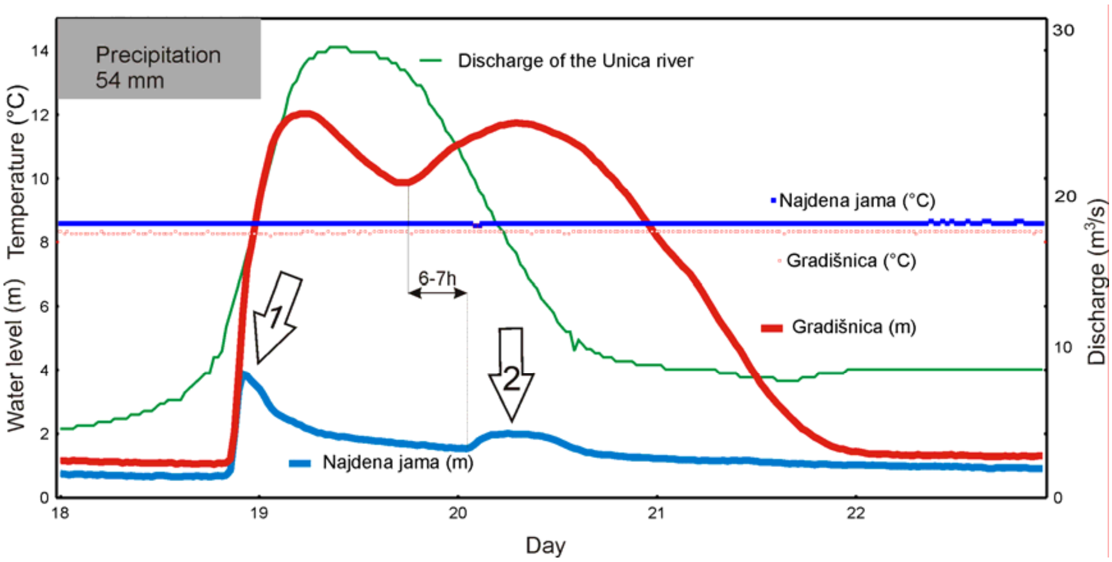

Figure 7.22: Small flood pulse recorded on September 18th – 22nd, 2007. Secondary peak in Najdena Jama (arrow No. 2) and Gradišnica correspond to flood inflow of the Unica River.

Temperature of base flow in **Najdena Jama** is around 8.5°C (Fig. 7.19 – see summer 2007 and Fig. 7.21). It is approximately the same as the mean year temperature of the discussed region. Local inflows, which induced small fluctuation of water level, did not change temperature of base flow at all in Najdena Jama in summer 2007, as can be seen from Fig. 7.19 and 7.21. But water temperature in Najdena Jama shows totally different properties in the summer 2006 than in the summer 2007, despite the fact that water conditions were similar and comparable during both summers. Small flood inflows do cause fluctuations of water temperature in Najdena Jama in summer 2006 (Fig. 7.19 - see August 2006 and Fig. 7.20 - August 2006). We tried to explain different temperature characteristics of summer 2006 and 2007 in section Discussion (7.8.2).

In comparison with Najdena Jama, fluctuations of **water level** are usually more distinctive in **Gradišnica**, after the same storm events (for example see Fig. 7.22, see also Fig. 7.23 – flood pulses smaller than 12 m are considered as small in Gradišnica). Small flood pulses were 6 m high in average in Gradišnica.

Rising and recession limbs are usually relatively uniform and steep (increase around 0.7 m/h, decrease around 0.2 m/h) in Gradišnica (Fig. 7.22). However some inflection points may appear occasionally at rising limb, where rising limb becomes less steep for some time (Fig. 7.20 - see August 4th). Inflection points may indicate occurrence of large reservoirs (such as chambers) at certain altitude, or interaction of more flood inflows of different surface origin in Gradišnica. Flood inflows of different surface origin may interact with each other (Fig. 7.22 – two peaks correspond to two different inflows).

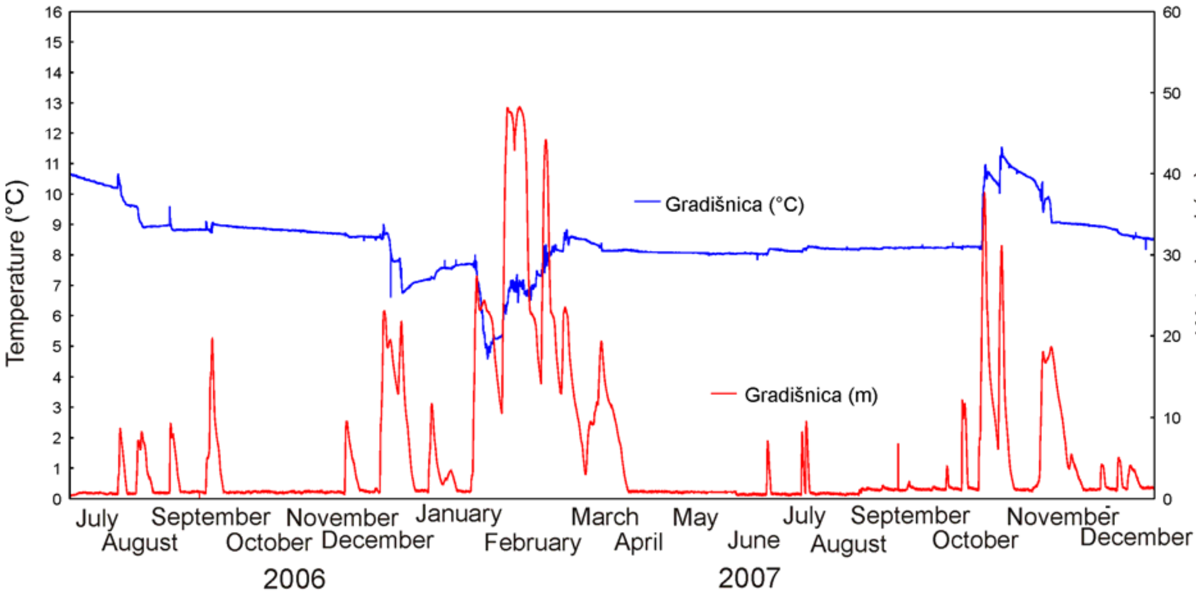

Figure 7.23: Hydrograph of Gradišnica. Cave was continuously monitored in period July 2006 – December 2007. Flood pulses higher than 12 m are considered as high and lower as small.

It may be assumed that small flood pulses travels from Najdena Jama to Gradišnica (Fig. 7.22), but there should be a time shift between flood pulses recorded in upstream and downstream cave. But secondary flood pulse in downstream Gradišnica can even overtake the one in upstream Najdena Jama. The inflection point from slow recession to raising limb in Gradišnica occurs 6-7 hours before the same inflection point in Najdena Jama (Fig. 7.22). Hence secondary flood input recorded in Gradišnica, entered the aquifer from different ponor as the one recorded in Najdena Jama. This is discussed in chapter "System Planinsko polje – eastern group of ponors – Gradišnica".

Temperature of underground water in **Gradišnica** remains usually relatively stable after every flood inflow with relatively low flow rate. Local summer storms may force water level to rise for 10 m, but changes in water temperature are usually negligible during transition of such flood inflow. Temperature remains equal to temperature of base flow, which is only 8°C – 8.3°C in Gradišnica (Figs. 7.23 and 7.24). There are some exceptions in summer 2006 (Fig. 7.22), similar as in Najdena Jama.

- **High flood pulses, corresponding to high and extreme high water conditions in the Planinsko polje**

Two flood inflows may be usually clearly distinguished in hydrographs in **Najdena Jama**, after every storm event (Fig. 7.24). First flood inflow causes slight fluctuation of water level in Najdena Jama. As already mentioned this flood inflow appears also during every local storm as well and presumably temporally coincides with duration and intensity of storm event. Another major inflow is caused by the Unica River, which breaks into the cave with some time delay, during the recession of first local inflow. The Unica has to pass more than 10 km along the polje, before it reaches northern ponors.

Input of the Unica River causes a high increase of water level in Najdena Jama. The curve of water level in the cave is in statistically significant linear relation with discharge curve of the Unica River (measured as total discharge) in such a case; $r = 0.87$. There may be also some other minor inputs which coincide with main input of the Unica River, but they are not visible from the hydrograph, due to their inferior contribution in comparison with contribution of the Unica River.

As mentioned, small flood inflows only occasionally change **temperature** of underground water in **Najdena Jama,** which is 8.5°C at base flow. However changes are relatively minor (not more than 1°C, according to so far measurements) and occur at specific conditions only (see section 7.8.2.). The Unica River, which breaks into the cave, has much higher flow rate than prior small flood inflows (presumably two or maybe even three orders of magnitude higher?). Such input induces high increase of water level (maximal level increase in observed period was 33 m). Moreover, the distance between ponors and Najdena Jama is short enough that the surface temperature signal is well preserved in the cave (Fig. 7.24). It also alters temperature field of the bedrock in karst massif.

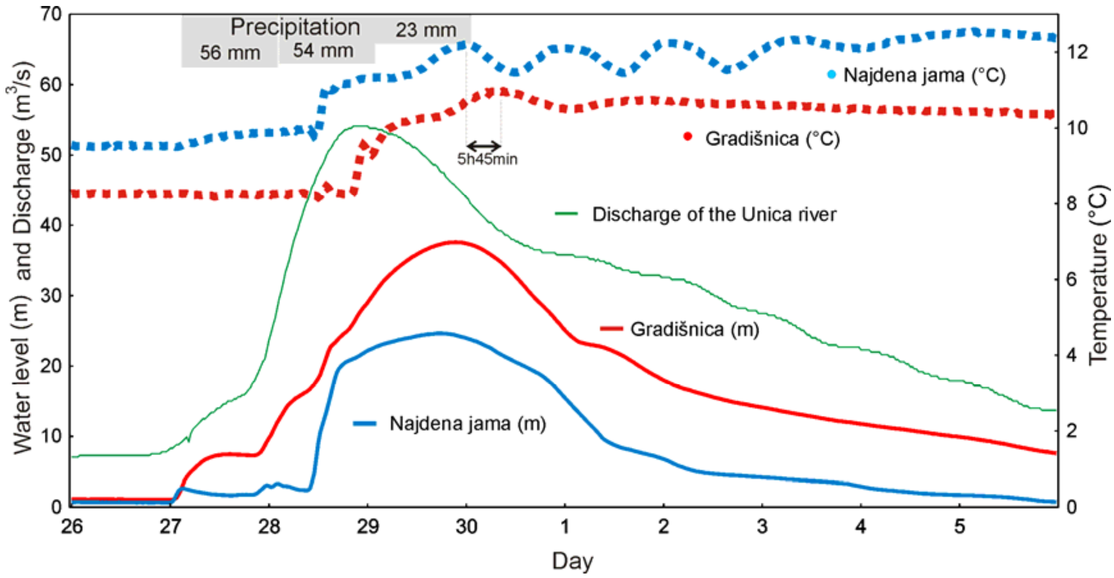

Figure 7.24: High flood pulses in Najdena Jama and Gradišnica recorded on September 26th – October 6th, 2007.

Rising limbs in hydrograph of **Gradišnica** are usually composed of a few segments (Fig. 7.24). Each segment presumably represents one or combination of more flood inflows. All this flood inflows do not have any significant influence on temperature of underground water in Gradišnica. Last flood input (see crest of the hydrograph in Fig. 7.24), which reaches Gradišnica, is periodic flow of the underground Unica River, arriving from northern ponors of Planinsko polje through Najdena Jama and other known and unknown caves in vicinity. Occurrence of diurnal temperature variations in Gradišnica proves that this flood inflow belongs to the Unica River. Water temperature changes rapidly in Gradišnica, when the Unica River reaches measuring station in the cave (Fig. 7.24).

7.8.2. Discussion

Hydrographs recorded in Najdena Jama have relatively rapid (around 0.7 m/h) and sharp response to the storm event in the first phase. But the rise of water level is relatively low in comparison with Gradišnica. Such fluctuations are probably caused by flood inflows of diffuse infiltration through the vadose zone above the cave and internal runoff from nearby polje.

Diffuse infiltration, which takes place through well permeable epikarst and vadose zone, may be rapid during the storm event. Bedrock above the Najdena Jama is highly fractured and relatively thin (thickness a few tens of metres). But according to some storage models (Mohhrlok & Sauter, 1999), only a small percentage of the infiltrating water (around 10 %) directly flows through well permeable vertical shafts into the conduit system of the aquifer. The remaining 90 % of the effective infiltration recharges the aquifer slowly, via the less permeable pathways. However, flow rate of trickles (rapid component of diffuse infiltration), which can contribute to total increase of water table in Najdena Jama, is totally unknown.

Another source of recharge is water, which infiltrates into the sediment cover of Planinsko polje (after the precipitation). Entire area of Planinsko polje is covered with Quaternary sediments of average thickness around 4 m (Ravnik, 1976). However effective infiltration may not be carried out the sediments, before the moisture exceeds the field capacity. It may take relatively long time and response of the hydrograph would be gentle. Exceptions are possible, if recharge is not conditioned by prior fulfillment of the soil moisture deficit. It happens if precipitated water infiltrates through cracks in the soil. Rapid recharge and sharp response of the hydrograph may occur in such a case (Petrič, 2002). Similar role as cracks may have also other well permeable structures, such as well permeable depressions or sinkholes, which are frequent in Planinsko polje. They may transmit concentrated overland flow into karst underground (conduit system) rapidly. Bonacci (1987) reported that overland flow occurs regularly in covered karst (such as Planinsko polje is), after heavy rain. Such recharge is called also internal runoff (White, 2002).

Small flood pulses have minor or no temperature influence in Najdena Jama. Different thermal response of Najdena Jama (and also Gradišnica) in summer 2006 in comparison with summer 2007 (accidentally?) coincide with prior change of temperature field of bedrock in early summer 2006 (Fig. 7.19). Bedrock and base flow were approaching to usual temperature field (8.5°C) slowly, after the highest measured flood input of the Unica River, which happened at the end of May 2006 (Fig. 7.25). Temperature field 8.5°C is established gradually in Najdena Jama, because also base flow gains changed temperature field from bedrock, after the retreat of the Unica River from the cave.

Based on this fact, we offer hypothetical explanation to explain totally different thermal significance of small flood pulses in summer 2006 than in summer 2007 (Fig. 7.19). Temperature field of the rock-mass in karst aquifer is disturbed after significant flood input of the Unica River (Figs. 7.19 and 7.25). After retreat of the Unica from northern part of polje (northern ponors respectively), the rock-mass in a part of the aquifer, which is recharged through northern ponors, tends to approach slowly toward usual temperature field (8.5 °C) (Fig. 7.25, see arrow).

Such tendency may be theoretically faster far from the margin of the polje (i.e. at monitored location in Najdena Jama), than at direct margin. Later, small flood pulses cause displacement of stored water from voids at the margin of the aquifer.

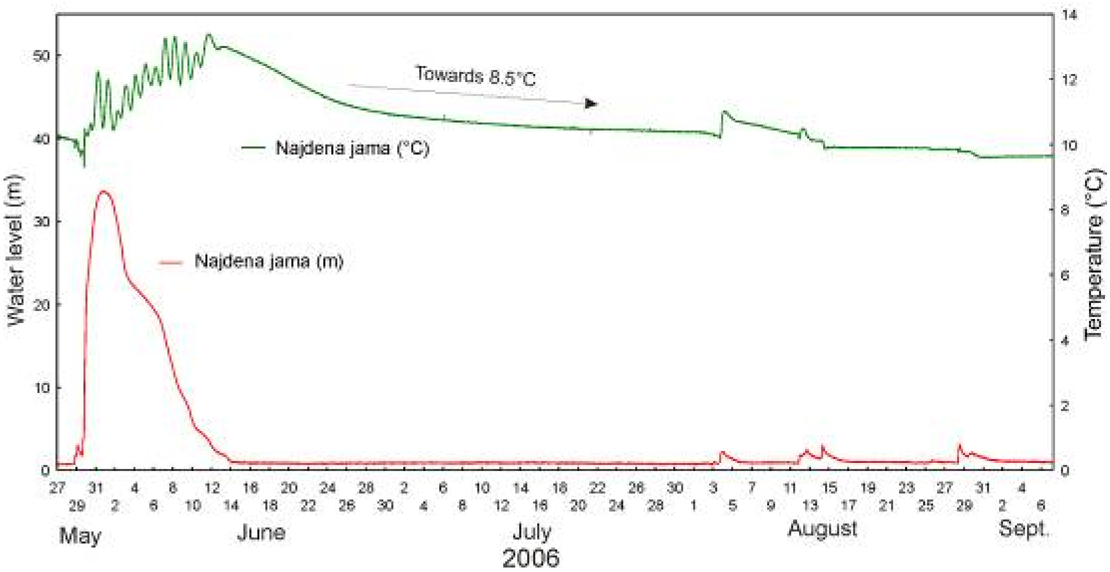

Figure 7.25: The highest measured flood input in Najdena Jama, caused by inflow of the Unica River, which occurred in May – June 2006. Observe tendency of base flow to approach toward 8.5 °C after the retreat of the Unica River from the cave. Base flow adopted temperature of the rock-mass, which temperature field was changed enormously by input of the warm Unica River. Usual temperature field 8.5 °C was re-establishing gradually.

Temperature of this displaced water is equal to temperature field of the rock-mass at the margin, hence slightly higher than in monitored location in Najdena Jama (according to our hypothesis). Hence such displaced water may induce temporal short increase of water temperature in Najdena Jama.
In contrast with summer 2006, thermal properties of the aquifer were totally stable in the summer 2007. Thermal field of the rock-mass was supposed to be 8.5°C within the entire discussed part of aquifer. Water displaced by small flood pulses did not cause any changes of water temperature in Najdena Jama at all.
This is hypothesis only, whether it is reliable or not is hardly to say, due to lack of measurements within the system.

Similar thermal properties as for Najdena Jama could be assumed also for Gradišnica (Figs. 7.19 and 7.23, see August and September 2006). High flood pulse in the May-June was not recorded in Gradišnica, as monitoring was established there not earlier than in July 2006). However temperature change (sharp peak) on August 29th 2006 (Fig. 7.20) could be most logically explained as inflow of rapid component of autogenic recharge. Such inflow may change temperature of water near the water table in Gradišnica, it is exactly where data logger was at this time (less than 1 m below the water table). This explanation seems reasonable, but such thermal response was observed only once, despite the fact that similar recharge conditions repeated several times.

In contrast with rapid response of the hydrograph to small flood inflows (caused by diffuse infiltration and internal runoff), also some secondary peaks with gentle crest occasionally appear in Najdena Jama. They may be observed in Najdena Jama exclusively at certain hydrologic conditions in the polje, as is discussed below. Such secondary peaks are not directly associated with storm event (Fig. 7.22, peak marked with arrow No. 2). It is assumed that water disappears into underground also from riverbed along entire reach between eastern and northern ponors. This underground water penetrates slowly to Najdena Jama, due to relatively low permeability of bottom of the polje, which is composed of Triassic dolomite. Consequence is short increase of water table, which is observed in Najdena Jama as a secondary peak with characteristic properties (gentle rising limb and blunt crest). Water temperature remains undisturbed during such increase. Such increase of water table in the margin of the aquifer and Najdena Jama respectively, is significant only when discharge of the Unica River exceeds 20 m^3/s, which is also some rough swallow capacity of eastern ponors. However, when discharge of the Unica River exceeds 30 m^3/s, water flow reaches final ponors at the northern margin of the polje. Input through northern ponors predominates over all other (smaller) inputs, such as presumably input of leaking water from riverbed into underground, toward Najdena Jama. Latter input is blurred when the Unica River begins to recharge northern ponors and may not be distinguished from prevailing one.

Flood water from Najdena Jama certainly drains towards Gradišnica. However, connections at relatively low water conditions are not totally clear. It is not known exactly, whether small local flood pulses are transmitted also to Gradišnica downstream (Fig. 7.22). Probably they are, but also flood inflows from other regions induce increase of water level in Gradišnica. These inflows have presumably higher magnitude and transition of small flood pulses deriving from Najdena Jama can not be observed in hydrograph in Gradišnica. They are blurred by other flood inflows in Gradišnica. The Hotenka stream is presumably the main recharging source of Gradišnica at low and medium water conditions in Planinsko polje.

However, when flow of the Unica River periodically recharges northern ponors, underground water undoubtedly drains from Najdena Jama toward Gradišnica. Input of the Unica coincides with sudden and dramatic change of water temperature in Najdena Jama at the time of breakthrough (Fig. 7.24). Similar process can be observed in Gradišnica. Breakthrough at the same time coincides also with sudden and high increase of water level in Najdena Jama, while its contribution to water level in Gradišnica looks like relatively less distinctive. Reason for less distinctive response of Gradišnica should be in interaction of several other inputs (which feed the cave already before) and in great extend of the aquifer (water is distributed laterally). The underground Hotenka stream is presumably one of the first flood inflows, which reaches Gradišnica. The underground Unica River is the only one flow, which may be undoubtedly and scientifically proved so far (as was only one monitored). It can change water temperature in Gradišnica significantly (Fig. 7.24), while all other flood inflows do not have any significant temperature influence ever at the monitored micro-location.

Diurnal temperature variations appear with some time delay in Gradišnica in comparison to Najdena Jama, hence transit times of underground water between both systems may be roughly calculated. Transit time of first temperature maximum (water flow respectively) in Fig. 7.24 was approximately 5 hours and 45 minutes.

7.9. System Planinsko polje – eastern group of ponors – Gradišnica

Characteristic secondary peaks appear on hydrographs recorded in Najdena Jama, Gradišnica and Gašpinova Jama, as has been partly already discussed in previous chapters. Such secondary peaks can be observed only when magnitude of flood pulses of the Unica River ranges between 15 m^3/s – 30 m^3/s (i.e. at medium water conditions), hence when the northern ponors remain dry (Fig. 7.26). At flow rate above 30 m^3/s, the Unica River recharges also northern group of ponors. Water drains from northern ponors directly to Najdena Jama and than towards Gradišnica (and Gašpinova Jama). This flow is of high magnitude and diminishes or even blurs influence of other inflows significantly.

Detailed study of hydrographs obtained in all four monitored caves revealed that some portion of water, which sinks underground through eastern ponors, should recharge not only Vetrovna Jama (see chapter 7.7), but also Gradišnica and Gašpinova Jama. Discussed secondary peaks, which occur in Gradišnica and Gašpinova Jama, are attributed to this inflow. But this underground flow has certainly no influence on hydrograph in Najdena Jama (Fig. 7.26).

The question is where does the underground Unica, which recharges Gradišnica from eastern ponors, flow? According to Šušteršič (2002), there is a hydrogeological barrier (Slavendol fault) just west of eastern ponors and Vetrovna Jama.

We expose three hypotheses about underground connections between eastern ponors and Gradišnica so far.

1. Underground water, which drains out from Vetrovna Jama, could indirectly induce increase of water level also in Gradišnica. Slavendol fault was determined somehow near to Laška kukava collapse doline, by structural geological mapping (Šušteršič, 2002). Outflow from Vetrovna jama can not be confined with

hypothetically low permeable Slavendol fault anymore; hence it may induce an increase of water level also in the NE (Gradišnica and Gašpinova Jama respectively).

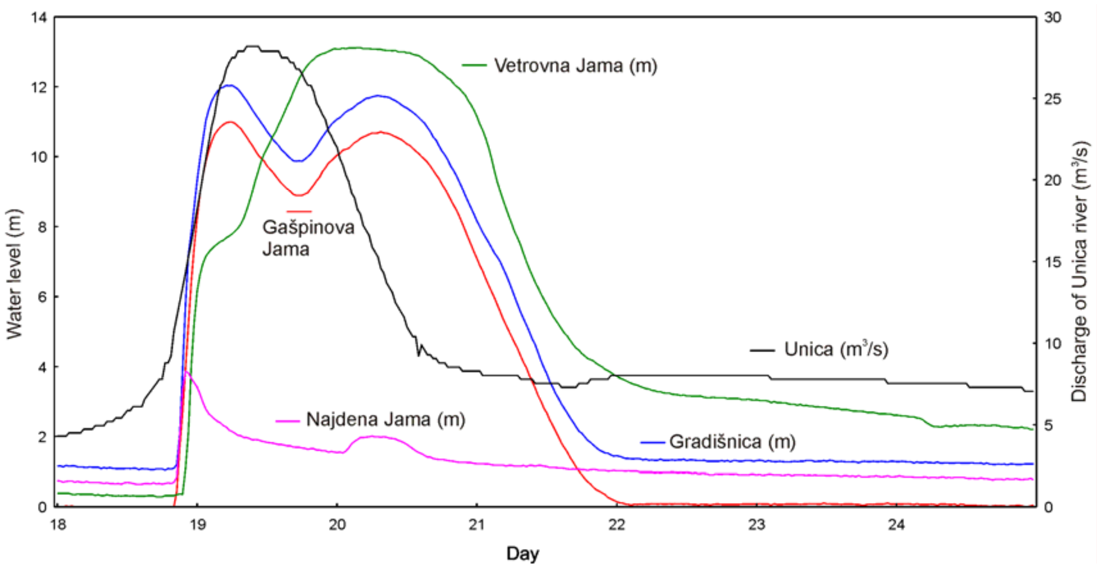

Figure 7.26: Hydrographs from September 2007. Flood pulse of the Unica River recharged eastern group of ponors, northern ponors remained dry. Secondary peak recorded in Gradišnica and Gašpinova Jama (see September 20th) is attributed to inflow of the Unica River arriving from eastern ponors. While secondary peak in Najdena Jama (see September 20th) is induced by relatively low surplus which passes eastern ponors, but sinks underground before it reaches northern ponors. The surface Unica represents an overflow, which leaks into aquifer not only through main ponor areas, but also through several other points situated along its surface pathway.

2. Laška žaga ponor is the most western and final ponor, which still belongs to eastern group of ponors. It is situated in direct vicinity of Laze village (Fig. 7.27). This ponor could convey water in somewhat different direction as other eastern ponors. It is situated just west from Slavendol fault, which represents hydrogeological barrier according to Šušteršič (2002). All other eastern ponors are situated east of this barrier. Hence, Laška žaga ponor may convey water in general direction SE-NW, in contrary with other eastern ponors, which drain water generally toward north. Conduits, which convey water from Laška žaga ponor, may avoid Vetrovna Jama. Laška žaga ponor may have important influence on hydrograph in Gradišnica, at certain hydrologic conditions. Significance and swallow capacity of

this ponor has not been studied in details yet, due to disposable literature. Such work should be done in future to illuminate hydraulic (hydrogeology) of aquifer along Planinsko polje.

Figure 7.27: There are presumably two directions of underground drainage from eastern group of ponors; S – N as main direction and SE – NW as secondary lateral direction, which occurs only at relatively higher water conditions, when Laška žaga ponor activates or when hypothetically some portion of water penetrates through Slavendol fault (line between E – ponors and Vetrovna Jama) to the NW. Also outflow from Vetrovna jama may partly diverge toward NE.

3. Some portion of underground water, which drains from eastern ponors toward north (Vetrovna Jama respectively), may diverge laterally from main direction of drainage (S – N) toward west. Divergence may occur somewhere between ponors and upstream part of Vetrovna Jama (Figs. 7.18 and 7.27). This laterally conveyed portion of water may influence on water level in Gradišnica and Gašpinova Jama.
Some conduits may penetrate Slavendol fault, which the most probably governs the drainage in this part of the aquifer. Or relatively well permeable horizons along low permeable Slavendol fault may exist, as one of the hypothesis to explain connections between eastern ponors and Gradišnica.

7.10. System Gradišnica – Gašpinova Jama

Beside in Vetrovna jama, the water table in the inner part of the investigated aquifer can be reached in Gradišnica and Gašpinova Jama. Entrance to the Gašpinova Jama is at the suburb of Logatec, while entrance to the Gradišnica is around 1600 m southern (Figs. 7.17 and 7.27). Distance between two monitored stations can be even for around hundred metres shorter.

South lakes were monitored in both caves. Exact absolute height of base flow, which represents base level for our measurements of water level, is not totally sure. Absolute height of water in Gradišnica is supposed to be 377 m a.s.l. (Nagode, 1997; Gams, 2004) or even 379 m a.s.l. (Gospodarič & Habič, 1976; Šušteršič, 2002). There is only one information about absolute height of water in Gašpinova Jama: 374 m, according to Volk (2007). All these heights may have an error of a few metres. Hypothetic hydraulic gradient between two caves is around 0.002 to 0.003 at base flow, regarding to available data.

Both discussed caves were simultaneously monitored in period from August 2006 to November 2007 (Figs. 7.6 and 7.7 in chapter "System Planinsko polje – eastern group of ponors – Vetrovna Jama").

7.10.1. Results and discussion

Water level fluctuates practically synchronically at both locations, as was undoubtedly proved by measurements (Fig. 7.7). Hence, the area between both caves can be treated as a part of the aquifer with uniform water table.

However temperature properties are not so equal in Gradišnica and Gašpinova Jama, on the contrary differences are significant for major part of the year.

Hence, interpretation of hydrodynamic of the underground water in the area between Gradišnica and Gašpinova Jama is mainly based on fluctuations of water temperature, due to the fact that both caves lie within part of the aquifer with uniform water table. Water table and especially thermal characteristics of both caves were studied at different water conditions at the polje, which greatly govern the recharge of both caves.

Low water conditions in the Planinsko polje

- Examples of stage hydrographs from Gradišnica and Gašpinova Jama at low water conditions in Planinsko polje

Examples are from November 2006 (Fig. 7.28) and July 2007 (Fig. 7.29). Water table between Gradišnica and Gašpinova Jama rose for 10 m in November 2006. Some small surface flood pulse occurs in the polje after the storm event, but maximal value of flow rate of the Unica remains low (bellow 15 m^3/s). Consequently there is absolutely no statistically significant correlation between flow hydrograph of the Unica River and stage hydrograph of the Gradišnica at all (r = 0.43).

Comparable flood pulse as was recorded in Gradišnica in the November 2006, was recorded in the cave also in July 2007. Important hydrological difference occurs in Planinsko polje. Depending on the spatial distribution of some moderate rain, discharge of the surface Unica River may increase (e.g. November 2006) or it may not increase at all after the rain (e.g. July 2007). However, the Unica did not induce any increase of water level in Gradišnica and Gašpinova Jama in neither example.

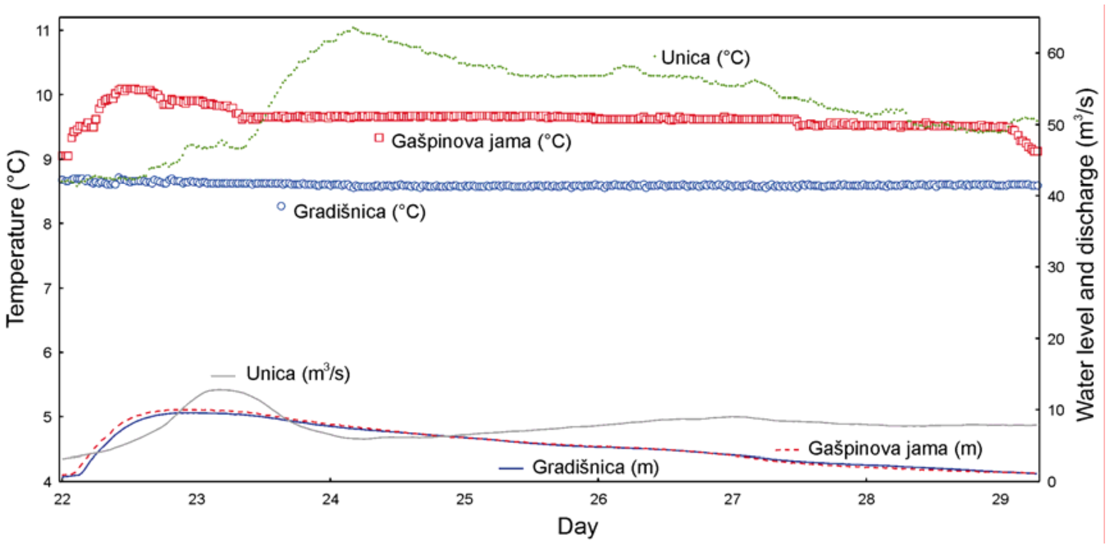

Figure 7.28: Hydrographs from November 2006

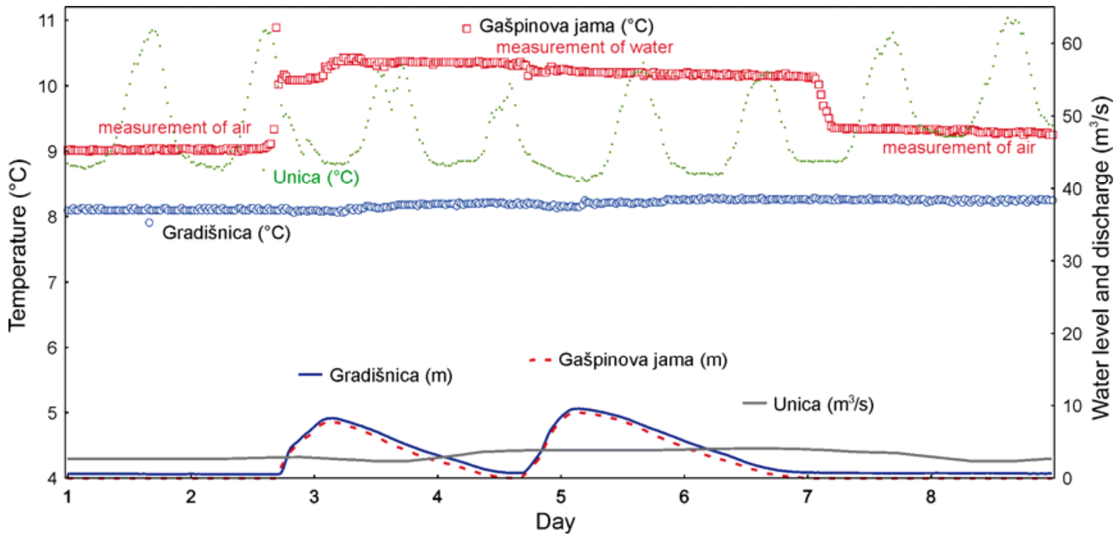

Figure 7.29: Hydrographs from July 2007. Note that data logger is above water table at base flow conditions in Gašpinova Jama and it measures temperature of air instead of water!

Part of the aquifer, where both caves are situated, was presumably fed by flood waters of Hotenka and Logaščica Streams (Fig. 7.4) and also by autogenic recharge. Discharge of both surface streams, which very probably recharge this part of aquifer (Gams, 1974; Gospodarič & Habič, 1976), is unknown for this time period. Anyway it is assumed to be relatively low. Discharge of Hotenka and Logaščica Streams has magnitude a few m^3/s after the storm event (Gospodarič & Habič, 1976). Therefore flood inflow of both known underground streams to the aquifer and contribution of autogenic recharge (at some moderate rain) could be supposed as low. Important input may come from Hrušica Mt., where also all water disappears underground like autogenic recharge.

However, fluctuations of water level are relatively high (around 10 m), especially regarding to low discharge of discussed sinking streams. Fluctuations are high also in comparison with fluctuations in Vetrovna Jama and Najdena Jama.

A concept which could explain such behaviour would include a hydrogeological barrier downstream from Gradišnica and Gašpinova Jama in direction toward springs of the Ljubljanica (Fig. 7.30). Such barrier would induce high fluctuations of a water level in some caves in the upstream part (such as in Gradišnica and Gašpinova Jama). Distance between Gradišnica and Gašpinova Jama is relatively short and hydraulic gradient between them is low. While Vetrovna and Najdena Jama are situated at higher altitude and therefore are not under hydraulic influence of such hydrogeological barrier.

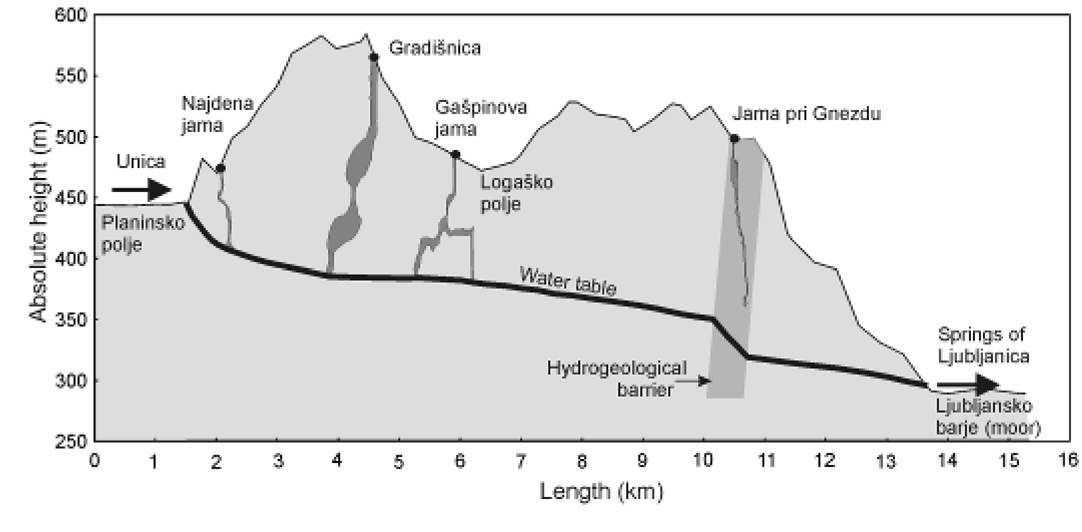

Figure 7.30: Cross-section through discussed aquifer (connect caves number 1, 2, 3 and 5 in figure 7.5). Also Jama pri Gnezdu is represented on this figure (it is marked with No. 5 in Fig. 7.5). This cave developed in Jurassic dolomite, which may represent a barrier for underground flows in the aquifer (see Fig. 7.5). Observe also reconstruction of water table at base flow. Reconstruction among upstream three caves (Najdena Jama, Gradišnica and Gašpinova Jama) is based on measurements, while it is hypothetic downstream in direction toward springs.

Medium water conditions in Planinsko polje

- Examples of stage hydrographs from Gradišnica and Gašpinova Jama at medium water conditions in the Planinsko polje

Relation between flow hydrograph of the Unica obtained at Haasberg and stage hydrograph from Gradišnica (Gašpinova Jama) may become statistically significant (r is above 0.9) at medium water conditions; as can be seen from example of first half of January 2007 (Fig. 7.31). Conclusion would be that at this certain flood event, Gradišnica and Gašpinova Jama were not fed only by flood waters of underground streams (the Hotenka, the Logaščica) and autogenic recharge, but also by flood waters of the Unica River, which drains from eastern ponors (see previous chapter No. 7.9).

Increase of water table usually occurs in two phases at medium water conditions (example first half of January 2007). It was has been already discussed in previous chapters. In first phase water table responses and rises because of flood inputs other than that of the Unica and maybe also because of autogenic recharge (marked with No. 1 in Fig. 7.31). Very similar process is at low water conditions (see example from November 2006 in Fig. 7.28). The underground Unica deriving from eastern ponors feeds part of the aquifer with two discussed caves later, in next phase (marked with No. 2 in Fig. 7.31).

Very distinctive is example from September 19th-22nd 2007 (Fig. 7.32), which has been already discussed in chapter No. 7.8. Water retention time of the underground Unica arriving from eastern ponors should be longer or response of the surface Unica to the storm event is longer, than response of some other streams (with non karstic catchment area), due to usual time delay of such secondary peaks.

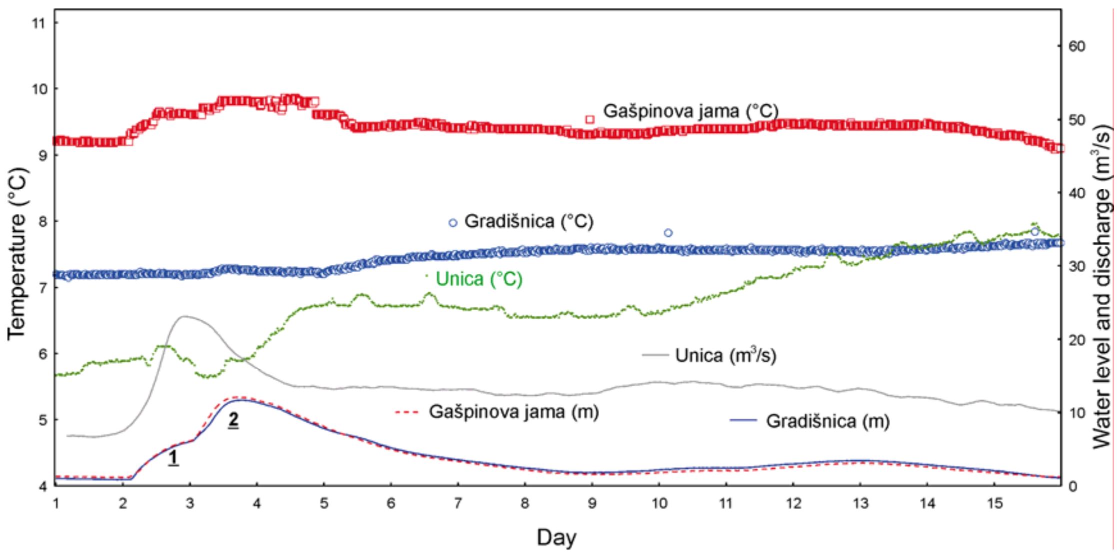

Figure 7.31: Hydrographs from January 2007. Peak marked with No. 1 represents flood inflow of different origin than peak marked with No. 2.

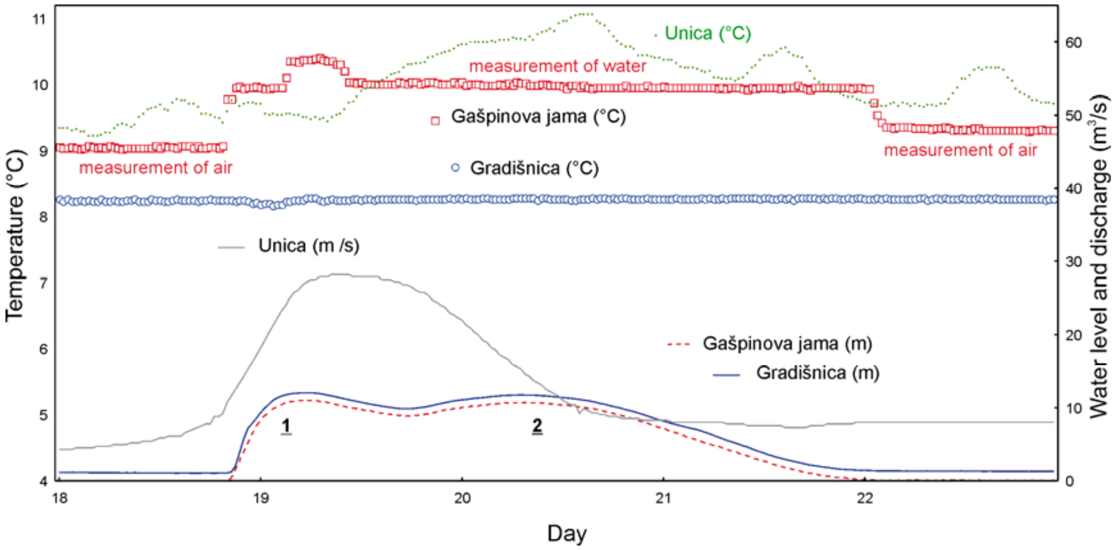

Figure 7.32: Hydrographs from September 2007. Note that data logger is above water at base flow conditions in Gašpinova Jama and it measures temperature air instead of water! Peak marked with No. 1 represents flood inflow of different origin than peak marked with No. 2.

- Temperature characteristics of underground water in Gradišnica and Gašpinova Jama at low and medium water conditions in Planinsko polje

Temperatures of underground water in Gradišnica and Gašpinova Jama are significantly different and they show no relation with temperature of the surface Unica River measured at Haasberg at discussed water condition. However, some fact of monitored locations should be taken into consideration.

Temperature of underground water does not fluctuate at all in Gradišnica, it is stable, around 8.2°C. Monitored lake in Gradišnica represents a shaft or piezometric level of water table (Fig. 7.33). Majority of drainage probably takes place in phreatic conduits, which are situated at least a few metres below this lake. Temperature of water may fluctuate much more at well drained zone, than in some shaft, where water is stagnant and therefore relatively immobile. Even if flow of surface origin (whether the Hotenka or the Unica), with characteristic temperature record, recharges discussed part of the aquifer (Gradišnica respectively), its temperature influence can not be detected at monitoring station in Gradišnica (at low and medium water conditions), because of the discussed reason (Gabrovšek, 2008).

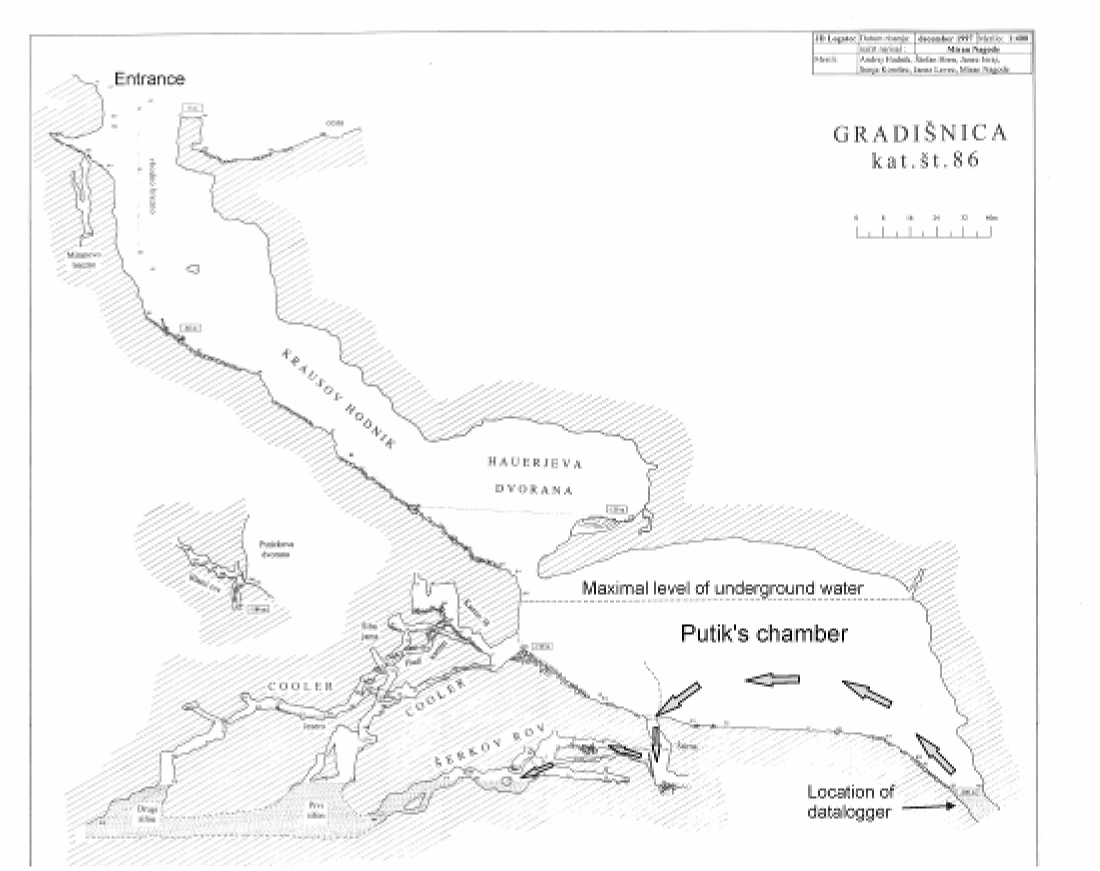

Figure 7.33: Sketch of longitudinal cross-section of Gradišnica with measuring station marked and direction of underground drainage (arrows), which can explain appearance of diurnal variations at the location of data logger at certain water conditions only (adapted from Nagode, 1997, modified).

Temperature variations are relatively small also in Gašpinova Jama. First it should be mentioned that we do not know always exact temperature of base flow in Gašpinova Jama. Data logger was installed into the cave not exactly at the base flow conditions, hence water table decreases for a metre or two bellow the height of data logger during the base flow. Data logger measures temperature of air at such conditions (Figs. 7.29 and 7.32). We assume that temperature of base flow is around 9.6°C, hence a little higher than air temperature, which we measure in such a case. However, temperature of water may fluctuate from 9.2 to 10.4°C at low and medium water condition, according to our measurements. Therefore, it may be assumed that water in monitored lake of Gašpinova Jama is well mixed, in comparison with

Gradišnica, i.e. we probably do not monitor shaft of stagnant (immobile) water such as in Gradišnica. But water in monitored lake in Gradišnica is stagnant at low and medium water conditions only, as will be discussed in continuation. Relatively low thermal variations of underground water in Gašpinova Jama can be explained by long retention time of underground water flow.

Water temperature in Gašpinova Jama is surprisingly higher than in Gradišnica, generally for around 1.5°C, the highest measured difference at medium water conditions was almost 3°C (Fig. 7.32). Data loggers are well synchronized, so differences are not a consequence of an error of the device. Error may be 0.1°C and certainly not higher.

Differences may be hypothetically argued by different morphology of two caves. Entrance to Gašpinova Jama is hundred metres deep sub-vertical crack, which was artificially enlarged. Crack ends in epiphreatic conduit system of Gašpinova Jama. Thermal influence from the surface is totally negligible, because of such morphology of the entrance. Monitored location is around five hundred metres south west from the location, where enlarged crack enters the conduit. The most southern known pool was monitored in Gašpinova Jama. No other known connections with the surface exist in the south part of the cave.

Entrance to Gradišnica is totally different from the entrance to Gašpinova Jama. More than 200 m deep shaft has dimensions of 20 x 40 m (Marrusig & Velkovrh, 1957) (Fig 7.33). Influence of cold air, which descents down the shaft and displaces the warmer air at the bottom of the cave, can be significant, but in the cooler part of the year only. Air does not circulate in the cave in the warmer part of the year, summer respectively. Influence of air circulation may have important role on temperature when data logger is near the surface of water table, but no role, when water table rises for several metres above the data logger.

The problem is that our measurements do not show cooling of water by cold air fluxes. Moreover, the temperature differences between two caves occurs independent on season. They can not be explained with air circulation in Gradišnica in the warmer part of the year, especially in the summer. So the thermal differences of two caves can not be reliably explained yet.

High water conditions in Planisko polje

- Examples of stage hydrographs from Gradišnica and Gašpinova Jama at high water conditions in Planinsko polje

Recharge characteristics are similar as at medium water conditions in first phase. Water level in Gradišnica and Gašpinova Jama begins to increase, before flood water of the underground Unica reaches the area. First flood input is by secondary inflows and autogenic recharge. In next phase two flood inputs of the underground Unica are distinguished, due to recharging eastern and northern groups of ponors. These two underground flows reach the area of Gradišnica and Gašpinova Jama at different times. Hence they can be distinguished on the hydrograph. However, flood inflow of the Unica River, which drains through northern ponors and caves along northern margin of the polje (such as Najdena Jama) is a major one in discussed part of the aquifer.

There are two examples, from December 2006 (Fig. 7.34) and from end of January 2007 (Fig. 7.35). Relation between flow hydrograph of the Unica River (measured at Haasberg) and stage hydrograph in discussed part of aquifer is statistically very significant at flood inflows, which occur at high water conditions in the polje (r = 0.96).

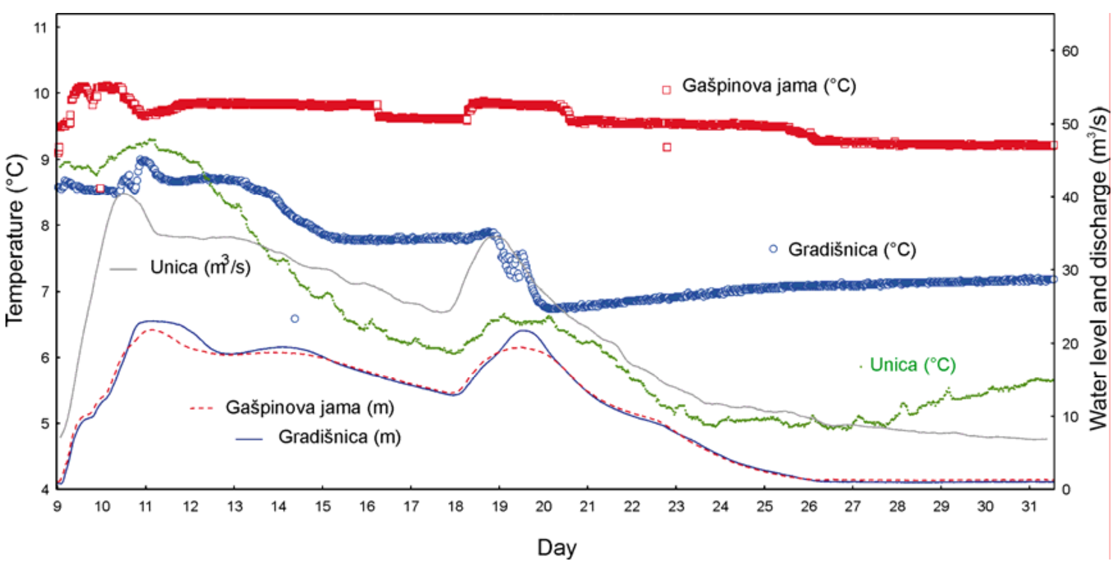

Figure 7.34: Hydrographs from December 2006

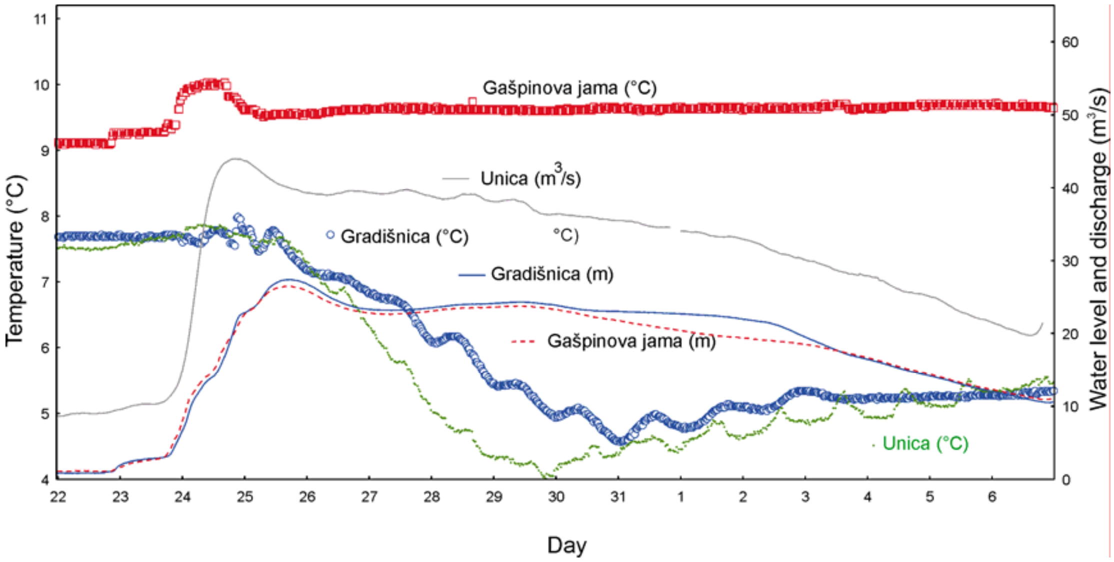

Figure 7.35: Hydrographs from January-February 2007

- Water temperature in Gradišnica and Gašpinova Jama at high water conditions in Planinsko polje

Temperature of underground water remains stable in both caves during first phase of flood inflow. Flood input of the Unica River, arriving in last phase from northern ponors, changes water temperature in Gradišnica only. Water temperature in Gradišnica have similar negative trend as the surface Unica River in December 2006 (Fig. 7.34), but diurnal variations do not occur. Variations occur during January 2007 flood pulse (Fig. 7.35). Hence, significant change of temperature of underground water occurs in Gradišnica at high water conditions.

There is significant relation among occurrence of diurnal variations, height of water level in caves and discharge of the Unica River (at the surface). Some patterns may be observed. For example, the underground water in Gradišnica has equal thermal trend as the surface Unica, when water level increases for 18 m above the level of data logger. Diurnal variations occur, when level reaches relatively height approximately 23 m. However water levels are also directly associated with discharge of the surface Unica River. For example, it may be observed that temperature influence of the underground Unica begins to diminish in Gradišnica, when discharge of the Unica River (at Haasberg) decreases below 30 m^3/s (see example December 20th in Fig. 7.34, examples are even more distinctive at extreme high water conditions, described in the continuation). It is also the lowest boundary flow rate, which still enables the Unica to recharge northern ponors in the polje.

Occurrence of diurnal variations in Gradišnica most probably depends on drainage of underground water in monitored lake. Majority of drainage in Gradišnica takes place through conduits, which are situated at unknown depth below the monitored lake. This happens at relatively lower flow rates and water levels as was already discussed. Monitored lake behaves as a shaft of stagnant water, where temperature of water is stable, regardless to temperature of the water in conduit below.
However, diurnal variations express at higher underground flow rates of the Unica, when water begins to circulate also within monitored lake (shaft). Underground water drains over data logger up to the Putik's chamber and it feeds another shaft at downstream part of the chamber (Fig. 7.33, see arrows, which indicate direction of water drainage through Putik's chamber). Water level in Gradišnica should be at least 18 m above data logger, to enable such circulation. Also this fact proves the reliability of this explanation.

In contrast with Gradišnica, the underground Unica River does not have any influence on water temperature in southern lake of Gašpinova Jama (examples are floods from December 2006 and end of January 2007, Figs. 7.34 and 7.35). Water temperature remains relatively stable; changes are temporally short and low. Temperature characteristics of water at high water conditions are similar as at low and medium water condition in Gašpinova Jama. Water temperature stabilizes somewhere between 9.6 and 10°C (data are for cooler part of the year only).

Difference between water temperature in Gradišnica and Gašpinova Jama can be very significant. Example is from end of January 2007 (Fig. 7.35). The surface Unica River was the most important input into Gradišnica, as usually at such water conditions. Water level increased for almost 30 metres; consequently diurnal variations occur in Gradišnica. The surface Unica cooled significantly in six days, consequently also water in Gradišnica cooled for 3°C in the same period. In the same period, temperature changes of water in Gašpinova Jama were low. Water in Gašpinova Jama was for 4 °C to 5°C warmer than water in Gradišnica, at the end of discussed flood event, when difference increased the most.

Similar difference may be observed in December 2006 (Fig. 7.34). Temperature of underground water in Gradišnica stabilizes at 7°C after the December 22nd. Underground water in Gradišnica was more than 2°C cooler than water in Gašpinova Jama.

Differences can be hardly explained by air circulation in Gradišnica. As already discussed, cool air really descents down the shaft and it may cool underground water, but in the cooler part of the year only. Moreover, air probably cools the most upper level of underground water only. Data logger was usually at least a few metres below the piezometric at such conditions.

Water should come into Gašpinova Jama also from Gradišnica. But due to the difference of water temperature (Figs. 7.34 and 7.35), waters of at least two important sources should not mix together at the monitored location in Gašpinova Jama. Portion of water flow, which drains from Gradišnica to Gašpinova Jama, is unknown. Inflow, which feeds Gašpinova Jama presumably from west should prevail at this certain location (the Hotenka or the Logaščica?, see Fig. 7.4). It has temperature dominance in Gašpinova Jama (at least at the location of data logger).

Extreme high water conditions in Planinsko polje

- Examples of stage hydrographs from Gradišnica and Gašpinova Jama caves at extreme high water conditions in Planinsko polje

Underground flow of the Unica River, which drains from northern ponors through Najdena Jama and neighbor caves toward Gradišnica, has high magnitude and is relatively rapid. Flow rate of the underground Unica has presumably range between 20 m^3/s and 40 m^3/s, which is supposed maximal swallow capacity of northern group of ponors (Šušteršič, 1982). All other inflows are of minor importance at such conditions. Huge flood inflow forces water level to increase above 30 m and up to 48 m in the aquifer.

As discussed, fluctuations of water level are synchronic in Gradišnica and Gašpinova Jama. Differences appear in relative rise of water level, which is usually relatively higher in Gradišnica (for a metre or two). Differences increase at high and extreme high water conditions. The highest difference was 5 m, as can be seen from peaks of hydrographs in Fig. 7.36.

Hence hydraulic gradient between Gradišnica and Gašpinova Jama varies with the absolute altitude of the water level in both caves. Gradient is much higher at extreme high water conditions (0.0056), than at low water conditions or base flow (around 0.002) (Fig. 7.37).

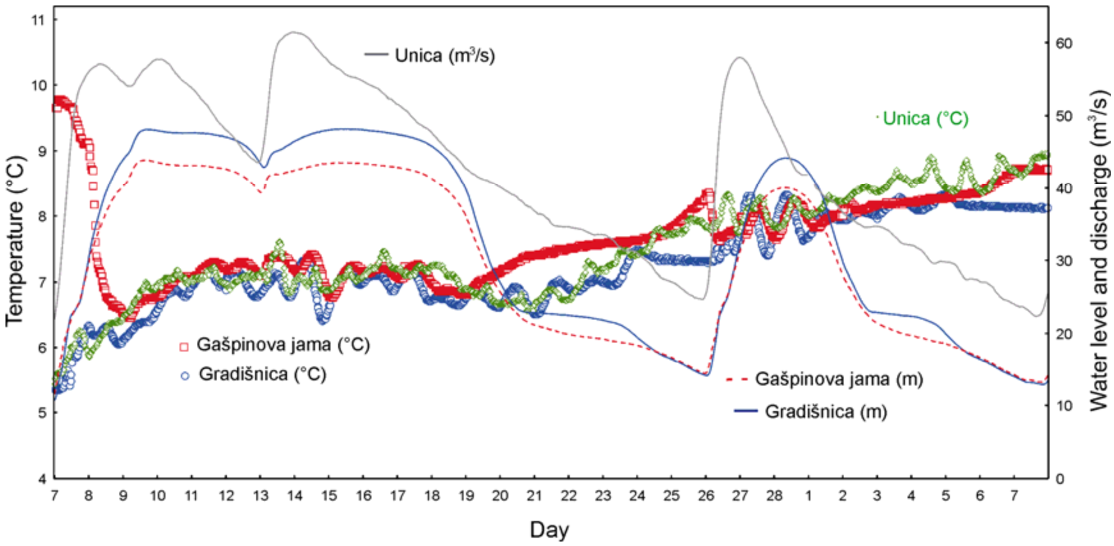

Figure 7.36: Flood pulse in February-March 2007

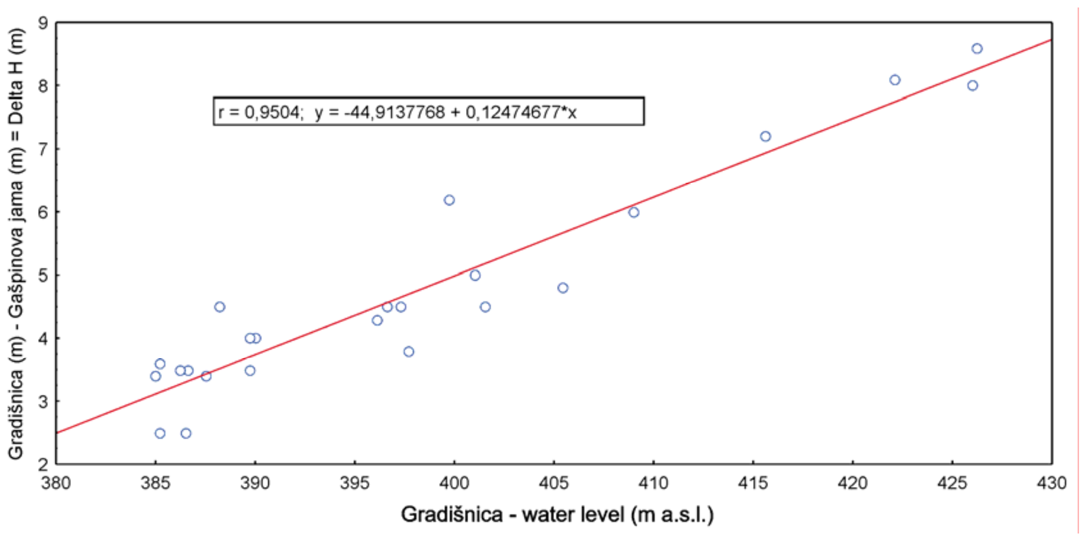

Figure 7.37: Difference of water level between Gradišnica and Gašpinova Jama depends on water conditions in the aquifer. Higher water conditions are, higher is difference and also hydraulical gradient is higher. Relation is almost linear.

Moreover, recession of water between certain levels (23 m to 17 m) is different in Gradišnica than in Gašpinova, as can be seen from Fig. 7.36 also. Recession is significantly slower in Gradišnica than in Gašpinova Jama. Putik's chamber appears in Gradišnica at this relative altitude. Chamber represents a great reservoir for flood water (Fig. 7.33). Velocity of emptying of such reservoir is relatively slow.

- Water temperature in Gradišnica and Gašpinova Jama at extreme high water conditions in Planinsko polje

The Unica River predominates also thermally in greater part of aquifer between Gradišnica and Gašpinova Jama, at the highest discharges. Distinctive temperature characteristics occur also in Gašpinova Jama. However, duration of inflow with high flow rate should last a few days at least. Otherwise diurnal temperature variations do not express completely neither in Gradišnica and even less in Gašpinova Jama.
Temperature of underground water is similar in both discussed caves at the highest flood pulses. However, frequency of such pulses is relatively rare.

If diurnal temperature variations occur in both caves, transit time of water from Gradišnica to Gašpinova Jama may be determined. Each diurnal temperature maximum or minimum recorded in downstream Gašpinova Jama, has some phase shift due to the same maximum or minimum recorded in Gradišnica. Temperature signal is transmitted between two stations by advection in draining water. Time delay between its appearance in discussed caves is supposed to be equal to transit time of water between two measuring stations. Also mean flow velocity can be calculated. Water traveled between discussed caves exactly 4.5 hours, during February flood pulse (Fig. 7.36). Mean velocity of water flow was approximately 350 m/h.

8. GENERAL CONCLUSIONS AND FURTHER PERSPECTIVES

Caves are integral part of karst conduit system. We showed that caves of the epiphreatic zone are suitable points for observation of groundwater dynamics in karst aquifers. Applied data loggers were found appropriate devices to measure physical parameters in caves. The measurements are accurate and trustworthy enough.

Measured parameters (level and temperature) are affected by the recharge – discharge conditions and aquifer's geometry. We have applied several methods to analyse the data. Some of them have been more successful, some less. But we must stress that we mainly indicate new approach in the karst hydrogeology (based on measurements with automatic devices directly in well permeable structures of the aquifer) and we demonstrated the potential use of the obtained data. Still, the exact methodology should be developed in the future.

In the local scale, we have tools and modeling skills to do it. However, a special challenge is posed by regional scale studies, where numerical modeling can not predict huge complexity and variability of aquifer.

On the local scale, we studied hydraulics and transport properties of the underground Pivka River. It shows out that the Martel's rock-fall is the most important hydraulic restriction in the system. We also applied computer program SWMM to simulate hydraulic processes within the conduit system. This program has great potentiality for modeling conduit flow. But it should be re-programmed for karst areas, as it does not enable lateral exchange of water between conduits and matrix, which may be important in some karst aquifers. It would be interesting also to enable dissolution processes along the pipe (conduit) system.

We built also simple model, to predict water level - discharge relation for each of monitored location. The model based on machine learning algorithms predicts hydraulic response of the system with high certainty.

Natural tracer - water temperature was applied to asses flow velocities at all possible flow rates. Artificial, water soluble tracer was injected to the underground Pivka, to asses flow velocity at certain discharge conditions. Maximum determined velocity of water soluble tracer (first arrival of the tracer) is equal to velocity of temperature signal.

Water transit time and flow velocity are two parameters, which are very important to validate vulnerability of the aquifer to pollution. Flow velocity varies significantly from location to location within the underground system (at constant discharge). Hydraulic gradient and conduit cross-section are highly variable parameters in the system, which may explain some of local variations in water transit time (flow velocity).
We attempted to determine equilibrium temperature between water and bedrock, sediments (hyporheic zone). A lot of work still waits to be done on this field, as only numerical modeling can give adequate solution of this problem. Model to study thermal processes within the Postojnska Jama system is already in progress; however some solutions may remain also for the near future.

We monitored four arbitrarily selected caves in the region between Planinsko polje and springs of the Ljubljanica River. However, there are more known water caves, but all other are situated directly at the margin of the aquifer (mainly at the margin of Planinsko polje).
The most problematic is the characterization of Vetrovna Jama. We stressed several hypotheses to explain characteristic hydraulic response of the Vetrovna Jama. But final conclusions can not be made, without additional measurements. Hence future work should be focused on monitoring of all important eastern ponors, synchronically with monitoring of water in Vetrovna Jama. We did not know which and how many ponors were active at certain discharge condition, what may be crucial information for evaluation of recharge into Vetrovna Jama. So far we do not know, if characteristic hydraulic response may be a consequence of steady flow through ponors.
We think that Vetrovna Jama should be monitored simultaneously also with Logarček cave (situated between ponors and Vetrovna jama) in the future, to validate its real representativity. It was also one of the main purposes of the research to study its representativity, based on measurements at few locations only within the aquifer. Measurements from Najdena Jama, Gradišnica and Gašpinova jama looks like representative.
Also tracer test may be performed. Tracer should be injected into Laška žaga and Dolenje Loke ponors. It would be interesting to see if water from Laška žaga really flows to Gradišnica and it avoids Vetrovna Jama. Tracer injected into Dolenje Loke

should appear in both caves, to confirm hypothesis about lateral drainage through hydrogeological barrier oriented S – N (Slavendol fault?), which may induce increase of water level in Gradišnica. However, such tracer tests are almost impossible to perform so far with available equipment, due to logistic problems.

One of the important findings is quite reliable occurrence of hydrogeological barrier downstream from all discussed caves. Belt of Jurassic dolomite may represent such a barrier, as it is relatively less karstified in comparison with limestone (Jurassic and Cretaceous).

There is a large chamber in Gradišnica, called Putik's chamber, which is also filled with water at high floods. Significance of this chamber can be seen on recession part of the hydrograph, when recession slows down because of the morphology of large chamber.

However to characterize entire aquifer with such measurements, several new water caves should be discovered in this aquifer, especially in the northern part of the area, where water has not been reached in no one cave yet. The most perspective and interesting of such caves is probably Jama pri Gnezdu. Flood mud was found at the known bottom of this cave at absolute altitude 366 m (Čekada et al., 2000), hence it looks like that bottom already belongs to the top of epiphratic zone. But to enter phreatic zone, bottom should be deepened by digging.

One of the questions is how to connect and transfer findings from local scale study to regional scale study. Findings are not very compatible from hydraulical point of view. System studied on local scale was short (around 3.5 km). Inflow is relatively uniform and underground flow is obstructed by local hydraulic restrictions exclusively. While distances among caves studied on regional scale are of a few km and recharge is far from uniform. Hydraulic response of studied caves is greatly induced by regional geological structure of the area (regional hydrogeologic barriers respectively).

However, we can apply thermal characteristics of Postojnska jama also in some other aquifers, even in such as ours studied on regional scale. Flood input of surface water, which enters the aquifer can alter temperature field of rock-mass enormously, under condition that temperature of inflowing water is very different than temperature of underground massif. Allogenic recharge has strong influence on thermal characteristic of Postojnska Jama system, which is relatively short and underground flow takes place mainly through one conduit. Similar thermal characteristic were observed also in caves studied on regional scale. But we should take into consideration that underground drainage diverges to numerous conduits there and distances are much longer.

9. POVZETEK

9.1. Definicija kraškega vodonosnika in njegove značilnosti, ter pomen

Kaj pravzaprav je vodonosnik? Vodonosnik je v osnovi geološka struktura v kateri se nahajajo večje količine vode. Voda v njem ni le shranjena, skozenj se tudi pretaka, predvsem pa so njene zaloge dovolj velike da je možno vodo ekonomsko upravičeno črpati (White, 1988; Ford & Williams, 1989).

Posebnost kraškega vodonosnika v primerjavi z medzrnskim je, da se je razvil v vodo topnih kamninah. Velika glavnina pretakanje podzemne vode se skozi t.i. kanale, ki so nastali iz manjših razpok zaradi raztapljanja okoliške kamnine. V vodonosniku se lahko razvije mreža velikih kanalov, skozi katere se voda pretaka izredno hitro, takšen vodni tok je turbulenten (Worthington et al., 2000; White, 2002).

Vodonosniki z medzrnsko poroznostjo so homogeni, zato je tok vode v njih laminaren in razmeroma enostavno predvidljiv. Opišemo ga lahko z Darcyjevim zakonom, ki pravi da je pretok skozi nek presek odvisen od hidravlične prevodnosti poroznega sredstva in hidravličnega gradienta.

Hidravlična prevodnost zrelih kraških vodonosnikov je nasprotno izredno anizotropna in heterogena. Razlog je v velikih kanalih, ki so sicer razmeroma redko razprostranjeni tudi v zrelih kraških vodonosnikih. Njihova prostorska razporeditev je običajno popolnoma neznana, zaradi česar je preučevanje takšnih vodonosnikov še dodatno oteženo.

Kraški vodonosniki imajo dvojno ali trojno poroznost, odvisno od njihove razvitosti. Trojna poroznost, ki je značilna za zrele kraške vodonosnike, je sledeča (Bonacci, 1987; White, 1988, 2002, 2003; Ford & Williams, 1989; Brenčič 1994; Motyka, 1998; Ralston, 2000):

- Medzrnska poroznost

Majhne praznine v kamnini, ki so nastale že v času med njeno litifikacijo (primarna poroznost) ali pa kasneje v času diageneze (sekundarna poroznost). Delež medzrnske poroznosti je torej odvisen tudi od starosti kamnine.

Takšne majhne pore ne prevajajo vode, razen če so med seboj povezane, pa še takrat v izredno majhnih količinah. Pač pa se v porah voda predvsem skladišči.

- Razpoklinska poroznost

Primarne razpoke so zelo ozke, premer njihovega ustja se giblje med 50 in 500 µm. Z raztapljanjem se razpoke večajo in sčasoma preidejo v kanale, ko premer preseže 1 cm. Razpoke nastanejo tudi ob raztapljanju kamnine vzdolž lezik ali vzdolž drugih mikrostruktur. (Bonacci et al., 2006).

Prevodnost razpok je lahko zelo različna, odvisna je od velikosti ustja razpoke, njene dolžine, širine, vijugavosti in hrapavosti sten (Motyka, 1998). Širina posamezne razpoke se lahko zelo spreminja, saj je odvisna od hrapavosti sten razpoke (Schwartz & Zhang, 2003). Tok vode skozi razpoke je laminaren (White, 2002). Kamnine z razpoklinsko poroznostjo smatramo za zmerno vodo prepustne (Gospodarič & Habič, 1976).

- Kanalska poroznost

Kraški kanali so lahko zelo različnih premerov. Kanali nastanejo z raztapljanjem iz razpok, v hidrološkem smislu pa se od njih razlikujejo predvsem v tem da vodni tok skoznje ni več laminaren pač pa turbulenten. Turbulentni tok se pojavi pri premeru cevi večjem od približno 1 cm (White, 2002), toliko tudi znašajo premeri najmanjših kanalov, največji premeri pa navzgor praktično niso omejeni. Premer kanalov običajno znaša nekaj metrov, v izjemnih primerih pa celo več 100 m. Dolžina kanalov na krasu običajno znaša nekaj kilometrov (Bakalowicz, 2005).

Kanali so sicer redko razporejeni v kraškem vodonosniku, predstavljajo le nekaj odstotkov celotnega vodonosnika, vendar prevajajo kar 90 % ali več vode, ki se pretaka skozenj (White, 1988; Worthington et al., 2000). Kamnine, v katerih se pojavljajo kanali, so torej izredno dobro vodo prepustne.

Kraški vodonosniki se torej razvijejo v vodotopnih kamninah in imajo kot rečeno vsaj dvojno ali pa trojno poroznost zaradi česar so heterogeni in anizotropni. Voda, ki raztaplja kamnino vzdolž lezik ali mikrorazpok, hkrati tudi širi njihov premer. Hitrost teh procesov se s časom spreminja, vendar na splošno velja da potekajo

razmeroma hitro v primerjavi z običajnimi geološkimi procesi. Kraški vodonosnik z dobro razvito mrežo kraških kanalov se lahko razvije v časovnem razponu od nekaj 100.000 let pa le do približno 10.000 let, kot so pokazali nekateri numerični modeli (Dreybrodt et al., 2005).
Vodni tok in transport v kraškem vodonosniku sta neposredno povezana s prostorsko razporeditvijo in geometrijo kraških kanalov. Kanali se razvijejo vzdolž glavnih smeri pretakanja vode (Bakalowicz, 2005). Voda raztaplja in širi predvsem tiste razpoke in mikrostrukture, ki so orientirane v enaki smeri kot lokalni hidravlični gradient in ki se nahajajo približno v nivoju vodne gladine podzemne vode (Kiraly, 2002). Takšne prevodne strukture so razmeroma redke, če primerjamo njihov delež s celotno prostornino vodonosnika. Posledično v kraških vodonosnikih v nasprotju z drugimi vodonosniki ni možno določiti neke reprezentativne elementarne prostornine.

9.2.Hidrogeološki pomen jam

Jame so ene najbolj značilnih geomorfoloških oblik, ki se pojavljajo v neki dobro razviti kraški pokrajini. Vodni tok v jamah je zelo lokaliziran, režim pretakanja je turbulenten. Za jame lahko štejemo tiste odseke kraških kanalov, ki so dovolj veliki da jih je možno fizično raziskovati. Dimenzije kanala morajo znašati vsaj 0.5 m. Vendar jame običajno predstavljajo le manjši delež celotnega kanalskega sistema v vodonosniku (pogosto celo manj kot 1 %; White, 2002). V jame običajno vstopamo prek ponorov ali izvirov (Sl. 1). Do podzemno vode lahko nemalokrat dostopimo tudi skozi različna brezna. Takšna vodna jama se obravnava kot samostojna jama, dokler ni fizično dokazana povezava s sosednjo ponorno ali izvirno jamo.

Jame torej predstavljajo povezan sistem kanalov, ki prevajajo veliko večino podzemne vode v kraškem masivu. Skoznje se lahko pretaka voda iz celotnega porečja, zato so pretoki lahko zelo veliki, celo več kot 100 m^3/s. Hitrosti pretakanja so visoke in podobne hitrostim površinskih rek.
V naši raziskavi smo se osredotočili na vodne jame, si se pojavljajo v epifreatični coni kraškega vodonosnika. Epifreatična cona predstavlja prehodno cono med freatično oziroma zasičeno (stalno zalito z vodo) in vadozno oziroma nezasičeno cono (ta ni nikdar poplavljena). Epifreatična cona je torej občasno oziroma vsaj

delno zalita z vodo, ob vsakem padavinskem dogodku. Vodni tok, ki se pretaka skozi kanale epifreatične cone ima lahko bodisi prosto gladino, ali pa gre za tok pod tlakom (posamezni odseki kanala so zapolnjeni z vodo po celotnem preseku) (Bakalowicz, 2005). Vodni nivo lahko niha celo do sto in več metrov v epifreatični coni. Nihanja so odvisna od hidravličnih lastnosti jame (kanalov), tipa napajanja in debeline kraškega masiva. Nihanja vode so izredno hitra, zato jame ne predstavljajo pomembnih skladiščnih struktur (Bonacci et al., 2006).

Jame predstavljajo primerna merilna mesta v kraškem vodonosniku. Najbolj pogosta praksa je bila da so se meritve opravljale na kraških izvirih (Bonacci, 1993; Brenčič, 2002; White, 2002; Kovács, 2003; Toran et al., 2006). Tam pridobljeni hidrogrami in kemogrami nakazujejo lastnosti napajanja vodonosnika in pretakanja vode skozenj. Sklepamo lahko na geometrijo vodonosnika, potovalne čase, izvor vode, tip toka in podobno.

Mi smo merili parametre vodnega toka v jamah in ne na izvirih. Fizikalno-kemični parametri, pridobljeni v jamah, odsevajo hidravlične in deloma hidrogeološke procese, ki se odvijajo neposredno pred in za merilno mikrolokacijo (ter tudi v širšem smislu vodonosnika), ter tudi hidrološke procese na površju, od koder voda v priteka v podzemlje. Vrtine predstavljajo precej manj reprezentativne merilne točke kot jame, saj z njimi le redko naletimo na vodo dobro prepustne strukture, oziroma kanale (White, 2002; Reinmann et al., 2008).

9.3. Ozadje in namen raziskave

Dejstvo je, da je hidrogeološki pomen velikih prevodnikov (jam) na krasu razmeroma slabo poznan. To velja celo za nekatere kraške sisteme, kjer so bile sicer opravljene obsežne raziskave s kombiniranim sledenjem. Razlogov je več, naj izpostavimo le dva med njimi:

- Epifreatična cona kraškega masiva je celo v najugodnejših primerih dostopna le skozi redke lokacije (jame) in še te so običajno tehnično težko dostopne.
- Do nedavnega so bili merilne naprave z dovolj veliko shranjevalno sposobnostjo zelo drage ali pa sploh niso bile dostopne na trgu.

V zadnjem desetletju so postale avtomatske naprave, ki omogočajo zvezno merjenje fizikalno-kemičnih parametrov vode, bolj dostopne (beri cenovno ugodnejše) in na področju hidrogeologije oziroma hidrologije so se pričele razmeroma množično uporabljati. Tudi mi smo se odločili da uporabimo novo opremo za meritve vodnega nivoja in temperature vode na Notranjskem krasu. Merilniki, oziroma data loggerji imenovani tudi »Diver«ji, proizvajalca Van Essen, so bili nameščeni v izbrane jame (Sl. 2). Natančnost temperaturnih meritev znaša 0.1°C, medtem ko znaša natančnost izmerjenega vodnega nivoja ±0.2 % vrednosti merilnega razpona (100 m ali 50 m, odvisno od vrste merilca). Podatke lahko beležimo v poljubnih časovnih razponih. Mi smo merili na vsakih 15 minut oziroma kasneje 30 minut. Merilni razpon je bil v vsakem primeru časovno dovolj kratek, da smo zaznali vse pomembne spremembe v temperaturi vode in njeni vodni gladini.

Število znanih vodnih jam na slovenskem krasu se je v zadnjih letih močno povečalo, kar je posledica predvsem obsežnih speleoloških raziskav, ki jih je omogočila tudi moderna jamarska tehnika.
Zaradi vseh teh dejstev smo menili, da bi bilo smiselno, natančno kot še nikdar dotlej v slovenskem prostoru, preučevati podzemno pretakanje vode v kraškem vodonosniku.

Z našo raziskavo smo si postavili dva pomembna cilja:
1. Izpolniti znanje o hidrodinamiki podzemnega pretakanja v kraškem vodonosniku
2. Prikazati uporabnost nove dostopne merilne opreme v kraški hidrogeologiji. Merilci so sicer prvinsko namenjeni za meritve površinskih vodotokov in podzemne vode v vrtinah. O njihovi uporabnosti v vodnih jamah (oziroma v epifreatični coni kraškega vodonosnika) do sedaj ni bilo mnogo znanega. To je bil prvi primer v Sloveniji, da smo takšne merilce uporabili v takšen namen. Zvezno smo merili kraške podzemne vode, ki napajajo izvire Ljubljanice (Notranjski kras), medtem ko so se meritve podzemne reke Reke (Matični Kras) pričele še kakšno leto prej (Gabrovšek & Peric, 2006) in so potekale časovno daljše obdobje.

Z našimi meritvami smo poskušali preučiti hidrodinamiko podzemne vode v regionalnem merilu. Vsak kraški vodonosnik ima hidrogeološke in hidravlične posebnosti, na katere lahko sklepamo, oziroma jih interpretiramo na podlagi meritev, ali pa s pomočjo matematičnega modeliranja. V kolikor bi želeli kraški sistem idealno preučiti, je zaželeno je podzemni kraški sistem dostopen skozi številne vodne jame, ki so čim bolj enakomerno razporejene po celem vodonosniku. Vendar je resničnost popolnoma drugačna. Podzemna voda je navadno dostopna le skozi redke jame in še te se običajno pojavljajo bolj ali manj zgoščeno na nekem razmeroma ozkem območje.

9.4. Tipi podzemnih tokov

Ločimo dva tipa podzemnega pretakanja: tok v poroznem sredstvu in tok skozi razpoke ter kanale.

Tok v poroznem sredstvu (npr. v medzrnskem vodonosniku) opisuje Darcyjev zakon, ki velja le za laminaren tok (White, 1988, Schwartz & Zhang, 2003). Medzrnski vodonosnik je homogen in anizotropen, zato lahko tok v njem laminaren. Darcyjev zakon pravi da je tok vode skozi porozno sredino premo sorazmeren s pretokom in razliko v višini gladin ter obratno sorazmeren z dolžino poti.

Tok skozi razpoke in kanale je bodisi **laminaren**, ali pa **turbulenten**. Reynoldovo število nam pove kateremu izmed dveh režimov tok pripada (Anwar, 2008). Kadar so hitrosti pretakanja zelo nizke in predvsem kadar premer cevi (razpoke, kanala) ne presega 1 cm, je tok običajno laminaren. Tokovnice pri laminarnem toku so ravne, do mešanja ne prihaja.

Pri večjih hitrostih pretakanja in večjih premerih cevi prihaja do mešanja tokovnic, oziroma govorimo o turbulentnem toku.

Tok v kanalih nadalje delimo še na tok s prosto gladino in tok pod tlakom.

Tok s prosto gladino je zelo podoben površinskim tokovom. Opisuje ga Manningova enačba.

Tok pod tlakom se pojavi, ko se kanal po svojem celotnem preseku zapolni z vodo. Ta tok lahko opišemo z Darcy-Weisbachovo enačbo.

9.5. Vodonosnik preučevan v lokalnem merilu

V lokalnem merilu smo preučevali sistem Postojnske jame, oziroma pretakanje podzemne Pivke skozenj. Pivka ponika v Postojnsko jama na SV obrobju Postojnske kotline, kjer se stikata eocenski fliš in kredni apnenec, v katerem se je jama tudi izoblikovala. Porečje površinske Pivke znaša okoli 300 km^2. Podzemna Pivka pride ponovno na površje v Planinski jami, kjer izvira kot reka Unica. Zračna razdalja med ponorom in izvirom znaša 5,5 km.

Podzemni tok Pivke smo preučevali med ponorom in Pivko jamo. Podzemni kanali večinoma omogočajo obstoj toka s prosto gladino, tok pod tlakom se vrši ob hidravličnih preprekah in še to običajno le ob relativno visokih pretokih. Prepreke večinoma predstavljajo nenadne zožitve ali pa freatične zanke, pogoste prepreke so tudi podori. Freatične zanke se pojavljajo predvsem med Magdaleno jamo in Pivko jamo. Pomembno prepreko predstavlja tudi Martelov podor, ki je zapolnil kanal z gruščem vse do jamskega stropa. Voda se deloma pretaka skozi podorni grušč, obstajajo pa tudi obvozni kanali, nekaj jih celo poznamo.
Pretakanje podzemne Pivke poteka večinoma po enem kanalskem sistemu. Ob višjih pretokih se aktivirajo tudi posamezni sekundarni prevodniki. Najpomembnejši razcep kanalov se pojavlja pred Martelovo dvorano. Tu se sekundarni kanal odcepi od glavnega (Sl. 6.3). Ta kanal prevaja del vode proti Črni jami in se glavnemu kanalu ponovno priključi v Pivki jami (Sket & Velkovrh, 1981; Habič, 1985). Vendar Kraševec (1981) meni da se nekaj vode iz Črne jame pretoči tudi neposredno proti Planinski jami.
Pivka jama se konča s freatično zanko, ki so jo potapljači sicer raziskali (Krivic & Praprotnik, 1975; Vrhovec, 200), vendar povezava s Planinsko jamo še ni bila fizično dokazana.

Povprečni pretok Pivke pri ponoru znaša okoli 4 m^3/s (Gospodarič & Habič, 1976), minimalni so lahko manjši od 100 l/s (npr. poleti ob dolgotrajni suši), maksimalni pa presežejo 60 m^3/s. V sistemu Postojnske jame ni pomembnejših podzemnih dotokov. V Otoški jami Pivko napaja Črni potok, vendar je njegov prispevek k celotnemu pretoku zanemarljiv (v povprečju okoli 100 l/s; Prelovšek, 2009). Podobno velja za izmenjavo vode, ki poteka iz matriksa v kanal. Peterson & Wicks (2005) sta ugotovila da predstavlja dotok vode iz območja matriksa v kanalski prevodnik manj kot 1% vode, ki teče skozi kanal. Tudi prispevek avtogenega dotoka s površja k celokupnemu pretoku podzemeljske Pivke je zanemarljiv.
Na podlagi teh dejstev lahko sklepamo da je pretok Pivke stalen vzdolž podzemne poti Pivke v Postojnski jami. Spreminja se v skladu z nihanji pretoka na ponoru, ki predstavlja daleč najpomembnejši vnos vode v preučevani sistem.

Merilne točke

Vzdolž poti podzemne Pivke v Postojnski jami smo namestili sedem merilcev (data logerjev). Meritve so potekale zvezno, in sicer vsakih 10 min ali 15 min. Zanimala so nas nihanja gladine vode na različnih lokacijah v sistemu, predvsem pred pomembnejšimi hidravličnimi preprekami, kamor smo merilce tudi namestili. Na podlagi temperaturnih meritev pa smo sklepali predvsem na potovalni čas vodnega toka med merilnimi mesti (temperatura vode je bila uporabljena kot naravno sledilo) in na termalne procese v podzemlju (toplotno izmenjavo med podzemno reko in okoliško kamnino, ter hiporeično cono (sedimenti na dnu struge).

Prvi merilec smo namestili v Veliko dvorano, ki se nahaja neposredno za ponorom. Naslednji je bil 700 m dolvodno v Tartaju. Sledili so v Otoški jami (500 m stran od Tartarja), pred Martelovim podorom (600 m od Otoške jame), v Martelovi dvorani (500 m od Martelovega podora), v Magdaleni jami (250 m od Martelove dvorane). Zadnjega smo namestili tik pred freatično zanko, ki predstavlja odtok iz Pivke jame (Sl. 6.3). Ta je bil od tistega v Magdaleni jami oddaljen nekoliko bolj, in sicer 1000 m. Skupna dolžina med najbolj oddaljenima merilcema (pri ponoru in v Pivki jami) je znašala 3500 m, nadmorska razlika med obema merilnima mestoma pa približno 32 m.

Metodologija obdelave podatkov pridobljenih v sistemu Postojnske jame:

- Uporaba računalniškega programa Storm water management model (SWMM)

Namen SWMM je simuliranje pretakanja vode po ceveh. Za sistem Postojnske jame lahko predpostavimo, da se voda pretaka po ceveh različnih dimenzij in te cevi imajo različne padce. Naredili smo zelo poenostavljen model Postojnske jame. V kolikor v takšen model spustimo poplavni sunek, katerega pretoke smo določili z merjenjem pred ponorom, lahko opazujemo odziv modela na nek realističen vnos poplavne vode. Hidravlični odziv modela nato primerjamo z realističnim hidravličnim odzivom, ki temelji na resničnih meritvah. Parametre modela nato spreminjamo toliko časa, dokler se modeliran odziv z zadostno zanesljivostjo ne ujema z realističnim odzivom sistema na poplavni vnos vode. Vendar morajo biti tudi parametri modela čim bolj realistični, oziroma podobnim dejanskim.

- Strojno učenje in rudarjenje podatkov za napovedovanje hidravličnega odziva v Postojnski jami

Prednosti strojnega učenja so da iz podatkov dobimo koristne, pred tem še nepoznane informacije. Med podatki iščemo koristne vzorce in zakonitosti, pri čemer uporabljamo metodo rudarjenja podatkov. Metoda temelji na določenih algoritmih, s katerimi iz velikega števila podatkov izluščimo značilne vzorce podatkov. Za obdelavo podatkov smo tudi mi uporabili omenjeno metodo, ki predstavlja proces v okviru strojnega učenja.

Za analizo podatkov s strojnim učenjem smo uporabili programski paket WEKA. Podatke smo obdelali z metodo regresije.

Regresija temelji na predpostavljanju vrednosti enega izmed atributov (odvisna spremenljivka), na podlagi ostalih atributov (neodvisne spremenljivke). Atribut, katerega vrednosti predpostavljamo, obravnavamo kot ciljnega (oziroma kot razred). Po končani obdelavi podatkov dobimo regresijska drevesa. Odločitvena drevesa nudijo enostavno preglednost nad medsebojno odvisnostjo podatkov. Vsako vozlišče na drevesu predstavlja testiranje atributa, veje, ki se razcepijo iz vozlišča pa rezultat testiranja. Na koncu dobimo liste, ki predpostavljajo vrednosti ciljnega atributa. Kadar so drevesa velika in razpolagajo s prevelikim številom manj pomembnih ali celo nerealnih podatkov, se odločimo za rezanje le teh.

Drugi način prikazovanja podatkov je v obliki pravil, ki predpostavljajo model. Rezultat predpostavlja vrednost ciljnega atributa, pri določenih vrednostih posameznih atributov (neodvisne spremenljivke). Naše podatke smo prikazali v obliki pravil.

- Preučevanje dnevnih temperaturnih nihanj Pivke v Postojnski jami

Površinska Pivka ima temperaturni dnevni višek pozno popoldne in dnevni temperaturni minimum zgodaj zjutraj. Višek je predvsem posledica sončnega obsevanja, medtem ko se ponoči površinska voda ohlaja. Ko Pivka vstopi v podzemlje se dnevna temperaturna nihanja ohranjajo do določene razdalje od ponora.

Vzdolž sistema Postojnske jame smo opazovali pojav dnevnih temperaturnih nihanj. Določen temperaturni višek (ali minimum) potuje od ponora skozi jamo s hitrostjo vodnega toka (Birk et al., 2004). Na vsakem izmed merilnih mest v podzemnem sistemu se temperaturni višek (ali minimum) pojavi z določenim časovnim zamikom glede na mesto vstopa v sistem (ponor) (Sl. 6.5). Z razdaljo se ta časovni zamik veča. Na podlagi časovnih zamikov lahko sklepamo na potovalni čas vode. Ker so razdalje med merilnimi mesti približno znane, lahko izračunamo tudi hitrosti pretakanja vode

med merilnimi mesti. Potovalni čas oziroma hitrost vodnega toka se seveda spreminjata s pretokom.
Ker voda izmenjuje toploto z okoliško kamnino in hiporeično cono, se amplituda dnevnih temperaturnih nihanj v podzemlju zmanjšuje, dokler voda ne doseže temperaturnega ravnovesja z okolico. Tedaj postane temperatura konstantna, dnevna nihanja so izničena. Na podlagi zmanjševanja amplitude dnevnega nihanja v podzemlju, lahko teoretično sklepamo koliko znaša ravnotežna temperatura med vodo in okoliško kamnino za določeno časovno obdobje.
- Sledilni poskus
Glavni namen sledilnega poskusa je bil izvesti primerjavo med potovanjem umetnega, v vodi topnega sledila (sulforodamin G) in naravnega sledila (temperature).

9.5.1. Uporaba SWMM in primerjava modela z dejanskimi meritvami

Za izdelavo modela Postojnske jame z računalniškim programom SWMM smo uporabili 20 kanalov, 4 prelive, 6 veznih zank, 10 velikih vodnih rezervoarjev in eno finalno, izhodno zanko. Model temelji na razmeroma dobro poznani geometriji jamskega sistema in znanih pretokih skozenj. Pomemben parameter je tudi koeficient hrapavosti sten in dna kanala. Ta parameter smo ocenili na podlagi podatkov iz literature (Schultze et al., 2005; Peterson & Wicks, 2006). Uporabili smo dinamičen izračun poplavnega vala, saj ta izračun upošteva tudi tok pod tlakom, energijske izgube in vpliv povratnega toka ob poplavah (Rossman, 2006).
Primerjave med modelom in realnimi meritvami temeljijo na izdelavi grafov, ki za vsako merilno mesto prikazujejo razmerje med višino vode in pretokom (merjenim pri ponoru). Realni podatki kažejo da v Tartarju voda narašča razmeroma linearno s pretokom (Sl. 6.18). Pri pretoku okoli 20 m^3/s krivulja preskoči iz enega linearnega območja v drugo, ki je strmejše. Ta preskok razlagamo z nenadnim dvigom gladine podzemne vode, ki ga povzroči zastajanja dolvodno od Tartarja. Voda lahko zastaja že pred sosednjo Otoško jamo, ker se na tem odseku kanal za kratek čas izrazito zoži. Zagotovo pa voda zastaja pred Martelovim podorom. Vpliv zastajajoče vode bi lahko segel tudi do Tartarja. Zagotovo ta vpliv seže do Otoške jame, kjer imamo podobno zvezo med nivojem in pretokom (Sl. 6.21). Le da se tu preskok iz položnejšega dela linearne krivulje v strmejši del linearne krivulje pripeti pri nižjem

pretoku, okoli 8 m^3/s. Menimo da pri takšnem pretoku voda pred podorom že znatno zastaja.
V SWMM modelu Postojnske jame smo dobili podobno razmerje med nivojem in pretokom za območje Tartarja. Takoj za Tartarjem smo upoštevali zožitev kanala, ki povzroči preskok na modelirani krivulji, ki prikazuje odvisnost nivoja od pretoka. Za model Otoške jame smo želeli da bi bil hidravlično odvisen od prepustnosti Martelovega podora. Vendar smo njegovo prepustnost v modelu precej precenili, saj nismo uspeli modelirati sistema tako da bi povratni tok segal od Martelovega podora do Otoške jame. Ta proces se v resnici zagotovo pripeti.
Geometrija kanalov, ki zapuščajo Martelovo dvorano, je razmeroma enostavna, zato smo lahko model geometrijsko zelo približali dejanskemu stanju. Ob nizkih pretokih vsa voda odteka iz dvorane skozi slap, ki polni razmeroma ozek kanal. Ob povečanem dotoku je prevodna sposobnost tega kanala hitro presežena, zato prične voda v Martelovi dvorani naraščati. Ko enkrat doseže določeno višino, se aktivira dodatni sekundarni kanal, ki se nahaja na višji višini. Ob nadaljnjem večanju pretoka in nivoja pa se aktivira še en kanal, ki se nahaja še na višji višini. Vse to je mogoče razbrati tudi iz krivulje, ki prikazuje razmerje med vodno gladino in pretokom (Sl. 6.24). Ker smo sekundarne kanale upoštevali tudi v modelu, se je modeliran hidravlični odziv iz Martelove dvorane zelo dobro ujemal z dejanskim.
Voda odteka iz Magdalene jame in Pivke jame skozi freatične zanke. Razmerje med nivojem in pretokom je linearno (Sl. 6.30 in Sl. 6.33). Menimo da gre le za nek linearni segment, celotna krivulja pa je v resnici logaritmična ali ima kakšno drugo funkcijo. Kakorkoli že, tudi z modelom smo uspeli dobiti linearno razmerje med nivojem in pretokom. V Pivki jami smo v modelu namesto odtoka skozi freatično zanko uporabili odtok skozi dolgo zožitev. Del odtoka pa se vrši s prelivanjem v drug, dobro prepusten prevodnik. Modelirane vrednosti bi bile praktično enake dejanskim, v kolikor ne bi bile vse nekoliko podcenjene za točno določen faktor (0,5 m).

9.5.2. Napovedovanje hidravličnega odziva sistema na poplavne sunke z uporabo metode strojnega učenja

Hidravlični odziv na merilnih lokacijah je neposredno povezan s pretokom. Za vsako merilno mesto smo pridobili razmerje med nivojem podzemne vode in pretokom. Iz krivulje, ki prikazuje to razmerje lahko odčitamo višino vode pri določenem pretoku. Poznati moramo le pretok na ponoru.

Vhodni podatki nastopajo v stolpcih in vrsticah. V dva stolpca smo vnesli atributa ki sta pretok na ponoru in temu pretoku ustrezni nivo vode na vsakem izmed merilnih mest. Kot vhodni podatek smo uporabili učno množico, ki sestoji iz več kot 20.000 vrstic (vsi možni pretoki in njim ustrezni nivoji na posameznem merilnem mestu). Rezultat modela je množica regresijskih pravil, ki povedo kako se giblje vodni nivo med točno določenim razponom pretoka. Uporabnost pravil, oziroma njihovo ustreznost preverimo na testni množici. V kolikor se model, ki temelji na pravilih ujema s testno množico, to pomeni da so ta pravila zanesljiva in uporabna. Na podlagi njih lahko sklepamo na nihanje nivoja podzemne vode na določeni lokacije, ne da bi tam meritve dejansko tudi izvajali. Seveda pa moramo poznati pretok vode na ponoru. Takšno sklepanje ima določeno zanesljivost, tega dejstva se moramo zavedati. Zanesljivost regresijskih modelov, ki napovedujejo hidravlični odziv na vseh merilnih mestih, je visoka. Zanesljivost je okoli 96 %.

9.5.3. Prenos snovi (mase in toplote) v vodnem toku

V vodi topne snovi in toplota potujeta v vodi s procesom advekcije in disperzije.
Advekcija poteka z vodnim tokom, torej je smer premikanja enaka premikanju vode.
Disperzija je mešanje dveh tekočin z različnimi značilnostmi (toplota, kemična sestava). Disperzija je v bistvu kombinacija kemičnih in fizikalnih procesov (Schwartz & Zhang, 2003).
- Kemični proces je *difuzija*. Primer je zlitje črnila v nek volumen vode. Molekule črnila se sčasoma enakomerno razporedijo po celotnem volumnu tekočine, gibanje je povezano s gradientom koncentracije.
- *Mehanska disperzija* je fizikalen proces. Zaradi lokalnih razlik v hitrosti vodnega toka prihaja do mešanja. Mehanska disperzija poteka v vzdolžni in prečni smeri glede na smer pretakanja vode. Vzdolžna mehanska disperzija je sorazmerna s hitrostjo vodnega toka. Prečna mehanska disperzija poteka v vodoravni in vertikalni smeri vzdolž prečnega preseka vodne poti.

Prenos mase vzdolž odprtega rečnega kanala

Vodotopno umetno sledilo, ki je izlito v vodni tok, potuje vzdolž struge na enak način kot delci vode v tem vodnem toku. Proces disperzija prične potekati takoj po izlitju vodotopnega sledila v reko. Prečno na strugo reke, v obeh smereh (vodoravni in vertikalni), se odvija proces difuzije, ki povzroči da se sledilo enakomerno porazdeli vzdolž celega preseka struge. Disperzija poteka tudi v vzdolžni smeri, vzdolž struge, ta proces je časovno neomejen (Jobson, 1996). Nasprotno pa je prečno mešanje končano razmeroma na kratko razdaljo od vnosa sledila v vodni tok. Koncentracija sledila je enakomerna po celotnem prečnem preseku struge, ko je prečno mešanje končano. Tedaj lahko na kateremkoli mestu v strugi reprezentativno merimo prehod sledila, in izrišemo prebojno krivuljo. Ta prikazuje kako se koncentracija sledila spreminja s časom na merilnem mestu v strugi. Oblika prebojne krivulje je torej neposredna posledica mehanske disperzije, difuzije in advekcije (Anwar, 2008).

Interpretacija prebojne krivulje, ki predstavlja prehod v vodi topnega sledila vzdolž odprtega kanala, temelji na enačbi masnega transporta. Gre za advekcijsko – disperzijsko enačbo, kateri moramo prišteti še izmenjavo z okolico. Mišljena je absorpcija in desorpcija mase na sedimente v rečni strugi in na kamnino ob bregovih, ter difuzni tok raztopine, ki poteka iz struge v hiporeično cono.

Prenos toplote vzdolž rečnega kanala

Za površinske vodne tokove velja da sta enačbi masnega transporta in toplotnega transporta enaki. Razlika je le v izmenjavi z okolico. Ta poteka v obliki izhlapevanja, sevanja toplote, prenosa toplote s kondukcijo (ob stiku z rečnimi bregovi, oziroma z okoliško kamnino) in difuznega toka v hiporeično cono (Sinokrot & Stefen, 1993; Mohrlok & Sauter, 1999; Socolofsky & Jirka, 2004).

Disperzija, ki poteka vzdolž smeri vodnega toka, je zanemarljiv proces za prenos toplote v rekah. Hitrosti pretakanja so razmeroma visoke, predvsem pa je nizek termalni gradient vzdolž rečne struge (Sinokrot & Stefen, 1993; Gu & Li, 2002). Posledično lahko disperzijo zanemarimo pri opisu transporta toplote z vodnim tokom. Ta je odvisen od advekcije in toplotne izmenjave z okolico (hiporeično cono, okoliško kamnino) v sistemu Podzemne Pivke.

9.5.4. Prenos toplote in snovi skozi sistem Postojnske jame kot izhodišče za določitev potovalnih časov in hitrosti vodnega toka

Površinska Pivka ima podobno kot vsi površinski vodotok svoj dnevni temperaturni višek in minimum. Ko tak višek ali minimum vstopi v podzemni sistem, potuje vzdolž njega z vodnim tokom. Na vsakem izmed merilnih mest ga zaznamo z nekim časovnim zamikom, glede na prejšnje, gorvodno merilno mesto. Opazovali smo časovne zamike dnevnih viškov in minimumov pri različnih pretokih. Na podlagi zamikov smo dobili potovalne čase med vsemi merilnimi mesti. Ker so potovalni časi odvisni od pretoka, smo narisali grafe, ki prikazujejo razmerje med potovalnim časom in pretokom (Sl. 6.72). Razdalje med merilnimi mesti so približno znane, zato smo iz potovalne čase pretvorili v hitrosti in narisali še grafe odvisnosti hitrosti od pretoka (Sl. 6.73). Hitrosti so v povprečju najvišje med ponorom in Tartarjem (25 m/min) in se zmanjšujejo proti notranjosti sistema. V povprečju so najnižje med zadnjima dvema merilnima mestoma (Magdalena jama in Pivka jama) – 6 m/min.
Na podoben način smo primerjali še hitrosti vodnega toka v dveh približno enako dolgih odsekih. Prvi odsek je bil med ponorom in Pivko jamo, drugi pa med Pivko jamo in Planinsko jamo. Ugotovili smo da so hitrosti v prvem odseku v poprečju še enkrat večje kot v drugem (Sl. 6.77).
Razlike v hitrostih, ki s pojavljajo na različnih odsekih med merilnimi mesti, so posledica različne morfologije in topografije kanalov, ter pojava hidravličnih preprek. Te vplivajo tudi na hidravlični padec. Hitrosti so najvišje tam kjer ni pomembnih hidravlični preprek in kjer se pretakanje vrši po enem kanalu. Hidravlične prepreke lokalno zmanjšajo hidravlični padec, ker voda pred njimi zastaja in se preko njih preliva. Ko se vodni tok razporedi po širšem območju, oziroma številnih kanalih, se poveča tudi površina kamnine, s katero je voda v stiku. To se pravi da se poveča trenje. Iz teh razlogov je povprečna hitrost vodnega toka na takšnih odsekih manjša.

9.5.5. Primerjava masnega in toplotnega transporta v sistemu Postojnske jame

Sulforodamin G (umetno, v vodi topno sledilo) smo v ponor Pivke izlili ob točno določenih hidroloških pogojih. Pretok Pivke je tedaj znašal 2 m^3/s in je le počasi upadal. Pojav sledila smo opazovali na treh lokacijah v jami, v Otoški jami, v Magdaleni jami in v Pivki jami. Z uporabo programa QTRACER2 smo izračunali povprečne hitrosti sledila, ki jih je to potrebovalo da je doseglo vse tri merilne točke (mišljeno od ponora). Ker razpolagamo tudi s hitrostmi temperaturnega signala pri enakih razmerah (pretoku), smo lahko neposredno primerjali hitrosti potovanja toplote in mase. Ugotovili smo da je prvi pojav sledila (maksimalna hitrost) na merilnem mestu, ki ustreza čisti advekciji, enak hitrosti temperaturnega signala. Povprečna hitrost sledila je neprimerno nižja, tu je potrebno upoštevati tudi proces disperzije, ki je pri temperaturnem signalu zanemarljiv.

9.5.6. Primerjava temperature Pivke na ponoru in v Pivki jami

Pivka, ki v jamo vstopa skozi ponor, predstavlja pomembno temperaturno motnjo za kraški sistem. Poleti se Pivka v jami ohlaja in toploto torej oddaja, pozimi pa se segreva in sprejema toploto od okoliške kamninske gmote. Zanimale so nas predvsem ravnotežne temperature, ki predstavljajo mejo med ohlajanjem in segrevanjem.

Podatki iz let 2007 in 2008 kažejo, da se je Pivka v podzemnem sistemu bolj ohlajala kot segrevala. Njena povprečna temperatura pri ponoru je bila leta 2007 10,4°C, medtem ko je bila v Pivki jami v povprečju hladnejša za 0,7°C. Povprečna letna temperatura pri ponoru leta 2008 pa je znašala 10,08°C, v Pivki jami pa je bila 9,65°C (torej 0,43°C nižja).

Ravnotežno temperaturo med Pivko in okoliško kamninsko gmoto smo poskušali oceniti na podlagi manjšanja amplitude dnevnih viškov in minimumov. Amplituda se manjša z razdaljo od ponora. Sčasoma se amplituda popolnoma izniči, tedaj se vzpostavi ravnotežje med vodo in okoliško kamnino. To se v Postojnski jami pripeti le ob zelo nizkih pretokih.

Ravnotežno temperaturo za neko določeno obdobje smo običajno ocenili tako, da smo izračunali temperaturno razliko med točno določenim temperaturnim viškom (ali minimumom) pri ponoru in v Pivki jami. Upoštevali smo večje število temperaturnih viškov in minimumov. Temperaturna razlika linearno narašča ali upada, oziroma se približuje ničelni vrednosti. Ko linearna krivulja preseka to ničelno vrednost, lahko ravnotežno krivuljo neposredno odčitamo iz grafa (Sl. 6.93) (Gabrovšek, 2006).

Po drugi strani velja da kadar je na primer temperatura dnevnega viška ali minimuma ob vstopu v sistem enaka ravnotežni temperaturi, tedaj se ta višek ali minimum temperaturno ne spreminja vzdolž svoje poti skozi podzemni sistem (Sl. 6.94).
Kakorkoli že, ugotovili smo da z omenjeno metodo ne merimo resničnega ravnovesja med vodo in celotno okoliško kamninsko gmoto, pač pa neko navidezno ravnotežje. To se vzpostavlja le z določeno plastjo v kamnini. Ker se vnos na ponoru temperaturno hitro spreminja, se procesa ohlajanja in segrevanja vode oziroma kamnine, v sistemu Postojnske jame izmenjujeta razmeroma hitro. Komaj se ohladi določena debelina kamnine, že se smer toplotnega toka spremeni, zaradi vnosa npr. tople vode in ta sloj kamnine se prične ponovno segrevati.
To je tudi razlog, da so najvišje določene ravnotežne temperature celo 13°C (poleti), kar je mnogo več kot znaša povprečna temperatura kamninske gmote (okoli 10°C). 13°C je neka navidezna ravnotežna temperatura, med vodo in le določenim slojem kamnine.

9.6. Kraški vodonosnik preučevan v regionalnem merilu

Meritve smo opravljali na šestih točkah med Cerkniškim in Planinskim poljem na jugu in izviri Ljubljanice (ob robu Ljubljanskega barja) na severu (Sl. 7.1). Na tem območju se razteza pomemben kraški vodonosnik, kjer se zbirajo vode iz celotnega porečja, ki napajajo izvire Ljubljanice pri Vrhniki in Bistri. Vode vstopajo v obravnavani vodonosnik predvsem s Planinskega polja. Le to predstavlja nekakšen površinski preliv za vode, ki pretakajo nanj večinoma z juga. Neznan, verjetno zelo majhen delež vode se proti severu in obravnavanemu vodonosniku pretaka tudi skozi triasni dolomit, ki gradi dno polja. Določen delež vode priteka tudi s Cerkniškega polja. Zato smo zvezno merili parametre tako Unice na Planinskem polju, kot tudi Cerkniškega jezera. Eden izmed namenov teh meritev je bil preveriti vire napajanja vodonosnika, oziroma njihovo pomembnost. Na območju Ravnika smo namreč opravljali zvezne meritve parametrov vodnega toka v štirih jamah (Vetrovna jama, Najdena jama, Gradišnica in Gašpinova jama). Vse štiri jame se nahajajo v skrajno južnem delu obravnavanega vodonosnika, vendar se prav tu pretaka glavnina podzemne vode (Gospodarič & Habič, 1976).
Ravnik gradijo močno zakrasele kredne kamnine z dobro razvito kanalsko poroznostjo. Kanali in razpoke prevajajo podzemno vodo proti izvirom na severu.

9.6.1. Metodologija in namen raziskave

Naša raziskava je imela več namenov. Želeli smo ugotoviti pomen Unice in Cerkniškega jezera za napajanje vodonosnika na območju Ravnika. Metoda dela temelji na analizah in primerjavah hidrogramov (nivojskih in temperaturnih). Hidrogrami so iz površinskih (Unica, Cerkniško jezero) in podzemnih vod (štiri jame). Meritve v vodnih jamah nam služijo za ugotavljanje hidravličnih in nekaterih hidrogeoloških značilnosti vodonosnika.

S primerjavo **nivojskih hidrogramov** iz štirih jam, lahko sklepamo na dinamiko podzemne vode, oziroma na hidravlično povezanost jam. Poskušamo lahko oceniti hidrogeološki pomen in morebitne posebnosti posamezne jame, v primerjavi z ostalimi preučevanimi jamami. Glede na nihanje vodnega nivoja v izbranih jamah lahko sklepamo na širše hidravlične razmere v vodonosniku.

Analiza **temperaturnih hidrogramov** nam pomaga pri določitvi vodnih zvez med površinskimi tokovi (ali požiralniki) in jamami, oziroma o podzemnih vodnih zvezah med različnimi jamami. Površinsko vodo, ki ponika v podzemlje lahko sledimo razmeroma daleč v vodonosnik. Določimo lahko potovalni čas in hitrost vodnega toka med dvema merilnima mestoma (bodisi na površju in v vodonosniku, ali samo v vodonosniku) in sicer pri določenem površinskem pretoku (ali ob določenih vodnih razmerah v vodonosniku).

9.6.2. Glavni vplivni dejavnik

Vodne razmere na Planinskem polju predstavljajo glavni dejavnik, ki vpliva na hidravlične in hidrogeološke razmere v vodonosniku (štirih izbranih jamah). Vodne razmere na polju so neposredno odvisne od pretoka Unice in požiralne sposobnosti požiralnikov. Na Planinskem polju ločimo dve glavni skupini požiralnikov. Vzhodna skupina požiralnikov je aktivna ves čas, ne glede na vodne razmere (Sl. 7.4). Ti požiralniki so sposobni prevesti v podzemlje vse nizke in srednje visoke vode reke Unice. Požiralniki iz severne skupine (Sl. 7.4) so aktivni le občasno, to se pravi ob razmeroma visokih pretokih Unice.

Pretoke Unice smatramo kot nizke kadar ne presegajo 15 m^3/s. Ob takšnih razmerah Unica skoraj v celoti ponika v vzhodne požiralnike. Tedaj govorimo o **nizkih vodnih razmerah** na polju.

Ob višjih pretokih, kadar ti segajo tja do 25 m^3/s ali 30 m^3/s, se pomemben del vodnega toka prebije preko območja kjer se nahajajo vzhodni požiralniki in nadaljuje pot po strugi proti severu polja. Vendar ta »presežek« vode ne doseže severnih požiralnikov, temveč počasi ponikne v kamninsko podlago polja skozi številne manjše požiralne cone, ki se nahajajo vzdolž struge. Severni požiralniki ostanejo suhi. Takšne vodne razmere smatramo kot **srednje visoke vodne razmere** na polju.
Unica napaja tako vzhodne, kot tudi severne požiralnike ob **visokih vodnih razmerah** na polju. Pretok Unice mora biti večji od 30 m^3/s, tedaj je požiralna sposobnost vzhodnih požiralnikov popolnoma presežena in pomemben delež vode nadaljuje svojo pot po strugi do severnih požiralnikov.
Požiralna sposobnost vseh požiralnikov na Planinskem polje je presežena ob **izjemno visokih vodnih razmerah**, tedaj je polje poplavljeno in pokrito z jezerom. Požiralna sposobnost vseh požiralnikov je ocenjena na približno 60 m^3/s (Šušteršič, 1982), odvisna je tudi od velikosti jezera, oziroma ali so res vsi požiralniki poplavljeni. Pretok Unice mora preseči vsaj 40 m^3/s, da Unica prestopi strugo in se prične razlivati po polju.

Glede na vodne razmere na Planinskem polju in aktivnost dveh glavnih skupin požiralnikov, delimo obravnavani del vodonosnika na štiri sisteme:
- Sistem Planinsko polje – vzhodna skupina požiralnikov – Vetrovna jama
- Sistem Planinsko polje – severna skupina požiralnikov – Najdena jama – Gradišnica
- Sistem Planinsko polje – vzhodna skupina požiralnikov – Gradišnica
- Sistem Gradišnica – Gašpinova jama

9.6.3. Sistem Planinsko polje – vzhodna skupina požiralnikov – Vetrovna jama

Vetrovna jama je med vsemi štirimi preučevanimi jamami najbolj vzhodna. Od SV roba Planinskega polja, oziroma vzhodnih požiralnikov, je oddaljena 2.7 km (Sl. 7.4).
Gladina podzemne vode v sušnih razmerah (ob baznem toku) v Vetrovni jami je ustaljena na nadmorski višini 410 m (Volk, 2007), kar je višje kot v ostalih treh preučevanih jamah. Voda se lahko iz Vetrovne jame pretaka v smeri kakšne izmed ostalih treh preučevanih jam, obratno ni možno. Kakorkoli že, generalne smeri

pretakanja naj bi glede na predhodne raziskave (Gospodarič & Habič, 1976) potekale v smeri proti severu, ne pa proti SZ ali zahodu, kjer se nahajajo Najdena jama, Gradišnica in Gašpinova jama.
Mikrolokacija Vetrovne jame je vezana na območje udornic, ki so sicer razmeroma pogost pojav na Ravniku. Jama je z udornicami obkrožena kar s treh strani (Sl. 7.4). Odtok iz jame poteka pod eno večjih udornic na Notranjskem krasu, Laško kukavo (Sl. 7.8) (Volk, 2007).

Povezava med pretočnim hidrogramom Unice in nivojskim hidrogramom iz Vetrovne jame je statistično značilna (r = 0,85) za celotno časovno obdobje (Sl. 7.7). Da pripada podzemna voda, ki se pretaka skozi jamo, resnično Unici, dokazujejo tudi dnevna temperaturna nihanja. Ta so značilna za površinske vodotoke (Sl. 7.9). Temperaturna nihanja vode v Vetrovni jami so popolnoma enaka kot temperaturna nihanja Unice na Planinskem polju. Dnevna temperaturna nihanja vode se v Vetrovni jami pojavljajo ob vsakem povečanem vodostaju (oziroma dotoku), občasno pa celo ob razmerah baznega toka.
Domneva o vodnih zvezah med talnimi požiralniki na Cerkniškem polju in Vetrovno jamo pa je bila veliko bolj dvomljiva. Jasnega odgovora na to hipotezo niso dala niti naša merjenja.

Primerjava nivojskih hidrogramov iz Vetrovne jame z nivojskimi hidrogrami iz ostalih treh preučevanih jama kaže na razmeroma slabo podobnost, korelacija je nizka (Sl. 7.7). Koeficient linearne regresije med Vetrovno jamo in Gradišnico (oziroma Gašpinovo jamo) znaša za celotno merilno obdobje 0,75, med Vetrovno jamo in Najdeno jamo pa le 0.58. Nasprotno pa je na primer nivojski hidrogram iz Najdene jame v razmeroma visoki korelaciji z nivojskim hidrogramom iz Gradišnice oziroma Gašpinove jame, koeficient linearne korelacije tu znaša 0,90. Po prehodu poplavnega sunka, upada vodna gladina v Najdeni jami, Gradišnici in Gašpinovi jami zelo podobno kot upada pretok Unice (primerjaj nivojske hidrograme s pretočnim hidrogramom Unice, Sl. 7.7). Vetrovna jama je tu posebnost. Nivojski hidrogrami kažejo izrazito počasno upadanje vodne gladine med točno določenimi nadmorskimi višinami. Prav tej posebnosti gre pripisati razlog, da nivojski hidrogrami iz Vetrovni jami ne kažejo vedno tako visoke korelacije z nivojskimi hidrogrami iz ostalih treh jam.

Opazovali smo prehod različno velikih poplavnih sunkov skozi Vetrovno jamo, z namenom da bi razložili nekaj osnovnih hidravličnih značilnosti jame.

Glede na velikost (pretok merjen na Planinskem polju) smo poplavne sunke, ki vstopajo v vodonosnik skozi vzhodne požiralnike, razdelili v dve skupini:

- Veliki poplavni sunki ustrezajo površinski pretokom Unice nad 30 m^3/s. Pri prehodu vseh šestih velikih poplavnih sunkov, opazujemo na hidrogramu iz Vetrovne jame značilen vzorec. Prehajanje vseh takšnih relativno velikih poplavnih sunkov skozi Vetrovno jamo je ovirano, nivo podzemne vode upada razmeroma počasi med točno določenima relativnima višinama (15 m do 12 m), zaradi česar je Vetrovna jama zalita s poplavno vodo relativno dalj časa v primerjavi s tremi obravnavanimi jamami zahodno od nje (Sl. 7.10 in 7.11).
- Relativno majhni poplavni sunki ustrezajo pretokom površinske Unice do 25 m^3/s, največ 30 m^3/s. Majhni poplavni sunki bodisi hitro in razmeroma neovirano preidejo skozi Vetrovno jamo (Sl. 7.12), bodisi je odtekanje poplavne vode moteno in razmeroma upočasnjeno (Sl. 7.13).

Regionalna umestitev Vetrovne jame znotraj vodonosnika temelji na primerjavi hidrogramov iz Vetrovne jame s hidrogrami iz ostalih treh preučevanih jam.

Hidravlični odziv Vetrovne jame na poplavne sunke je zelo različen od odziva ostalih treh jam, ki se vse nahajajo Z oziroma SZ od Vetrovne jame. Na podlage tega dejstva bi lahko preprosto sklepali da se Unica, ki ponika v vzhodne požiralnike, pretaka predvsem v smeri proti severu (kjer je tudi Vetrovna jama) in torej in nima pomembnega hidravličnega vpliva na jame ki se nahajajo na SZ (Sl. 7.17). Takšno podzemno pretakanje bi najlažje razložili s prisotnostjo hidrogeološke bariere. Šušteršič (2002) meni Slavendolski prelom preprečuje odtekanje te podzemne vode proti SZ (Sl. 7.17).

Lokalna hidrogeološka študija Vetrovne jame kaže pomembno posebnost, ki se odraža pri prehodu vseh relativno velikih poplavnih sunkov skozi sistem. Prehod sunka skozi jamo naj bi bil moten zaradi domnevne hidrogeološke prepreke, ki se zelo verjetno pojavlja nizvodno od Vetrovne jame. Na lokalno hidrogeološko prepreko sklepamo v neposredni bližini jame, kjer dopuščamo možnost, da odtok vode pod udorno dolino Laška kukava pogojuje domnevni skalni podor.

Razpolagamo z dvema hipotezama, ki lahko pojasnita značilen hidravlični odziv Vetrovne jame. Katera je verjetnejša žal ne moremo zanesljivo sklepati. Na podlagi prve hipoteze je dotok v Vetrovno jamo pogojen z omejeno požiralno sposobnostjo požiralnikov. Ta je presežena ob vsakem relativno večjem poplavnem sunku (nad 15 m^3/s). To dejstvo lahko že samo po sebi razloži značilen hidravlični odziv Vetrovne jame, odtok iz nje potemtakem ni nujno oviran s hidravlično prepreko (npr. podor pod Laško kukavo).

Po drugi hipotezi naj bi na značilen hidravlični odziv vplivala tako omejen dotok v jamo, kot tudi oviran odtok iz nje. Vendar dotok ni omejen zaradi presežene požiralne sposobnosti požiralnikov, pač pa zaradi lateralnega prelivanja podzemne vode proti SZ, torej po vodnih poteh ki se Vetrovni jami izognejo (Sl. 7.18).

9.6.4. Sistem Planinsko polje – severna skupina požiralnikov – Najdena Jama – Gradišnica

Najdena jama je edina izmed štirih jam obravnavanih v naši raziskavi, ki se nahaja v neposredni bližini Planinskega polja. Od severnih požiralnikov je oddaljena zgolj 100 m. Ti požiralniki so hidrološko neposredno povezani z Najdeno jamo, ter tudi s precej bolj oddaljeno Gradišnico, kot sta ugotovila že Gospodarič in Habič (1976) (Sl. 7.4).

Vendar Unica le občasno napaja Najdeno jamo, saj so severni požiralniki večino leta suhi. Unica jih doseže le ob visokih pretokih, v nasprotnem primeru pa večina vode ponikne v vzhodne požiralnike. Visoki pretoki so značilni predvsem za spomladansko in jesensko obdobje. V Najdeno jamo priteka voda tudi iz drugih virov, vendar so ti dotoki tako majhni da povzročijo le majhna nihanja v gladini podzemne vode.

Nivojski hidrogrami zabeleženi v Najdeni jami kažejo izrazit in hiter odziv na vsak padavinski dogodek. Vodna gladina narašča s hitrostjo okoli 0.7 m/h. Takšen odziv je značilen za prvo fazo, med katero vodna gladina zaniha le za par metrov. Menimo da izvor poplavne vode v tej prvi fazi predstavlja razpršeni (difuzni) dotok, ki s površja pronica skozi nezasičeno cono v jamo in neposredni (notranji) odtok padavinske vode z bližnjega polja v vodo dobro prepustne kraške depresije.

Difuzni dotok v Najdeno jamo, ki poteka skozi dobro prepustno epikraško in nezasičeno cono, je lahko zelo hiter v času med in neposredno po padavinskem dogodku. Kamninska gmota nad jamo je zelo razpokana in razmeroma tanka

(debelina znaša nekaj deset metrov). Vendar so nekateri modeli (Mohhrlok & Sauter, 1999) pokazali, da le okoli 10 % prenikle vode doseže kanalske prevodnike neposredno skozi vertikalne, vodi dobro prepustne razpoke. Preostalih 90 % prenikle vode napaja vodonosnik počasi, skozi manj prepustne, poševne razpoke.
Drugi možen vir dotoka v Najdeno jamo, v prvi časovni fazi, je voda, ki na Planinskem polju pronica v podzemlje skozi sedimentni nanos (mišljeno je v času padavin). Planinsko polje je v celoti prekrito s kvartarnimi sedimenti, povprečna debelina sedimentnega nanosa znaša 4 m (Ravnik, 1976). Vendar efektivna infiltracija površinske vode skozi sediment do kamninske podlage ni možna, dokler tla ne postanejo zasičena z vodo. Proces lahko traja razmeroma dolgo in odziv nivojskega hidrograma na takšno napajanje bi bil zelo blag (oziroma položen zaradi časovno dolgega procesa). Napajanje je lahko precej hitrejše v primeru da ni pogojeno z stopnjo zasičenosti tal z vodo. Voda lahko na primer odteče skozi razpoko v prsti in posledično je odziv nivojskega hidrograma v podzemlju hiter in oster (Petrič, 2002).
Na Planinskem polju se na dnu manjših depresij oziroma kotanj pojavljajo številni manjši požiralniki in druge za vodo dobro prepustne strukture. Del padavinske vode, ki pade na obrobju polja, lahko koncentrirano odteče proti takšnim depresijam, od koder hitro doseže kanalske prevodnike v vodonosniku. Takšni koncentrirani površinski tokovi se razmeroma pogosto pojavljajo na kraških poljih v času padavinskih dogodkov (Bonacci, 1987).

Večina majhnih poplavnih sunkov zabeleženih na nivojskem hidrogramu iz Najdene jame je posledica hitrega avtogenega odziva na padavinski dogodek. Zanimiv pa je pojav redkih majhnih poplavnih sunkov, ki kažejo na zapoznel in bolj postopen odziv na padavinski dogodek. V Najdeni jami takšne majhne poplavne sunke, z zaobljenim vrhom, opazujemo izključno ob določenih hidroloških razmerah, ki vladajo na Planinskem polju. Ti majhni poplavni sunki z zaobljenim vrhom časovno ne sovpadajo neposredno s padavinskimi dogodki, oziroma z avtogenim napajanjem (Sl. 7.22, nivojski vrh označen s puščico št. 2). Sklepamo da Unica ne ponika le v glavne požiralnike, temveč v določeni meri pronica v podzemlje tudi skozi manjše požiralnike, še posebej na odseku med glavnima skupinama požiralnikov (med vzhodno in severno skupino). Tok skozi takšne drugotne požiralnike je razmeroma majhen in bi lahko vplival na vodostaj v Najdeni jami. Podzemni tok se vrši skozi triasni dolomit, ki je razmeroma slabo prepusten v primerjavi s sosednjim krednim apnencem, ki na SV obroblja polje in v katerem se je razvila Najdena jama. Voda se skozi dolomit pretaka večinoma po razpokah, zato je ta tok razmeroma počasen in kot tak bi lahko povzročil zapoznel, blag hidravlični odziv v Najdeni jami, z zaobljenim nivojskim vrhom. Temperaturno nima ta dotok nikakršnega vpliva, saj je dovolj počasen, da popolnoma prevzame temperaturo okoliške kamnine. Ta dotok lahko opazujemo na nivojskih hidrogramih v Najdeni jami le v primeru, ko pretok Unice za nekaj kubičnih metrov na sekundo preseže 20 m^3/s. Tedaj se del vodnega toka prebije mimo vzhodnih požiralnikov proti severu polja, vendar voda ponikne v podzemlje še preden doseže severne požiralnike. Ko pretok Unice preseže 30 m^3/s, se Unica prebije tudi do severnih požiralnikov in vpliv manjših dotokov na nivojskem hidrogramu iz Najdene jame je zabrisan. Dotok skozi severne požiralnike je namreč tako velik, da zabriše vse ostale dotoke.

Poplavna voda se iz Najdene jame zagotovo pretaka proti Gradišnici, vendar vodne povezave ob razmeroma nizkih vodnih razmerah niso popolnoma jasne. Problematični so mali poplavni sunki, za katere ne vemo ali iz smeri Najdene jame potujejo tudi v Gradišnico (Sl. 7.22). Poplavne vode pritekajo v Gradišnico tudi iz drugih smeri in njihov pretok bi znal biti večji od pretoka iz smeri Najdene jame. Večji pretoki pa na hidrogramu zabrišejo manjše, v primeru da so poplavni sunki sočasni. Zaradi tega razloga je korelacija malih poplavnih sunkov med Najdeno jamo in Gradišnico lahko problematična. Kadar vladajo na Planinskem polju nizke in srednje visoke vodne razmere, tedaj predstavlja verjetno prav Hotenka glavni dotok v območje kjer se nahaja Gradišnica in ne vode ki pritekajo iz smeri Najdene jame.

Podzemna voda se iz Najdene jame brez dvoma v veliki meri pretaka proti Gradišnica ko na Planinskem polju vladajo visoke vodne razmere (oziroma ko Unica napaja tudi severne požiralnike). Prodor Unice v Najdeno jamo povzroči v jami nenadno in zelo izrazito temperaturno spremembo (Sl. 7.24). Podoben proces opazujemo tudi v Gradišnici. Preboj Unice v Najdeno jamo povzroči tudi nenaden pričetek naraščanja vodne gladine, ki zlahka preseže relativno višino 10 m ali 20 m. Nasprotno pa je prispevek tega toka k višini vodnega nivoja v Gradišnici razmeroma skromen (nekaj metrov). Razlogov je več. Dejstvo je da Gradišnico najprej doseže poplavna voda iz drugih virov. Posledično lahko vodna gladina preseže relativno višino 15 m, še preden prične v Gradišnico zatekati Unica iz severnih požiralnikov. Podzemni tok Unice se v vodonosniku porazdeli tudi lateralno, kar je ena izmed razlag za razmeroma majhen doprinos tega toka k nivojskemu hidrogramu v Gradišnici, v primerjavi z Najdeno jamo. Podzemna Hotenka je domnevno eden izmed prvih vodnih tokov, ki ob padavinskem dogodku vpliva na dvig vodnega nivoja v Gradišnici. Vendar lahko zaenkrat popolnoma zanesljivo dokažemo le tok podzemne Unice skozi Gradišnico, saj je bila Unica edini vodotok, katerega parametre smo merili tudi na površju. Tok Unice lahko temeljito vpliva na temperaturo vode v Gradišnici (Sl. 7.24), medtem ko vsi ostali vodni tokovi nimajo nikakršnega temperaturnega vpliva na mikrolokacijo, kjer imamo v Gradišnici nastavljen merilec.

Dnevna temperaturna nihanja vode, ki se ob določenih pogojih pojavljajo v Gradišnici (zaradi toka podzemen Unice), imajo nek časovni zamik v primerjavi z nihanji v Najdeni jami. Na podlagi tega zamika lahko sklepamo na potovalni čas vode med dvema jamama (oziroma merilnima mestoma) in na hitrost vodnega toka. Potovalni čas vode je, glede na časovni zamik prvega temperaturnega viška na sliki 7. 24, znašal 5 ur in 45 minut.

9.6.5. Sistem Planinsko polje – vzhodna skupina požiralnikov – Gradišnica

Na podlagi natančne študije hidrogramov iz vseh štirih jam, smo ugotovili da se določen delež Unice, ki napaja vzhodne požiralnike, pretoči tudi v Gradišnico in Gašpinovo jamo, in ne samo v Vetrovno jamo. Nekateri značilni sekundarni vrhovi na nivojskih hidrogramih iz Gradišnice in Gašpinove jame so posledica tega toka. Ta tok pa zagotovo nima nikakršnega vpliva na hidrogram v Najdeni jami (Sl. 7.26).

Glavno vprašanje, ki se nam je porajalo je bilo, kako oziroma po katerih podzemnih poteh pravzaprav Unica priteče iz vzhodnih požiralnikov v Gradišnico. Šušteršič (2002) trdi da je pretakanje podzemne vode močno omejeno s slabo prepustno hidrogeološko bariero, ki jo je interpretiral kot Slavendolski prelom.

Izpostavili smo tri najverjetnejše hipoteze o možnih vodnih zvezah med vzhodno skupino požiralnikov in Gradišnico.

1. Voda, ki odteče iz Vetrovne jame, bi lahko vsaj posredno vplivala na vodostaj v Gradišnici. Šušteršič (2002) je sledil Slavendolskemu prelom približno do bližine udornice Laška kukava. V kolikor se tu nekje hidrogeološka bariera prekini, potem lahko voda iz Vetrovne jame odteka tudi v smeri proti SZ in vsaj posredno vpliva na nivo vode v Gradišnici in Gašpinovi jami.

2. Požiralnik Laška žaga je zadnji, skrajno »zahoden« požiralnik v skupini vzhodnih požiralnikov, nahaja se v neposredni bližini Laz (Sl. 7.27). Ta požiralnik bi domnevno lahko odvajal vodo v nekoliko drugačni smeri kot ostali požiralniki JV od Laz. Laška žaga se v nasprotju z ostalimi vzhodnimi požiralniki nahaja na zahodni strani Slavendolskega preloma, ki po Šušteršičevem (2002) mnenju predstavlja pomembno hidrogeološko prepreko. Potemtakem bi se voda, ki ponika v požiralnik Laška žaga, lahko podzemno pretakala v smeri JV-SZ, v nasprotju z ostalimi vzhodnimi požiralniki, ki naj bi odvajali vodo v generalni smeri J-S. Prevodniki, ki se navezujejo na Laško žago, naj bi se izognili Vetrovni jami, zelo verjetno pa voda teče tudi proti Gradišnici. Ob določenih hidroloških pogojih bi ta požiralnik lahko imel pomemben vpliv na hidrogram v Gradišnici. O pomenu tega požiralnika in njegovi kapaciteti nismo zasledili dovolj podatkov za detajlnejšo študijo, vsekakor bi ga bilo v prihodnosti smiselno dobro preučiti.

3. Domnevamo da se del podzemne vode, ki se generalno pretaka od vzhodnih požiralnikov proti severu oziroma Vetrovni jami, na neznanem odseku prečno prelije na zahod (Sl. 7.18 in Sl. 7.27). Ta del vode naj bi vplival na nivo vode v Gradišnici in Gašpinovi jami, ne pa tudi Najdeni jami.

Porajata se dve možnosti, bodisi da redki kanali prečno vendarle presekajo domnevno hidrogeološko bariero, ki močno pogojuje pretakanje podzemne vode v preučevanem vodonosniku. Druga možnost bi bila da se vzdolž bariere pojavlja za vodo razmeroma dobro prepusten horizont. Ena ali druga možnost bi lahko razložili vodne povezave med vzhodnimi požiralniki in Gradišnico in posledično značilen hidravlični odziv Vetrovne jame.

9.6.6. Sistem Gradišnica – Gašpinova jama

Gradišnica in Gašpinova jama sta zaenkrat dve izmed treh jam na območju Ravnika (tretja je že obravnavana Vetrovna jama), ki omogočata dostop do podzemne vode razmeroma daleč od Planinskega polja. Vse ostale znane vodne jame na Ravniku so v neposredni bližini polja. Gradišnica in Gašpinova jama se nahajata razmeroma blizu ena drugi. Vhod v Gašpinovo jamo se nahaja na obrobju Logatca, vhod v Gradišnico pa le 1500 m južneje (Sl. 7.17 in 7.27). Dejanska razdalja med merilnima mestoma v obeh jamah je verjetno še za kakšnih 100 m krajša.

Meritve so pokazale, da so nihanja vodne gladine v Gradišnici in Gašpinovi jami dejansko enaka, spremembe so sočasne (Sl. 7.7). Na podlagi tega dejstva zanesljivo sklepamo da pripadata jami nekemu širšemu območju v vodonosniku, kjer je vodna gladina sklenjena.

Vendar pa temperaturne značilnosti vode v Gradišnici in Gašpinovi jami niso enake, celo nasprotno, razlike so velike in značilne za večji del leta. Hidrodinamiko podzemne vode na širšem območju med obema jamama razlagamo predvsem s pomočjo temperature podzemne vode, glede na dejstvo da so nihanja vodnega nivoja enaka. Temperatura nihanja vode in razlike med obema jamama smo opazovali ob različnih hidroloških razmerah na Planinskem polju, od koder v vodonosnik priteka zelo pomembni dotok.

-Nizke vodne razmere na Planinskem polju

V Gradišnici (in seveda tudi v Gašpinovi jami) smo novembra 2006 (Sl. 7.28) in julija 2007 (Sl. 7.29) zabeležili dva primerljivo velika poplavna sunka. Hidrološke razmere na Planinskem polju pa si nikakor niso bile podobne. Odvisno od razporeditve nekih zmernih padavin lahko pretok Unice naraste (november 2006) ali pa se sploh ne spremeni (julij 2007) med in tik po padavinskem dogodku. Vendar pa je bistveno da Unica v nobenem od dveh primerov ni povzročila dviga nivoja podzemne vode na območju med Gradišnico in Gašpinovo jamo.

Na nihanje gladine podzemne vode v obeh jamah po našem mnenju vpliva podzemni dotok Hotenke in Logaščice (Sl. 7.4), ter tudi avtogeni dotok. Pretoka ponikalnic Hotenke in Logaščice nismo merili. Vendar so v povprečju pretoki teh dveh ponikalnic majhni, najvišji ne presegajo nekaj kubičnih metrov na sekundo (Gospodarič & Habič, 1976). Podzemni tok obeh ponikalnic in avtogeni dotok vsi skupaj predstavljajo razmeroma majhen dotok v vodonosnik. Razmeroma pomemben dotok bi lahko prišel z SV območja Hrušice, kjer vsa voda ponikne v podzemlje kot avtogeni dotok.

Ne glede na razmeroma majhen pretok ponikalnic Hotenke in Logaščice, so nihanja podzemne vode v Gradišnici in Gašpinovi jami dokaj velika (okoli 10 m), še posebej v primerjavi z istočasnimi nihanji v Vetrovni in Najdeni jami. Za takšno obnašanje podajamo sledečo razlago. Razdalja med Gradišnico in Gašpinovo jamo je kot rečeno razmeroma kratka in hidravlični padec majhen. Menimo da se nekje nizvodno od obeh jam nahaja pomembna hidrogeološka prepreka, zaradi katere so nihanja vodne gladine v obeh jamah razmeroma velika že ob manjšem padavinskem dogodku, spremembe pa enake in skoraj istočasne. Bazni tok skozi obe jami se vrši na precej nižji absolutni nadmorski višini kot v Vetrovni in Najdeni jami (okoli 30 m nižje). Vetrovna in Najdena jama se nahajata na dovolj visoki nadmorski višini, da vpliv omenjene hidrogeološke prepreke ne seže več do njiju.

- Srednje visoki vodostaj na Planinskem polju

Za časa srednje visokega vodostaja na Planinskem polju je običajno razmerje med pretočnim hidrogramom Unice in hidrogramom iz Gradišnice (oziroma Gašpinove jame) statistično značilno (koeficient linearne regresije r znaša okoli 0,9), kot lahko razberemo iz slike 7.31, ki se nanaša na hidro(geo)loške razmere iz prve polovice januarja 2007. Na podlagi tega lahko zanesljivo sklepamo da se Gradišnica in Gašpinova jama za časa tega poplavnega dogodka nista napajali zgolj (predvsem) s Hotenko, Logaščico, avtogenim dotokom, temveč v veliki meri tudi z Unico, ki je napajala vodonosnik skozi vzhodne požiralnike.

Vodna gladina na hidrogramih iz obeh obravnavanih jamah naraste v dveh jasno ločljivih fazah, ob srednje visokem vodostaju na Planinskem polju (Sl. 7.31 in 7.32). Unica doseže Gradišnico oziroma Gašpinovo jamo z določenim časovnim zamikom, torej v drugi fazi.

Ob takšnih hidro(geo)loških pogojih sta si temperaturi podzemne vode v Gradišnici in Gašpinovi jami zelo različni in ne kažeta nikakršne povezave s temperaturo Unice pri Starem gradu. Vendar moramo pri interpretaciji temperaturnih hidrogramov upoštevati nekaj pomembnih dejstev.

Temperatura vode v Gradišnici je zelo stabilna in znaša 8.2°C. Vendar v Gradišnici merimo temperaturo vode v podzemnem jezercu (Sl. 7.33), ki v resnici predstavlja le vrhnji del z vodo zapolnjenega brezna, vodoravni kanali skozi katere se vrši glavnina pretakanja pa se nahajajo precej nižje. V takšnem jezercu, ki predstavlja lokalni piezometer, je voda bolj ali manj ujeta, oziroma slabo premešana. Tudi če se na primer Hotenka neposredno pretaka skozi Gradišnico, njenega temperaturnega vpliva ne moremo zaznati na omenjenem merilnem mestu. Zaznali bi ga le v glavnih vodoravnih pretočnih kanalih, ki pa niso dostopni brez potapljaške opreme. Enako velja za temperaturni vpliv reke Unice.

Temperaturne spremembe podzemne vode so majhne tudi v Gašpinovi jami. Vendar ne razpolagamo vedno z dejanskim podatkom o temperaturi vode. Merilec smo namestili v jamo ne ravno ob najnižjih vodnih razmerah, kar pomeni da ob dolgotrajnem baznem toku vodna gladina upade kakšen meter pod višino, na kateri je nameščen merilec. Ta tedaj namesto temperature vode meri temperaturo zraka (Sl. 7.29 in 7.32). Menimo da je temperatura baznega toka rahlo višja od temperature zraka, oziroma da znaša okoli 9.6°C. Naše meritve kažejo da temperatura vode v Gašpinovi jami niha med 9.2°C do 10.4°C, mišljeno je kadar je vodostaj na Planinskem polju nizek oziroma srednje visok. Glede na razmeroma visoka nihanja v primerjavi z Gradišnico, bi lahko sklepali da je podzemna voda v Gašpinovi jami v nasprotju z Gradišnico razmeroma dobro premešana. To bi pomenilo da se pretakanje dejansko vrši skozi jezero kjer imamo nameščen merilec in ne gre le za piezometer "ujete vode" kot v Gradišnici. Vendar dnevnih temperaturnih nihanj vode v Gašpinovi jami nismo zaznali, kar bi lahko razlagali s počasnim podzemnim tokom in dolgim zadrževalnim časom (domnevno Hotenke) v podzemlju.

Temperatura vode v Gašpinovi jami je zanimivo stalno za okoli 1.5°C višja od temperature vode v Gradišnici. Največja temperatura razlika pa je znašala skoraj 3°C (Sl. 7.31). Merilca v obeh jamah sta med seboj temperaturno dobro umerjena, torej razlike nikakor niso posledica napake v merilcih. Po podatkih proizvajalca je natančnost merilcev 0.1°C.

Takšne velike razlike v temperature podzemne vode lahko delno razložimo z morfologijo obeh jam, ki sta si zelo različni. Do merilnega mesta v Gašpinovi jami ne sežejo nikakršni temperaturni vplivi s površja, prav nasprotno pa je z Gradišnico (Sl. 7.33). Predvsem pozimi se v jamo spušča mrzel zrak, ki na dnu izpodriva toplejšega, ta pa se vrača na površje.

- Visok vodostaj na Planinskem polju

V prvi fazo poteka napajanje obeh jam podobno kot ob srednje visokem vodostaju na Planinskem polju. Vodni nivo v Gradišnici in Gašpinovi jami pričenja naraščati še preden v širše območje obeh jam priteče Unica. Poplavne vode predstavljajo vnos Hotenke, Logaščice in avtogenega dotoka. Unica priteče v območje vodonosnika s sklenjeno vodno gladino (med Gradišnico in Gašpinovo jamo) šele v naslednji fazi. Ločimo celo dva podzemna tokova Unice. Najprej širše območje med obema jamama doseže Unica, ki ponika v vzhodne požiralnike in šele kasneje z nekim časovnim zamikom Unica, ki ponika v severne požiralnike. Potovalna časa obeh tokov sta različna, pri drugem toku moramo upoštevati tako površinski tok od vzhodnih požiralnikov proti severnim in nato še podzemno pretakanje preko Najdene jame proti Gradišnici. Oba tokova Unice lahko običajno razberemo tudi s hidrogramov (Sl. 7.31 in 7.32). Običajno se na hidrogramu vsaj delno prekrivata, tako da smo ju prepoznali oziroma ločili šele z natančno analizo hidrogramov. Tok Unice, ki vstopa v vodonosnik skozi severne požiralnike, običajno prispeva največ vode v širše območje Gradišnice in Gašpinove jame, zato je prevladujoč.

Poplavna voda, ki v prvi fazi vpliva na dvig sklenjene vodne gladine med obema jamama, ne spremeni temperature podzemne vode v nobeni od obeh jam. Unica, ki v zadnji fazi priteči v obravnavani del vodonosnika, spremeni le temperaturo vode v Gradišnici. Decembra 2006 (Sl. 7.34) je imela podzemna voda v Gradišnici enak (negativen) temperaturni trend kot Unica pri Starem gradu, le dnevna temperaturna nihanja se niso pojavila v Gradišnici. Ta so se pojavila med januarskim poplavnim sunkom 2007 (Sl. 7.35). Iz tega sledi da se v Gradišnici pojavijo izrazite spremembe v temperaturi podzemne vode, kadar je vodostaj Unice na polju visok.

Opazili smo da se dnevna temperatura nihanja podzemne vode v Gradišnici pojavijo le kadar se nivo vode dvigne za vsaj 23 m nad nivo merilca. Če se pa voda dvigne vsaj za 18 m, ima podzemna voda v Gradišnici enak temperaturni trend kot površinska Unica, dnevna nihanja se pa še ne pojavljajo. Nivo podzemne vode v Gradišnici pa je neposredno odvisen od vodostaja oziroma pretoka Unice na Planinskem polju. Pretok mora znašati približno 30 m^3/s, da se v Gradišnici nivo podzemne vode vzdržuje na relativni višini 23 m. To je tudi minimalni pretok, ki še omogoča napajanje severnih požiralnikov.

Pojav temperaturnih dnevnih nihanj podzemne vode je zelo verjetno povezan s pretakanjem vode mimo merilca. Kot rečeno se glavnina pretakanja ob manjših pretokih (kadar je vodostaj na Planinskem polju nizek ali srednje visok) vrši po nižje ležečih kanalih. Voda v jezercu, kjer je nameščen merilec, se slabo meša z svežim dotokom, zato tudi temperaturno stabilna.

Kadar so podzemni pretoki večji (visok vodostaj na Planinskem polju), voda v jezercu z merilcem naraste do te mere da prične polniti Putikovo dvorano. Ko doseže odtočne kanale v Putikovi dvorani pa prične voda tudi dejansko teči skozi dvorano (Sl. 7.33, glej puščice ki kažejo smer vodnega toka skozi Putikovo dvorano). Mimo merilca tedaj dejansko prične teči podzemni tok in pojavijo se temperaturna nihanja,

značilna za Unico. Vodna gladina v Gradišnici mora narasti vsaj za 18 m, oziroma 23 m nad nivo merilca, da prične voda odtekati na drugi strani iz Putikove dvorane.
V nasprotju z Gradišnico pa tudi ob takšnih vodnih razmerah Unica nima nikakršnega temperaturnega vpliva v južnem podzemnem jezeru v Gašpinovi jami (Sl. 7.34 in 7.35). Temperatura podzemen vode je še vedno razmeroma stabilna (nekje med 9.6°C in 10°C), oziroma podobna temperaturi ob nizkem vodostaju. Skratka spremembe so kratkotrajne in majhne.
Razlika med temperaturo vode v Gradišnici in Gašpinovi jami je lahko zelo velika. V drugi polovici januarja 2007 (Sl. 7.35) je predstavljala Unica najpomembnejši vir vode za Gradišnico. Gladina podzemne vode se je dvignila kar za 30 m, pojavila so se dnevna temperaturna nihanja. Površinska Unica se je januarja 2007 v šestih dneh izrazito ohladila, enak negativen trend smo opazovali tudi v Gradišnici, kjer je temperatura voda v šestih dneh padla za 3°C. V istem obdobju pa se temperatura vode v Gašpinovi jami skoraj ni spreminjala. Voda v Gašpinovi jami je bila konec januarja in na začetku februarja kar za 4°C do 5°C toplejša kot voda v Gradišnici (Sl. 7.35).
Temperaturne razlike vode v Gradišnici in Gašpinovi jami bi težko razložili z morfologijo obeh jam, oziroma kroženjem zraka v Gradišnici. Kot je bilo že razloženo hladen zrak nima kakšnega vpliva na temperaturo vode ob merilcu, kadar je ta potopljen za več metrov. V obeh opisanih primerih je bil merilec 10 m do 25 m pod vodno gladino.
Malo verjetno je da se vsaj del podzemne vode ne bi pretočil iz Gradišnice še v Gašpinovo jamo. Vendar glede na temperaturne značilnosti podzemnih vod na dveh mikrolokacijah (Sl. 7.34 in 7.35), sklepamo da se vode dveh izvorov ne mešata na merilni mikrolokaciji v Gašpinovi jami. Delež vode, ki se iz Gradišnice pretaka proti Gašpinovi jami je neznan. Podzemni dotok, ki domnevamo da prihaja z zahoda temperaturno prevlada vsaj na lokaciji, kjer smo imeli nameščen merilec v Gašpinovi jami.

- Izredno visok vodostaj na Planinskem polju

Unica, ki se podzemno pretaka od severnih požiralnikov skozi sisteme Najdene in drugih jam proti Gradišnici, ima ob takšnih razmerah velik pretok (po oceni nekje med 20 m^3/s in 40 m^3/s, kolikor znaša tudi maksimalna prevodna sposobnost severnih požiralnikov; Šušteršič, 1982). Vsi ostali podzemni tokovi so neprimerno

manjši. Ker je vnos vode v območje vodonosnika s sklenjeno vodno gladino zelo velik, se nivo v tem delu vodonosnika dvigne vsaj do relativne višine 30 m in vse do 48 m (po naših podatkih).
Čeprav so nihanja vodne gladine v Gradišnici in Gašpinovi jami izredno podobna, smo vendarle opazili da se predvsem ob velikih poplavah vodni nivo v Gradišnici dvigne relativno višje kot v Gašpinovi jami (Sl. 7.36). Največja zabeležena razlika je znašala pet metrov. Višje kot naraste podzemna voda, večje so razlike med višino vode v Gradišnici in Gašpinovi jami. To pomeni da se hidravlični padec med obema jamama ob velikih poplavah poveča. Najvišji izmerjeni je znašal 0,0056, medtem ko ob baznem toku znaša le okoli 0,002 (Sl. 7.37).
Ob izredno visokih pretokih Unica temperaturno prevlada ne samo v Gradišnici, pač pa tudi v Gašpinovi jami, torej v večjem delu vodonosnika s sklenjeno gladino podzemne vode. Takšne razmere so redke in se ne pojavijo vsako hidrološko leto. Značilna dnevna temperaturna nihanja vode se šele ob takšnih razmerah pričnejo pojavljati tudi v Gašpinovi jami. Vendar morajo biti pretoki izredno visoki vsaj več dni zapored, v nasprotnem primeru dnevnih temperaturnih nihanj ne moremo opazovati niti v Gradišnici, še manj pa v Gašpinovi jami.
V primeru da se dnevna temperaturna nihanja pojavljajo v obeh jamah, lahko ugotavljamo potovalni čas, ki ga potrebuje voda da premosti razdaljo med Gradišnico in Gašpinovo jamo. Vsak temperaturni maksimum ali minimum, ki ga zabeležimo v Gašpinovi jami, se tod pojavlja z nekim časovnim zamikom v primerjavi z istim maksimumom ali minimumom, ki ga zabeležimo v gorvodni Gradišnici. Temperaturni signal potuje skupaj z vodo, s procesom advekcije. Časovni zamik tega signala med dvema točkama (jamama) je enak potovalnemu lasu vode. Februarja 2007 (Sl. 7.36) je voda med Gradišnico in Gašpinovo jamo potovala natanko 4,5 ure, hitrost vodnega toka je potemtakem znašala približno 350 m/h.

9.6.7. Sklepi in nadaljnji raziskovalni izzivi

Naša raziskava je pokazala da predstavljajo jame epifreatične cone primerna mesta za opazovanje hidrodinamike voda v kraškem vodonosniku. Merili smo nihanje vodnega nivoja in temperaturo vode, oba parametra pa sta povezana z geometrijo vodonosnika (v našem primeru predvsem kanalov) in načinom napajanja, ter odtoka vode iz vodonosnika. Pri obdelavi podatkov smo se poslužili različnih že uveljavljenih metod. Nekatere so se izkazale primerne tudi za naš pristop, druge pa kot manj primerne. Kakorkoli že, dejstvo je da smo predvsem prikazali nov pristop k preučevanju kraškega vodonosnika. Natančna metodologija za obdelavo podatkov pa bo morala biti morda šele razvita, in sicer takrat ko bo takšen pristop k raziskavi postal bolj razširjen.

Za obdelavo podatkov v lokalnem merilu so metode že razvite, tu prednjači predvsem numerično modeliranje. Slednje pa ne pride do izraza pri obdelavi podatkov v regionalnem merilu, saj modeli niso uspešni pri predvidevanju velike kompleksnosti in raznolikosti kraškega vodonosnika.

Lokalna raziskava se je osredotočila na sistem podzemne Pivke, kjer smo preučevali predvsem hidravlične značilnosti sistema in transport toplote ter mase v podzemni vodi. Meritve so pokazale da predstavlja Martelov podor najpomembnejšo hidravlično prepreko v sistemu. Delovanje hidravličnih procesov smo poskušali prikazati z uporabo programa SWMM. Ta program je zelo uporaben za simuliranje kanalskega toka, vendar bi ga bilo potrebo deloma predelati za potrebe kraškega vodonosnika.

Naredili smo model, na podlagi katerega sklepamo na razmerje med vodnim nivojem in pretokom za vsako izmed merilnih točk. Model temelji na metodi strojnega učenja, predvideni hidravlični odziv ob določenem pretoku ima veliko zanesljivost.

Temperaturo vode smo uporabili kot naravno sledilo, da smo določili hitrosti vodnega toka med sosednjimi merilnimi mesti ob različnih pretokih. V ponor Pivke smo izlili tudi umetno vodotopno sledilo (sulforodamin G), namen je bil isti, določiti hitrost vodnega toka v jami. Ugotovili smo da je prvi pojav umetnega sledila na merilni točki, ki ustreza maksimalni hitrosti vodnega toka, enak pojavu oziroma hitrosti temperaturnega signala.

Zadrževalni čas vode v vodonosniku oziroma hitrost podzemnega toka sta dva pomembna parametra, na podlagi katerih lahko ocenimo ranljivost vodonosnika na morebitno izlitje onesnaževala. Hitrosti podzemnega toka se spreminjajo od lokacije do lokacije že ob konstantnem pretoku. Takšne spremembe lahko delno razložimo s spreminjajočim hidravličnim padcem in različno morfologijo (geometrijo) kanalov.

Poskušali smo ugotoviti tudi ravnotežno temperaturo med podzemno vodo in okoliško kamninsko gmoto. Na tem področju naš čaka še veliko dela, verjetno je možno sistem pravilno termalno opredeliti le s pomočjo numeričnega modela.

Takšen model je že v izdelavi, določene rešitve lahko počakajo tudi na bližnjo prihodnost.

Regionalna raziskava se je osredotočila na območje med Planinskim poljem in izviri Ljubljanice. Na tem območju smo merili parametre podzemne vode v štirih izbranih jamah. Večina znanih jam se nahaja v neposredni bližini roba Planinskega polja in na južnem delu območja. Nekaj manj pomembnih jam je še na ostalih obrobjih vodonosnika.
Opredelitev Vetrovne jame se je pokazala za razmeroma težavno. Izpostavili smo več teorij, da bi razložili nenavaden hidravlični odziv Vetrovna jame na poplavne sunke. Vendar končnega odgovora nismo našli, za to bodo potrebne dodatne raziskave in meritve. Te se bodo morale osredotočiti na vzhodne požiralnike na polju, v katerih mi nismo izvajali neposrednih meritev. Ne vemo kateri oziroma koliko požiralnikov je aktivnih ob določenih vodnih razmerah (pretoku Unice) na Planinskem polju. Prav ta podatek pa lahko predstavlja pomembno informacijo za določitev dotoka v Vetrovno jamo. Ni popolnoma jasno ali je dotok v jamo lahko stalen zaradi morebitne presežene prevodne sposobnosti požiralnikov.
Da bi opredelili reprezentativnost meritev v Vetrovni jami, bi bilo potrebno istočasno spremljati parametre vodnega toka tudi v jami Logarček. Ta se nahaja med vzhodnimi požiralniki in Vetrovno jamo.
Meritve, ki so potekale v jamah Najdena jama, Gradišnica in Gašpinova jama so nasprotno zelo verjetno reprezentativne.
Določene odgovore na nerešena vprašanja bi nam dali tudi rezultati sledilnega poskusa. Sledilo bi morali izliti v požiralnika Laška žaga in Dolenje Loke. Zanimivo bi bilo videti ali voda, ki ponika v Laško žago, res teče v Gradišnico in se Vetrovni jami izogne. Nasprotno pa bi se moralo sledilo zlito v Dolenje Loke pojaviti v obeh jamah, v kolikor je hipoteza o prečnem pretakanju preko hidrogeološke bariere (s smerjo J – S) realna. Vendar je takšne sledilne poskuse zelo težko izvesti, saj so jame težko dostopne.
Ena izmed pomembnejših ugotovitev je, da se dolvodno od obravnavanih jam z veliko verjetnostjo pojavlja pomembna, regionalna hidrogeološka bariera. Takšno bariero bi lahko predstavljal pas jurskega dolomita, ki je razmeroma slabše zakrasel v primerjavi z jurskim in krednim apnencem.

Zanimiv je primer Putikove dvorane v Gradišnici. Ob velikih poplavah je dvorana zalita z vodo. Odtekanje vode iz dvorane je razmeroma počasno, kar se še posebej lepo vidi na hidrogramu iz Gradišnice.
Na podlagi naših meritev seveda nismo mogli preučiti celotnega vodonosnika. Predvsem nam manjkajo meritve iz severnega dela vodonosnika, kjer do sedaj ni bila odkrita še nobena vodna jama. Zelo obetavna je Jama pri Gnezdu. Na njenem dnu, ki se nahaja na nadmorski višini 366 m, so odkrili poplavno ilovico (Čekada et al., 2000). Torej sklepamo da se dno jame že nahaja v zgornjem delu epifreatične cone. Z nadaljnjim širjenjem jamskega dna bi znali jamarji prodreti tudi do freatične cone, oziroma do podzemne vode ki teče proti izvirom Ljubljanice.

Eno izmed pomembnih vprašanj je kako uporabiti in povezati dognanja pridobljena z raziskovanjem vodonosnika v lokalnem merilu (Postojnska jama) z dognanji pridobljenimi pri raziskovanju vodonosnika severno od Planinskega polja (regionalno merilo). Sistem Postojnske jame je razmeroma kratek (3,5 km). Dotok v jamo je enostaven, podzemno pretakanje se vrši večinoma po enem sistemu kanalov, kjer se pojavljajo le lokalne hidravlične prepreke. Nasprotno pa so bile razdalje med jamami v vodonosniku severno od Planinskega polja velike, znašale so po več km. Dotok v vodonosnik in jame je kompleksen, na hidravlični odziv jam v veliki meri vplivajo regionalne geološke strukture.
Nekatere termalne značilnosti Postojnske jame so tiste, ki jih lahko uporabimo tudi v drugih vodonosnikih, preučevanih tudi v večjem merilu. Vnos poplavne vode lahko temeljito spremeni termalne značilnosti kamninske gmote v vodonosniku, v kolikor je temperatura vode pri ponoru zelo različna od temperature podzemlja. Alogeni dotok pomembno vpliva na termalne značilnosti Postojnske jame, saj je njen sistem razmeroma kratek in tok skoznjo je dokaj enovit. Podobne termalne vplive smo opazovali tudi v vodonosniku preučevanem v regionalnem merilu. Pri tem pa je potrebno poudariti da se podzemno pretakanje tod vrši po zelo razvejanem sistemu kanalov, kjer prihaja do razporeditve vodnega toka po širšem območju vodonosnika. Tudi razdalje od požiralnika do merilnih točk (jam) so tu precej večje.

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11. APPENDICES

All units are in metres and cubic metres per second!

1. RULES FOR TARTAR MODEL TREE

RULE num: 1

If discharge (Q) is $0.75 \geq Q > 0$, then: Tartar_WaterLevel = 0.0624 * Discharge + 18.8491

Number of instances: 6573

RULE num: 2

If discharge (Q) is $0.95 \geq Q > 0.75$, then: Tartar_WL = 34.958 * Discharge - 7.0836

Number of instances: 2086

RULE num: 3

If discharge (Q) is $2.95 \geq Q > 0.95$, then: Tartar_WL = 7.6432 * Discharge + 21.6957

Number of instances: 4080

RULE num: 4

If discharge (Q) is $5.55 \geq Q > 2.95$, then: Tartar_WL = 7.0929 * Discharge + 24.2996

Number of instances: 1950

RULE num: 5

If discharge (Q) is $7.15 \geq Q > 5.55$, then: Tartar_WL = 6.3639 * Discharge + 27.9803

Number of instances: 1130

RULE num: 6

If discharge (Q) is $7.55 \geq Q > 7.15$, then: Tartar_WL = 0.09 * Discharge + 77.3334

Number of instances: 537

RULE num: 7

If discharge (Q) is 8.55 ≥ Q > 7.55, then: Tartar_WL = 0.0654 * Discharge + 80.2868

Number of instances: 1436

RULE num: 8

If discharge (Q) is 9.15 ≥ Q > 8.55, then: Tartar_WL = 0.0488 * Discharge + 78.5297

Number of instances: 656

RULE num: 9

If discharge (Q) is 11.05 ≥ Q > 9.15, then: Tartar_WL = 3.2329 * Discharge + 55.2243

Number of instances: 1398

RULE num: 10

If discharge (Q) is 13.45 ≥ Q > 11.05, then: Tartar_WL = 0.1656 * Discharge + 94.1656

Number of instances: 1480

RULE num: 11

If discharge (Q) is 14.65 ≥ Q > 13.45, then: Tartar_WL = 0.188 * Discharge + 98.6374

Number of instances: 624

RULE num: 12

If discharge (Q) is 16.75 ≥ Q > 14.65, then: Tartar_WL = 0.2091 * Discharge + 108.125

Number of instances: 647

RULE num: 13

If discharge (Q) is 23.75 ≥ Q > 16.75, then: Tartar_WL = 11.6874 * Discharge - 71.2188

Number of instances: 1255

RULE num: 14

If discharge (Q) is Q > 23.75, then: Tartar_WL = 12.7678 * Discharge - 96.9495

Number of instances: 1027

2. RULES FOR OTOŠKA JAMA MODEL TREE

RULE num: 1

If discharge (Q) is $0.65 \geq Q > 0$, then: Otoska_WaterLevel = -5.2254 * Discharge + 68.1196

Number of instances: 5770

RULE num: 2

If discharge (Q) is $1.05 \geq Q > 0.65$, then: Otoska_WL = 60.1457 * Discharge + 33.6778

Number of instances: 3775

RULE num: 3

If discharge (Q) is $2.35 \geq Q > 1.05$, then: Otoska_WL = 18.3538 * Discharge + 83.6873

Number of instances: 2556

RULE num: 4

If discharge (Q) is $4.35 \geq Q > 2.35$ then: Otoska_WL = 17.762 * Discharge + 89.4115

Number of instances: 1914

RULE num: 5

If discharge (Q) is $5.45 \geq Q > 4.35$, then: Otoska_WL = 16.793 * Discharge + 94.5474

Number of instances: 687

RULE num: 6

If discharge (Q) is $7.05 \geq Q > 5.45$, then: Otoska_WL = 7.3992 * Discharge + 148.8376

Number of instances: 1061

RULE num: 7

If discharge (Q) is 9.05 ≥ Q > 7.05, then: Otoska_WL = 13.026 * Discharge + 114.3833

Number of instances: 2696

RULE num: 8

If discharge (Q) is 11.35 ≥ Q > 9.05, then: Otoska_WL = 27.9673 * Discharge - 10.427

Number of instances: 1651

RULE num: 9

If discharge (Q) is 15.95 ≥ Q > 11.35, then: Otoska_WL = 20.8225 * Discharge + 75.766

Number of instances: 2328

RULE num: 10

If discharge (Q) is 17.75 ≥ Q > 15.95, then: Otoska_WL = 27.1918 * Discharge - 22.0379

Number of instances: 490

RULE num: 11

If discharge (Q) is 20.65 ≥ Q > 17.75, then: Otoska_WL = 16.6471 * Discharge + 168.4306

Number of instances: 745

RULE num: 12

If discharge (Q) is 39.5 ≥ Q > 20.65, then: Otoska_WL = 12.0442 * Discharge + 272.8663

Number of instances: 932

RULE num: 13

If discharge (Q) is 42.25 ≥ Q > 39.5, then: Otoska_WL = 12.9652 * Discharge + 248.7391

Number of instances: 14

RULE num: 14

If discharge (Q) is 43.25 ≥ Q > 42.25, then: Otoska_WL = 10.7057 * Discharge + 347.8124

Number of instances: 6

RULE num: 15

If discharge (Q) is 44.15 ≥ Q > 43.25, then: Otoska_WL = 10.7057 * Discharge + 348.3733

Number of instances: 6

RULE num: 16

If discharge (Q) is 44.45 ≥ Q > 44.15, then: Otoska_WL = 10.7057 * Discharge + 348.0573

Number of instances: 2

RULE num: 17

If discharge (Q) is 47.9 ≥ Q > 44.45, then: Otoska_WL = 12.9328 * Discharge + 254.587

Number of instances: 23

RULE num: 18

If discharge (Q) is 56.5 ≥ Q > 47.9, then: Otoska_WL = 11.6595 * Discharge + 317.5262

Number of instances: 60

RULE num: 19

If discharge (Q) is 70.85 ≥ Q > 56.5, then: Otoska_WL = 10.9623 * Discharge + 354.5954

Number of instances: 33

RULE num: 20

If discharge (Q) is Q > 70.85, then: Otoska_WL = 10.3205 * Discharge + 409.6409

Number of instances: 210

3. RULES FOR MARTEL'S ROCK-FALL MODEL TREE

RULE num: 1

If discharge (Q) is $0.55 \geq Q > 0$, then: rock-fall_WL = 0.126 * Discharge + 25.9691

Number of instances: 2755

RULE num: 2

If discharge (Q) is $0.75 \geq Q > 0.55$, then: rock-fall_WL = 5.9353 * Discharge + 19.283

Number of instances: 6233

RULE num: 3

If discharge (Q) is $0.85 \geq Q > 0.75$, then: rock-fall_WL = 0.3569 * Discharge + 28.7457

Number of instances: 1596

RULE num: 4

If discharge (Q) is $1.15 \geq Q > 0.85$, then: rock-fall_WL = 0.2106 * Discharge + 38.1865

Number of instances: 4358

RULE num: 5

If discharge (Q) is $1.35 \geq Q > 1.15$, then: rock-fall_WL = 14.4359 * Discharge + 29.4606

Number of instances: 1378

RULE num: 6

If discharge (Q) is $1.75 \geq Q > 1.35$, then: rock-fall_WL = 0.7278 * Discharge + 55.4077

Number of instances: 805

RULE num: 7

If discharge (Q) is $1.95 \geq Q > 1.75$, then: rock-fall_WL = 0.8667 * Discharge + 60.4264

Number of instances: 487

RULE num: 8
If discharge (Q) is 2.55 ≥ Q > 1.95, then: rock-fall_WL = 18.3467 * Discharge + 31.6527
Number of instances: 1278

RULE num: 9
If discharge (Q) is 3.95 ≥ Q > 2.55, then: rock-fall_WL = 27.5037 * Discharge + 11.1362
Number of instances: 1707

RULE num: 10
If discharge (Q) is 6.65 ≥ Q > 3.95, then: rock-fall_WL = 31.1945 * Discharge - 3.5241
Number of instances: 2176

RULE num: 11
If discharge (Q) is 7.65 ≥ Q > 6.65, then: rock-fall_WL = 56.7951 * Discharge - 157.0611
Number of instances: 1628

RULE num: 12
If discharge (Q) is 8.05 ≥ Q > 7.65, then: rock-fall_WL = 0.7383 * Discharge + 285.0318
Number of instances: 673

RULE num: 13
If discharge (Q) is 9.25 ≥ Q > 8.05, then: rock-fall_WL = 0.6387 * Discharge + 298.0476
Number of instances: 1872

RULE num: 14

If discharge (Q) is $10.35 \geq Q > 9.25$, then: rock-fall_WL = 61.3943 * Discharge - 233.5322

Number of instances: 1023

RULE num: 15

If discharge (Q) is $20.25 \geq Q > 10.35$, then: rock-fall_WL = 26.0725 * Discharge + 157.8744

Number of instances: 4367

RULE num: 16

If discharge (Q) is $Q > 20.25$, then: rock-fall_WL = 9.9503 * Discharge + 498.7333

Number of instances: 1358

4. RULES FOR MARTEL'S CHAMBER MODEL TREE

RULE num: 1
If discharge (Q) is $0.55 \geq Q > 0$, then: Martelova_WaterLevel = 0.4567 * Discharge + 20.6791
Number of instances: 2519

RULE num: 2
If discharge (Q) is $0.75 \geq Q > 0.55$, then: Martel_WL = 129.8303 * Discharge - 49.912
Number of instances: 4706

RULE num: 3
If discharge (Q) is $0.95 \geq Q > 0.75$, then: Martel_WL = 0.5424 * Discharge + 39.4769
Number of instances: 2253

RULE num: 4
If discharge (Q) is $1.55 \geq Q > 0.95$, then: Martel_WL = 174.2396 * Discharge - 127.2088
Number of instances: 2376

RULE num: 5
If discharge (Q) is $1.75 \geq Q > 1.55$, then: Martel_WL = -132.6548 * Discharge + 353.8408
Number of instances: 249

RULE num: 6
If discharge (Q) is $1.95 \geq Q > 1.75$, then: Martel_WL = 2.5796 * Discharge + 136.807
Number of instances: 361

RULE num: 7

If discharge (Q) is 2.55 ≥ Q > 1.95, then: Martel_WL = 15.1008 * Discharge + 127.9822

Number of instances: 1035

RULE num: 8

If discharge (Q) is 2.85 ≥ Q > 2.55, then: Martel_WL = 36.0577 * Discharge + 90.4008

Number of instances: 325

RULE num: 9

If discharge (Q) is 3.65 ≥ Q > 2.85, then: Martel_WL = 35.6965 * Discharge + 94.9316

Number of instances: 836

RULE num: 10

If discharge (Q) is 4.85 ≥ Q > 3.65, then: Martel_WL = 25.5766 * Discharge + 131.194

Number of instances: 806

RULE num: 11

If discharge (Q) is 5.95 ≥ Q > 4.85, then: Martel_WL = 18.1583 * Discharge + 167.2508

Number of instances: 580

RULE num: 12

If discharge (Q) is 7.05 ≥ Q > 5.95, then: Martel_WL = 10.5004 * Discharge + 213.6896

Number of instances: 582

RULE num: 13

If discharge (Q) is 7.65 ≥ Q > 7.05, then: Martel_WL = 14.9923 * Discharge + 184.9948

Number of instances: 824

RULE num: 14

If discharge (Q) is 8.95 ≥ Q > 7.65, then: Martel_WL = 0.1901 * Discharge + 299.8359

Number of instances: 1753

RULE num: 15

If discharge (Q) is 9.55 ≥ Q > 8.95, then: Martel_WL = 15.2413 * Discharge + 167.0576

Number of instances: 500

RULE num: 16

If discharge (Q) is 11.25 ≥ Q > 9.55, then: Martel_WL = 7.1177 * Discharge + 244.8669

Number of instances: 1247

RULE num: 17

If discharge (Q) is 13.35 ≥ Q > 11.25, then: Martel_WL = 2.8495 * Discharge + 297.1484

Number of instances: 1273

RULE num: 18

If discharge (Q) is 16.75 ≥ Q > 13.35, then: Martel_WL = 6.4829 * Discharge + 250.6824

Number of instances:1347

RULE num: 19

If discharge (Q) is 22.75 ≥ Q > 16.75, then: Martel_WL = 5.9059 * Discharge + 264.1711

Number of instances: 1162

RULE num: 20

If discharge (Q) is 31.65 ≥ Q > 22.75, then: Martel_WL = 4.0492 * Discharge + 304.9665

Number of instances: 662

RULE num: 21

If discharge (Q) is $70.85 \geq Q > 31.65$, then: Martel_WL = 3.8854 * Discharge + 304.1069

Number of instances: 248

RULE num: 22

If discharge (Q) is $Q > 70.85$, then: Martel_WL = 10.3543 * Discharge - 131.2261

Number of instances: 210

5. RULES FOR MAGDALENA JAMA MODEL TREE

RULE num: 1

If discharge (Q) is $0.55 \geq Q > 0$, then: Magdalena_WaterLevel = -0.0839 * Discharge + 102.2384

Number of instances: 3042

RULE num: 2

If discharge (Q) is $0.65 \geq Q > 0.55$, then: Magdalena_WL = -0.0326 * Discharge + 94.6186

Number of instances: 4285

RULE num: 3

If discharge (Q) is $1.05 \geq Q > 0.65$, then: Magdalena_WL = 19.3562 * Discharge + 73.7482

Number of instances: 6716

RULE num: 4

If discharge (Q) is $1.15 \geq Q > 1.05$, then: Magdalena_WL = 0.5847 * Discharge + 92.2723

Number of instances: 1070

RULE num: 5

If discharge (Q) is $1.35 \geq Q > 1.15$, then: Magdalena_WL = 0.587 * Discharge + 96.9933

Number of instances: 1063

RULE num: 6

If discharge (Q) is $2.05 \geq Q > 1.35$, then: Magdalena_WL = 8.1133 * Discharge + 90.3849

Number of instances: 891

RULE num: 7

If discharge (Q) is 2.35 ≥ Q > 2.05, then: Magdalena_WL = 26.6994 * Discharge + 52.881

Number of instances: 381

RULE num: 8

If discharge (Q) is 2.95 ≥ Q > 2.35, then: Magdalena_WL = 0.5047 * Discharge + 116.1766

Number of instances: 698

RULE num: 9

If discharge (Q) is 3.25 ≥ Q > 2.95, then: Magdalena_WL = 0.706 * Discharge + 120.2569

Number of instances: 290

RULE num: 10

If discharge (Q) is 3.65 ≥ Q > 3.25, then: Magdalena_WL = 0.6231 * Discharge + 122.058

Number of instances: 274

RULE num: 11

If discharge (Q) is 4.35 ≥ Q > 3.65, then: Magdalena_WL = 6.065 * Discharge + 107.1569

Number of instances: 412

RULE num: 12

If discharge (Q) is 4.55 ≥ Q > 4.35, then: Magdalena_WL = -97.1224 * Discharge + 560.577

Number of instances: 138

RULE num: 13

If discharge (Q) is 4.75 ≥ Q > 4.55, then: Magdalena_WL = -42.5204 * Discharge + 335.1545

Number of instances: 159

RULE num: 14

If discharge (Q) is 7.05 ≥ Q > 4.75, then: Magdalena_WL = 4.7443 * Discharge + 119.8988

Number of instances: 1169

RULE num: 15

If discharge (Q) is 9.95 ≥ Q > 7.05, then: Magdalena_WL = 4.5208 * Discharge + 126.1422

Number of instances: 963

RULE num: 16

If discharge (Q) is 14.65 ≥ Q > 9.95, then: Magdalena_WL = 0.1679 * Discharge + 176.6882

Number of instances: 623

RULE num: 17

If discharge (Q) is 36.3 ≥ Q > 14.65, then: Magdalena_WL = 4.138 * Discharge + 117.2707

Number of instances: 707

RULE num: 18

If discharge (Q) is 44.95 ≥ Q > 36.3, then: Magdalena_WL = 4.0323 * Discharge + 119.9919

Number of instances: 45

RULE num: 19

If discharge (Q) is 61.8 ≥ Q > 44.95, then: Magdalena_WL = 4.4977 * Discharge + 101.9915

Number of instances: 79

RULE num: 20

If discharge (Q) is 87.65 ≥ Q > 61.8, then: Magdalena_WL = 5.0978 * Discharge + 65.2936

Number of instances: 58

RULE num: 21

If discharge (Q) is Q > 87.65, then: Magdalena_WL = 6.9745 * Discharge - 100.3981

Number of instances: 57

6. RULES FOR PIVKA JAMA MODEL TREE

RULE num: 1
If discharge (Q) is $0.55 \geq Q > 0$, then: Pivka_WaterLevel = 0.0801 * Discharge + 46.6276
Number of instances: 2755

RULE num: 2
If discharge (Q) is $0.75 \geq Q > 0.55$, then:Pivka_WL = 27.3388 * Discharge + 28.6003
Number of instances: 6233

RULE num: 3
If discharge (Q) is $1.15 \geq Q > 0.75$, then:Pivka_WL = 18.836 * Discharge + 35.9698
Number of instances: 5813

RULE num: 4
If discharge (Q) is $1.35 \geq Q > 1.15$, then: Pivka_WL = 14.1905 * Discharge + 43.4162
Number of instances:1378

RULE num: 5
If discharge (Q) is $1.45 \geq Q > 1.35$, then: Pivka_WL = 0.3891 * Discharge + 64.3802
Number of instances: 426

RULE num: 6
If discharge (Q) is $1.65 \geq Q > 1.45$, then: Pivka_WL = -105.929 * Discharge + 228.8973
Number of instances: 148

RULE num: 7
If discharge (Q) is $1.75 \geq Q > 1.65$, then: Pivka_WL = 0.749 * Discharge + 62.8536
Number of instances: 231

RULE num: 8

If discharge (Q) is 1.95 ≥ Q > 1.75, then: Pivka_WL = 0.6609 * Discharge + 65.4025

Number of instances: 487

RULE num: 9

If discharge (Q) is 2.15 ≥ Q > 1.95, then: Pivka_WL = 13.5424 * Discharge + 41.7196

Number of instances: 393

RULE num: 10

If discharge (Q) is 2.35 ≥ Q > 2.15, then: Pivka_WL = 0.5907 * Discharge + 72.5575

Number of instances: 430

RULE num: 11

If discharge (Q) is 2.95 ≥ Q > 2.35, then: Pivka_WL = 0.3773 * Discharge + 79.9327

Number of instances: 988

RULE num: 12

If discharge (Q) is 4.95 ≥ Q > 2.95, then: Pivka_WL = 15.0897 * Discharge + 41.2334

Number of instances: 2042

RULE num: 13

If discharge (Q) is 5.95 ≥ Q > 4.95, then: Pivka_WL = 0.1872 * Discharge + 123.8389

Number of instances: 795

RULE num: 14

If discharge (Q) is 6.45 ≥ Q > 5.95, then: Pivka_WL = 10.4614 * Discharge + 65.5859

Number of instances: 354

RULE num: 15
If discharge (Q) is 7.05 ≥ Q > 6.45, then: Pivka_WL = 0.1179 * Discharge + 126.7444
Number of instances: 756

RULE num: 16
If discharge (Q) is 7.45 ≥ Q > 7.05, then: Pivka_WL = 8.7389 * Discharge + 68.7149
Number of instances: 564

RULE num: 17
If discharge (Q) is 7.95 ≥ Q > 7.45, then: Pivka_WL = 0.2725 * Discharge + 135.4885
Number of instances: 678

RULE num: 18
If discharge (Q) is 8.35 ≥ Q > 7.95, then: Pivka_WL = 0.2991 * Discharge + 138.2318
Number of instances: 546

RULE num: 19
If discharge (Q) is 9.95 ≥ Q > 8.35, then: Pivka_WL = 14.6987 * Discharge + 19.5434
Number of instances: 1757

RULE num: 20
If discharge (Q) is 16.45 ≥ Q > 9.95, then: Pivka_WL = 8.532 * Discharge + 83.1207
Number of instances: 2788

RULE num: 21
If discharge (Q) is 21.55 ≥ Q > 16.45, then: Pivka_WL = 9.1035 * Discharge + 79.9414
Number of instances: 708

RULE num: 22

If discharge (Q) is Q > 21.55, then: Pivka_WL = 11.013 * Discharge + 37.9576

Number of instances: 307