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EPIKARST CONTROL OF THE DISCHARGE, WATER QUALITY AND BIODIVERSITY IN THE VELIKA PASICA CAVE (CENTRAL SLOVENIA)

DISSERTATION

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Izjavljam, da je doktorsko delo v celoti moje avtorsko delo.

I declare that this thesis is exclusively my own authorship.

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SUMMARY

Due to its specific geological position, epikarst is crucial for the surface and subsurface ecosystems, performing as an important ecological water reservoir. However, its complex structure results in the relatively non-homogeneous distribution of the water storage, which is also difficult to extract for human use. Thus, it is of great significance to uncover the mystery of this karstic layer. Drip water in an epikarst cave is one of the most direct and practical research sources, as it flows out from epikarst containing vital information.

Within the framework of this thesis, commencing in June 2006, four permanent drip sites (designated as VP1-VP4) were monitored in the small epikarstic Velika Pasica Cave, located south of Ljubljana (Slovenia). In order to 1) investigate the hydrological, hydrochemical and eco-hydrological characteristics of the drip water, 2) reveal their variation with the seasonal micro-climate change at different sites, and 3) explore the relationship between the environmental factors and the aquifer fauna, two regimes of field monitoring were conducted. The first was the continuous automatic measurements by means of sensors connected to two data-loggers. One was set in the cave for recording the discharge, the water temperature and the adjacent air temperature from four different drips. The second data-logger with sensors for air temperature, precipitation and soil humidity was set on the surface, near the entrance to the cave. The second regime was the field water and fauna sampling.

From this research, I found that:

1) The hydrodynamic of the drip water in the cave is a functional response to the precipitation, epikarst storage capacity, and undefined underground structures. According to the speed and intensity in response to the precipitation, the drips can be divided into four types: “rapid response without hysteresis”, “fast response with lag”, “rapid response with congests discharge” and “slow response with congest discharge”. Those drip water discharge types indicate different groundwater flows within the epikarst zone, most of them related to the seasonal flow, while the extreme events of individual drips are clustered in distinct groups, providing some additional

information on the cave cover structure. In order to assess the storage capacity at different drip sites, several recession analyses methods were applied for the slow water in the epikarst. Combining the hydrological characteristics of four drips, I found that the matching strip method was the more appropriate one for the drip water recession analyses. The water flow in the epikarst could be divided into: the fast flow, the intermediate flow and the slow flow with different recession coefficient k. The volume of water (the epikarst storage) retained in the reservoir could be presented as a function of its specific recession coefficient.

2) Drip VP1 and VP2 were analyzed in order to clarify the hydrochemical response of drip water to the water supplement regime. It was found that two types of rainfall could be identified: "diffuse rainfall" and "concentrated rainfall", and they affected the variation of electrical conductivity (EC) differently. At VP1: i) an expected response to the dilution effect was apparent whenever intensive rainfall occurred; ii) after the fast flow from concentrated rain events, it had a process of slow flow dissolution, with decreased EC; while during the diffuse rain events it could arrive at the dissolution equilibrium, rising to a stable EC. Due to the seepage flow at VP2, the piston effect was dominated there. Meanwhile, the Mg/Ca ratio in the cave drip water showed a distinct pattern over time, influenced by the prior calcite precipitation effect and the retention time, which was affected by different rain patterns.

When drip VP1 was studied during a period which occurred at the end of a long wet, cold winter, the drip water was continually supplied by both rain water and snowmelt water, thus the dilution effect was the dominant mechanism in the hydrochemical processes, and the effect of CO_2 corrosion and prior calcite precipitation was weakened with that condition. The recharge regime is one of the principal impacts on drip water hydrochemistry, but other factors should be considered in future studies.

3) In the small and relatively closed cave, the cave temperature is controlled by the external climate, due to seasonal oscillations. The temperature curve of the inner

cave area was much smoother in comparison with the surface, indicating that thermal energy was transferred from the surface through the matrix by conduction. Air convection also occurred in the cave, especially during the winter time in the section close to the entrance. In addition, the temperature variations in dripping water during the rain events indicated strong relationship between the water discharge and drip water temperature.

4) Various aquatic species (predominantly stygobionts) were found in the Velika Pasica Cave. The specific composition and distribution of different dripping sites was the result of the combined effects from various environmental factors. After the aquatic species had colonized, the quantity and quality of the water in epikarst was crucial for them to adapt and survive in the new environment. According to the Canonical Correspondence Analyses of the species with different hydrological and hydrochemical parameters, it was found that there are significant differences in species response to environmental parameters at different drips. Species are differently distributed across drips, and other factors, such as organic matter, also should be considered in future research in order to ascertain more accurate impacts on this difference of bio-micro-distribution. Thus, it can be concluded that the drip water carries the hydrological, hydrochemical and ecohydrological information of the epikarst. Concurrently, these factors have close correlation between each other, such as the hydrological factors that affect the drip water hydrochemical characteristics and both the hydrological and hydrochemical factors affect the faunal composition at different sites.

This study represents a part of a comprehensive analysis of karstic aquifers, focused to a better understanding of the karst hydrology and biology, even if several aspects of such relationships are still poorly known and in urgent need to be discovered.

Key words: eco-hydrology, epikarst, cave drip water, rain regime, recession analysis, Mg/Ca, snowmelt water, vadose flow

Vpliv epikrasa na količino in kakovost vode ter biotsko raznovrstnost v jami Velika Pasica (osrednja Slovenija)

POVZETEK

Zaradi svojega posebnega geološkega položaja je epikras ključnega pomena za površinske in podzemne ekosisteme, saj opravlja pomembno vlogo kot ekološki vodni rezervoar. Vendar pa je njegova kompleksna zgradba posledica relativno nehomogene porazdelitve zmožnosti za shranjevanje vode, obenem pa je le-ta težko dostopna za neposredo uporabo. Zato je zelo pomembno, da se ugotovijo značilnosti te kraškega plasti. Prenikla voda v jamah je ena izmed najbolj neposrednih in praktičnih virov za tovrstne raziskave, saj priteče neposredno iz epikrasa in vsebuje pomembne informacije.

V okviru te doktorske naloge, ki obsega obdobje od junija 2006 dalje, smo spremljali štiri stalne curke prenikle vode (poimenovane VP1-VP4) v majhni epikraški jami Velika Pasica, ki se nahaja južno od Ljubljane (Slovenija).

Z namenom da se: 1) raziščejo hidrološke, hidrokemične in eko-hidrološke lastnosti prenikle vode, 2), pokažejo sezonske razlike v mikro-klimatskih pojavih na različnih lokacijah, in 3) raziščejo odnosi med okoljskimi dejavniki in vodno favno, sta bila izvedena dva načina spremljanja dogodkov na terenu. Prva je bila z neprekinjenimi samodejnimi meritvami s pomočjo senzorjev, povezanih z dvema zapisovalniki podatkov (data-logger). Eden je bil v jami za ezapisovanje pretokov, temperature vode in zraka iz štirih različnih curkov. Drugi zapisovalnik podatkov s senzorji za temperaturo zraka, količine padavin in vlage v tleh je bil nameščen na površju, v bližini vhoda v jamo. Drugi način je bil vzorčenje vode in favne.

Iz te raziskave sem ugotovil, da je:

1) pretok prenikle vode v jami neposreden odziv na padavine, skladiščne zmogljivosti epikrasa in neopredeljenih podzemnih struktur. Glede na hitrost in intenzivnost odgovora na padavine, se curke prenikajoče vode lahko razdeli v štiri skupine: "močan odziv brez zamika", "močan odziv z zamikom", "hiter odziv s zmanjšano intenzivnostjo" in "počasen odziv z zmanjšano intenzivnostjo". Tej tipi intenzivnosti curkov prenikajoče vode kažejo na različne tokove podzemne vode v epikrasu. Večina od njih je povezanih s sezonsko dinamiko, medtem ko so izjemni dogodki posameznih curkov zbrani v ločenih skupinah, ki nudijo dodatne informacije o zgradbi plasti nad jamo. Da bi ocenili skladiščne zmogljivosti posameznih curkov prenikle vode, so bile uporabljene različne metode analiziranja recesije za počasni iztek vode iz epikrasa. Z združevanjem hidroloških značilnosti štirih curkov prenikle vode, sem ugotovil, da je bila metoda »najboljšega prilagajanja krivulji«, najbolj primerna za analizo recesije curkov prenikle vode. Pretok vode v epikrasu lahko razdelimo na: hiter pretok, zmerni pretok in počasni pretok, vsak z drugačnim koeficientom recesije »*k*«. Količina zadržane vode vode (epikraški vodonosnik) v rezervoarju se lahko predstavi kot funkcijo njenega specifičnega koeficienta recesije.

2) curka VP1 in VP2 sta bila analizirana, da bi razjasnili hidrokemični odziv prenikle vode na režim padavinske vode. Ugotovljeno je bilo, da je mogoče opredeliti dve vrsti padavin: "razpršene padavine" in "intenzivne padavine«, in le-te so vplivale na spremembo električne (ES) prevodnosti

prenikle vode različno. Na VP1: i) pričakovani odziv na učinek redčenja prenikle vode je bil očiten, kadar je prišlo do intenzivnih padavin; ii) po hitrem toku iz intenzivnih padavin je prišlo do počasnega pretoka, z zmanjšano ES; medtem ko je v primeru razpršenih padavin prišlo do ravnotežja v raztapljanja, kar je vodilo do stabilnosti ES. Zaradi počasnega pretoka z zamikom na VP2, je prevladoval učinek batne črpalke. Razmerje Mg / Ca v prenikli vodi je pokazalo značilen vzorec tekom časa, kar je bila posledica predhodnega kalcitnega obarjanja in retencijskega časa, ki je bil pod vplivom različnih vzorcev dežja.

Ker je bil curek prenikle vode VP1 preučevan ob koncu dolge mokre, mrzle zime, je bila prenikla voda v curkih mešanica deževnice in snežnice, s čimer je bil učinek redčenja prevladujoč mehanizem v hidrokemičnih procesih, medtem ko je bil učinek korozije CO_2 in predhodnega obarjanje kalcita oslabljeno. Način polnjenja epikraškega vodonosnika je eden glavnih vplivov na hidrokemijo prenikle vode, vendar so še drugi dejavniki, ki jih je treba obravnavati v prihodnjih raziskavah.

3) Pri majhni in razmeroma zaprti jami, temperaturo v jami nadzirajo zunanji klimatski pogoji, v skladu z sezonskimi nihanji. Temperaturna krivulja v notranjem delu jame je bila veliko bolj gladka v primerjavi s tisto na površini, kar kaže, da se toplotna energija prenese s površine skozi kamnino s prevajanjem. Kroženje zraka v jami je bilo prisotno, še posebej v zimskem času, v oddelku, ki je blizu vhoda. Poleg tega so nihanja temperature v prenikli vodi iz obdobja deževnih dogodkov nakazala na močan odnos med prenikanjem vode in temperaturo prenikle vode.

4) Različne vrste vodnih živali (pretežno stigobionti) so našli v jami Veliki Pasica. Enkratna sestava in porazdelitev med različnimi curki prenikle vode je posledica kombiniranih učinkov različnih okoljskih dejavnikov. Potem ko so vodne vrste kolonizirale podzemlje, je bile količina in kakovost vode v epikrasu ključnega pomena za njih, da se prilagodijo in preživijo v novem okolju. Glede na rezultate kanonične korelacijske analize vrst z različnimi hidrološkimi in hidrokemijskimi parametri, je bilo ugotovljeno, da obstajajo velike razlike v odzivu vrst na okoljske parametre v različnih curkih prenikle vode. Vrste so različno porazdeljeni glede na curke prenikle vode, in drugi dejavniki, kot so organske snovi, je treba obravnavati tudi v prihodnjih raziskavah, da bi ugotovili natančnejše vplive na te razlike v bio-mikro-porazdelitvah.

Tako je mogoče sklepati, da prenikla voda nosi s seboj hidrološke, hidrokemijske in eko-hidrološke informacije o epikrasu. Hkrati imajo ti dejavniki, kot so hidrološki dejavniki, tesno povezavo med seboj, ki vplivajo na hidrokemijske značilnosti prenikle vode in oboji, hidrološki in hidrokemijski dejavniki, vplivajo na sestavo živalstva v različnih curkih prenikle vode.

Ta študija predstavlja del celovite analize kraških vodonosnikov, ki je usmerjena k boljšemu razumevanju kraške hidrologije in biologije, čeprav več vidikov te zveze še vedno slabo poznamo in je zato nujno, da jih bolje razumemo.

Ključne besede: eko-hidrologija, epikras, prenikla voda, dežne padavine, analiza recesije, Mg / Ca, topljenje snega, vadozni tok

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Chapter 1 Introduction

1.1 The layer called epikarst and related topics

1.1.1 The basic facts about epikarst

The word “karst” refers to a type of terrain, formed on carbonate rock (limestone and dolomite) where rainwater and groundwater have enlarged openings and small cracks in order to form a subsurface drainage system, both in the unsaturated (vadose zone) and saturated (phreatic) zones (White, 1988; Ford and Williams, 2007). Carbonate rocks are primarily made up of carbonate minerals, such as calcite ($CaCO_3$) in the case of limestone and marble, and dolomite ($CaMg(CO_3)_2$) in the case of dolostone. As indicated in Figure 1-1, a rain droplet containing dissolved CO_2 from the atmosphere, enhances its concentration as it percolates through the soil layer, thus forming a weak solution of carbonic acid ($H_2O + CO_2 = H_2CO_3$). This slightly acidic water is then the main corrosion source to form the specific karst geomorphology of a karst area.

The word “epikarst” emerged during 1970s, when Mangin (1973) introduced it, and it was later improved by Williams (1983), and finally applied as a sub-system of vadose zone with specific functions within a karst system by Klimchouk (2004). Approximately 40 years have passed, hundreds of research studies have been published, and the role of the epikarst is now widely acknowledged and well accepted (White and Culver, 2012).

The cave biologist Rouch (1968) recognised the existence of a permanent aquifer probably perched between the surface and caves after he found some specific aquatic fauna in cave drips. Several years later, Mangin (1973) named and defined the epikarst aquifer by its hydrological function. Bakalowicz et al. (1974) analysed the delaying function of storm water which passed through the vadose zone. Williams (1972) noticed the subcutaneous processes in the evolution of surface landforms, and combined it with several hydrological and geomorphological concepts (Williams, 1983, 1985). In parallel, speleological investigations demonstrated a substantial flow in the vadose zone in the arid mountains of Central

Asia (Klimchouk, 1987). Further important contributions to the understanding of epikarst systems were made by Klimchouk (1995, 2000, 2004), Perrin et al. (2003), Trček (2003), Bakalowicz (2004), Palmer (2004), Jones et al. (2004), Williams (2004, 2008), and Ford and Williams (2007) .

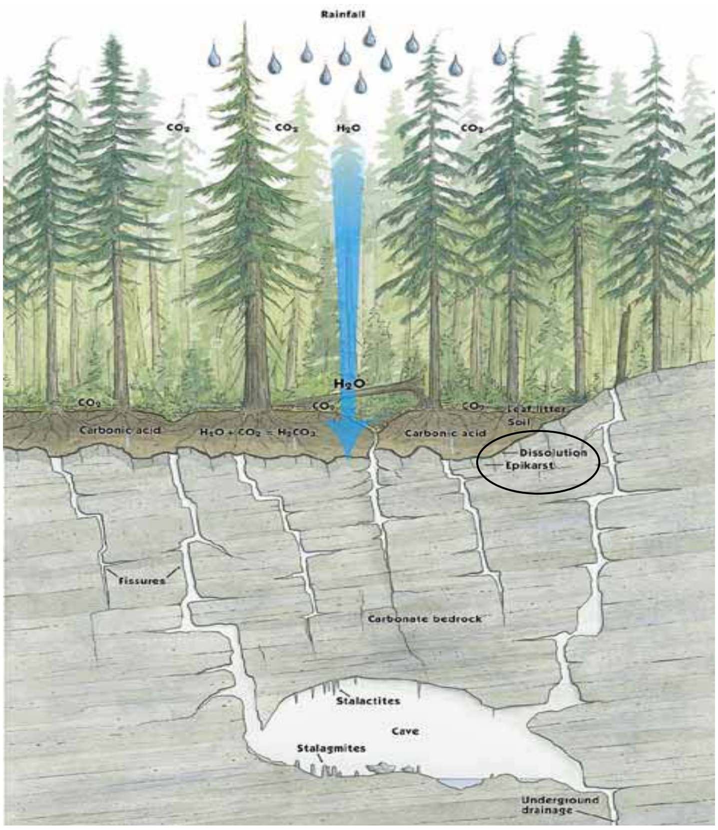

Figure 1-1: A schematic diagram of epikarst and cave formations in the karst system and water flow in the shallow karst system (British Columbia Ministry of Forests, Canada, 1997).

1.1.2 The definition of epikarst

However, “What is epikarst?” was asked by Jones et al. (2004). The vadose zone in karst comprises the soil (if there is any), the epikarst zone, and the transmission zone (Figures 1-1 and 1-2). Klimchouk (2004) defined it as: epikarst is “the uppermost weathered zone of carbonate rocks with homogeneously distributed porosity and permeability, above the bulk rock mass below; it is also a regulative subsystem that functions to store, split into several components and temporally distribute authogenic infiltration recharge to the vadose zone". Williams (2008) expressed it more simply as: "Epikarst, also known as the subcutaneous zone, comprises highly weathered carbonate bedrock immediately beneath the surface or beneath the soil (when present) or exposed at the surface". The best developed epikarst is typically found in the approximately 10 m thick pure, crystalline limestone or marble block, which contains a suspended aquifer (Williams, 2008).

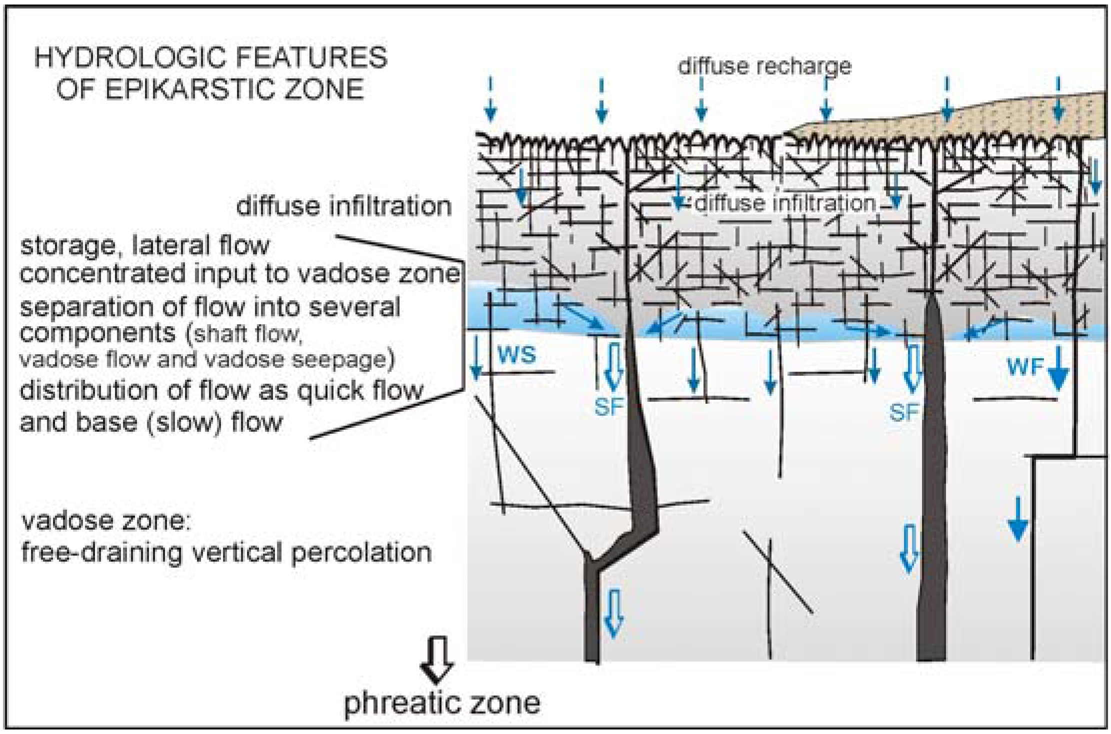

Figure 1-2: Diagram illustrating principal structural and hydrologic features of epikarst, and its relationship with the vadose zone. SF = shaft flow, WF = vadose flow, WS = vadose seepage (Klimchouk, 2004).

According to its definition and geological location, epikarst is a crucial for the karst hydrology. Seepage discharge by slow leakage paths from the epikarst, such as cave drip water, contains crucial information of the epikarst. Most hydrogeologists consider that in the epikarst, water percolates downwards through a zone dominated by transmission rather than a storage that delivers recharge to the saturated or phreatic zone. In fact, epikarst also acts as an important storage subsystem. Perrin et al. (2003) suggested that epikarst can potentially store significantly more water than the phreatic zone does. In conveying water flow downward, epikarst performs a different activity. Gunn (1974, 1981) used the terms: “vadose seepage”, “vadose flow” and “”shaft flow”, as also indicated in Figure 1-2 (Klimchouk, 2004). Another popular description of epikarst flow was derived from Smart and Friedrich (1987), which was based on the maximum discharge and coefficient of variation, where the epikarst flow was classified into seepage flow, seasonal flow, percolation stream, vadose flow, shaft flow and subcutaneous flow.

1.1.3 The function of epikarst

Generally, the water in karst aquifers is recharged from the surface by either rapid injection into the system (via sinkholes, or via sinking streams or rivers) or more slowly via dispersed infiltration (rain and snowmelt water). In practice, the recharge into most karst systems is a mixture from different sources (Ford and Williams, 2007). When the recharge enters into the sub-surface, some of it is stored in voids in the bedrock.

Due to the specific position of the epikarst, water is recharged from the surface by rainwater or snowmelt water through fractures and conduits. During its transmission, some is retained in the epikarst and the rest infiltrates into deeper systems. In order to interpret the complex structure of the subsurface, several hydrological features need to be incorporated.

The jagged epikarst interface can frequently be observed in road cuts and quarry walls (William, 2008). In some areas of the world, the epikarst is overlaid by a thin soil layer. Carbon dioxide (CO_2) within the soil (from the respiration of plant roots and microbes) enhances the amount of CO_2 in water as it percolates down to the water table. This increased CO_2 is crucial in increasing the dissolutive capacity of water (Ford and Williams, 2007). It is also the main driving force for the formation of the voids in the subsurface.

In karst systems, these voids have been classified into three categories by size: (a) microscopic voids between grains, (b) fractures and (c) solution-developed conduits within the rock. Conduits are the largest openings and allow for quick transport of large volumes of water at high velocities through the system to the spring. The minimum size for a conduit has been suggested to be 1 cm (White, 1988). At this dimension, the water flow becomes turbulent and is capable of moving fine particles of sediment. Fractures are smaller than conduits and range from 0.1 to 1 mm (Tudek and Vesper, 2011). Water flows more slowly through the fracture network than through the conduit network. Thus, fractures can also play a significant role in the transmission of water. However, they may also play a major role in water storage.

Bedrock porosity is the storage space between individual particles of small rocks, which represents the largest potential storage reservoir in a karst aquifer. It is also the most difficult reservoir to access. Water trapped in the bedrock matrix is released very slowly and accounts for the most of storage (Ford and Williams, 2007). The distribution of water between the three types of aquifer permeability controls the total volume of water stored in the epikarst aquifer. While scientists know that epikarst aquifers have significant storage capacities, little is still known about its role in the overall system or how to quantify the storage capacity.

1.2 An overview on related research on cave drip waters

1.2.1 The main global studied drips

The research on cave drips has been conducted for several decades. Although it is not an exhaustive summary, Table 1-1 lists studies of various drips and has highlighted some key studies from different parts of the world. Initial studies were carried out on the measurement and characterization of cave drips in the vadose zone (Pitty, 1966, 1971; Gunn, 1974; Smart and Friedrich, 1987), and these monitoring cave drip water behaviour characteristics were conducted in order to define flow patterns through the vadose zone. Furthermore, drip classification schemes were proposed based on the maximum discharge (Q_{max}) and flow rate variability (coefficient of variation, CV) during a certain time (see section 3.4.1) in order to classify the drip response to surface weather and infer the possible water flow pattern in the unsaturated zone together with the complexity of flow routes (Smart and Friedrich, 1987; Baker and Brunsdon, 2003). These original classifications were based largely on manually timed drip rate data, recorded on a monthly basis.

Table 1-1: A partial summary of published and unpublished sources of cave drip rate monitoring data for the purpose of characterizing flow regimes in the unsaturated zone of karst aquifers (Jex et al., 2012). Stalagmate [TM]: a stalagmate drip counter.

Author	Cave Region	Monitiring period (yrs)	Method		Sampling interval	Total number of monitoring sites	Number of automatic monitoring sites
Genty and Deflande 1998	Frence	5	auto	Tipping bucket	10min	1 drip	-
Baker and Brundson,2003	N England	4	auto	Tipping bucket	15min	6drips	Not stated
Fairchild et al., 2006	S England	2	Manual	Stopwatch	-	15 drips	-
Baldini et al., 2006	SW Ireland	3	Manual	Calibrated bottle (rapid drips) and stop watch (slow drips)	-	Not stated	
Fernandez-Cortez et al., 2007	SE Spain	4	Auto	Unknown automated logging system	1 hr	1 drip	1 drip
MacDonald and Drysdale, 2007	Australia	4	Auto	Unknown automated logging system	Unknown	10 drios	Not stated
Fuller et al., 2008	NW Scotland	2	Manual	Stopwatch	-	14 drips	-
Hu et al., 2008	Central China	3	Manual and Auto	Stopwatch and Unknown automated logging system	10 min (auto)	Unknown number of drips	-
Miorando et al., 2010	NE Italy	3 yrs (auto) 6 yrs (manual)	Manual and Auto	Stopwatch and Stalagmate TM	1hr (auto)	11 drips	Not stated
Treble et al., unpublished	SE Australia and W Australia	5 (manual) <1 (auto and ongoing)	Manual and Auto	Stopwatch and Stalagmate TM	15 min (auto)	3 drips	3 drips
Jex et al. unpublished	SE Australia	1 (ongoing)	Auto	Stalagmate TM	15 in	>30 drops	>30drips
Pronk et al., 2009	Jura Mountains, Switzerland	2 x 0.5	Auto	Unknown automated logging system	Unknown	1 drip	1 drip
Arbel et al., 2010	Northern Israel	3	Auto	Tipping bucket (8 ml capacity)	Variable (10 mins to a lew hours)	9 drips	9 drips
Kogovsek, 2010	Postojna, Slovenia	Since 1988	Manual and Auto	Stopwatech and Logotronic Gealog S unit	20 - 60 min	11 drips	3 drips
Sheffer et al., 2011	Northern Israel	3	Auto	Pressure transducer in a water collection barrel	5 min	3 integreted areas of multiple (102) drips, collectied on PVC sheeting	
Riechelmann et al., 2011	NW Germany		Manual (7 drips) and Auto (2 drips)	Stopwatech and Stalagmate TM	-	7 drips in 2 cave chambers	2 drips

To date, there is no study that replicates standard classifications using a spatial set of drip rate monitoring that applies a continuous, automatically logged drip rate data set (Jex et al., 2012). The more recent studies identified the non-linear discharge of cave drips (Genty and Deflandre, 1998; Baker and Brunsdon, 2003, Kogovsek, 2010) and the hydrochemical profiles of cave drips (McDonald and Drysdale, 2007, Kogovsek, 2010). Combined with other studies, cave drip water was also utilized as an initial media, such as in palaeo-climate reconstruction (Tooth and Fairchild, 2003; Cai et al., 2011; Hu et al., 2011; Fairchild and Baker, 2012) and eco-hydrology (Brancelj, 2002; Pipan and Brancelj, 2004; Pipan and Culver, 2005, 2007).

1.2.2 Hydrological research on cave drip waters

Karst aquifers could be divided into those within: (i) the soil zone, (ii) the epikarst and (iii) the saturated (phreatic) zone. In recent years, significant progress has been made in the area of karst hydrodynamic research. In some studies, the focus has been directed towards finer scale i.e. 'karst sub-catchments' (Baker and Brunsdon, 2003), with cave drip studies receiving particular attention (Fairchild et al., 1996; Baker et al., 1997; Genty and Deflandre, 1998; Baker et al., 2000; Tooth and Fairchild, 2003; McDonald and Drysdale, 2007). Many of the existing studies that focus on cave drip water were high-resolution studies of climatic and environmental change using speleothems (Gascoyne, 1983; Baker et al., 1993; Tan et al., 1996; Li et al., 1998; Li et al., 2000; Zhang and Yuan, 2001; Liu et al., 2002; Tan et al., 2003), while others have contributed significantly to basic cave hydrological research (Baker et al., 2000; Baker and Brunsdon, 2003; Tooth and Fairchild, 2003; McDonald et al., 2004; Fairchild et al., 2006). Some research focused on the catchment scale, where the hydrology of the karst aquifers were conceived as a three-component model comprising recharge (diffuse or concentrated), storage (vadose or phreatic) and flow (diffuse or concentrated) (Atkinson, 1977; Williams, 1983; Smart and Friedrich, 1987; White, 1988; Ford and Williams, 1989).

Cave drip water pertaining to the unsaturated zone, is mainly affected by soil properties, epikarst thickness and structure, and the degree of its weathering (Bottrell and Atkinson, 1992; Baker and Brunsdon, 2003; Fairchild et al., 2006). Therefore, the study of cave drip water can provide important information toward an understanding of the complex dynamic processes involved in the provision of karst water resources. In cave environments, the drip water flow mostly commences to vary when a rain event occurs, and its time series variation remains the similar patterns but the variation always has certain time delay comparing with the rain event. The hysteresis of the drip water response to rainfall is mainly determined by the transport duration of rain water through the soil and rock (Genty and Deflandre, 1998). Such delayed variation was also found in the Lower Cave, Bristol (Baker et al., 1997) and the French Pere Cave, Belgium (Genty and Deflandre, 1998).

In the area of the Pearl River, Guizhou Province China, the response time scales for cave drip water to rain events varied from 0-40 days in four different caves due to the differences in the cave environment, the connectivity of water migration paths and inconsistency in the hydrodynamic processes (Zhou et al, 2005). Baker et al. (1997) studied the drip rate in the Lower Cave, Bristol, in Great Britain over two hydrological years (1991-1992, 1994-1995). Their results showed that within a hydrological year there was significant variation in the drip rate. In winter (November to March), the drip rate had close correlation to rainfall events, but in summer, due to higher evaporation, the drip rate did not correspond accurately. Drip rate variability also existed between the years studied. In 1991-1992, the drip rate calculated from all the drip points showed that the hysteresis time was from 24 to 30 days, while in 1994-1995, due to higher rainfall levels, drip rate performance relative to the rainfall response showed significant difference. The hysteresis times were 1-6 days and 1-20 days, respectively. Thus a different intensity and duration of precipitation can cause a significant variation in the dynamic processes of drip rates. Crag Cave, in southwest Ireland, also indicated that there were four kinds of drip drop patterns in response to rainfall after monitoring the drip rates with calibrated vessels and stop watch: (1) rapid response, there is no hysteresis; (2) quick response, but with some lag; (3) intermittent response; (4) no response to rainfall, drip rate remained stable all the year round (Tooth and Fairchild, 2003).

The obvious spatio-temporal variation of the drip rate is mainly affected by the pattern and intensity of the rainfall, the complexity of hydrological recharge system, the ceiling thickness and landscape characteristics (Baker and Genty, 1999; Baker and Brunsdon, 2003; Tooth and Fairchild, 2003). During dry periods, the discharge from drips depends on the volumetric storage capacity of the soil and rock factures from previous precipitation. During the rain events, as abundant water recharges the system, the conduit flow and large fracture flow functioned preferentially. An increased amount of water in the epikarst triggers the piston flow, resulting in rapidly increasing the rate in drip discharge (Genty and Deflandre, 1998; Tooth and Fairchild, 2003). Sheffer et al. (2011) identified three distinct types of flow regimes in a dry karst cave, Sif Cave, Israel: quick flow, intermediate flow and slow flow, according to the water flow media. Therefore, the ratio of different water-containing structures (small pores, fractures and large conduits) at different drip sites is one of the major factors determining the response speed to precipitation.

Much drip hydrological research has been built upon the earlier work of Smart and Friedrich (1987), and has enabled the hydrological categorization of drip waters according to their response to a recharge event (Tooth and Fairchild, 2003; Zhou et al. 2005). The maximum amount of discharge (Q_{max}) and coefficient of variation (CV) was used to classify the recharge patterns of cave drip water, while Baker et al. (1997) modified this methodology in order to classify the cave drip water. White (1988, 2002) thought the higher CV meant the recharge from conduit flow. Only little research has been conducted on the detailed processes of the cave drip water in response to rain events, which might result in an inaccurate interpretation of the hydrodynamic process in the vadose zone.

Recently, with technological advancement, the high-resolution multi-parameter data loggers have become available to monitor continuous hydrodynamic variations.

Research on hydrodynamics in the small Velika Pasica Cave (Slovenia) was synchronised with ecological monitoring, which found that the epikarstic aquatic fauna there was unique for each neighbouring drip (Brancelj, 2002). This indicates that discharge patterns and intensity determine the resident cave faunal communities.

1.2.3 Hydrochemical research on cave drip waters

In recent years, significant progress has been made in the study of karst hydrochemistry. The springs are important sampling points that are commonly used as monitoring locations in order to collect water quality data in karst hydrogeology (Quinlan and Ewers, 1985; Liu et al., 2007). As a special intermediary outlet in karst regimes, the cave also presents an important monitoring point for karst hydrochemistry. Cave percolating water acts as a more accurate indicator than the spring water when interpreting the local water quality variations (Liu et al. 2014).

In recent decades, more and more attention was focused on the cave water (Williams, 2008). Cave water includes all the waters in the caves regarding the amount, the flow conditions and the present state in the karst system, such as, soil water, percolation water (drip water and water flow on the wall), and pool water (Luo, 2007). The chemical composition of cave water at an intermediate position in the karst system is affected by several factors, including land cover / land use, recharge mechanism (diffuse vs. concentrated), climatic conditions, lithology and type of flow paths (diffuse vs. conduit). Cave drip water, as one of the most active factors in the cave hydrological system, reflects the variations in surface recharge via changes in discharge and chemistry (Bar-Matthews et al., 1996; Fairchild et al., 1996; Baker et al., 1997; Baker et al., 2000; Fairchild et al., 2000; Huang et al., 2001; McDonald et al., 2004; Musgrove and Banner, 2004; Cruz et al., 2005, Kogovšek, 2010).

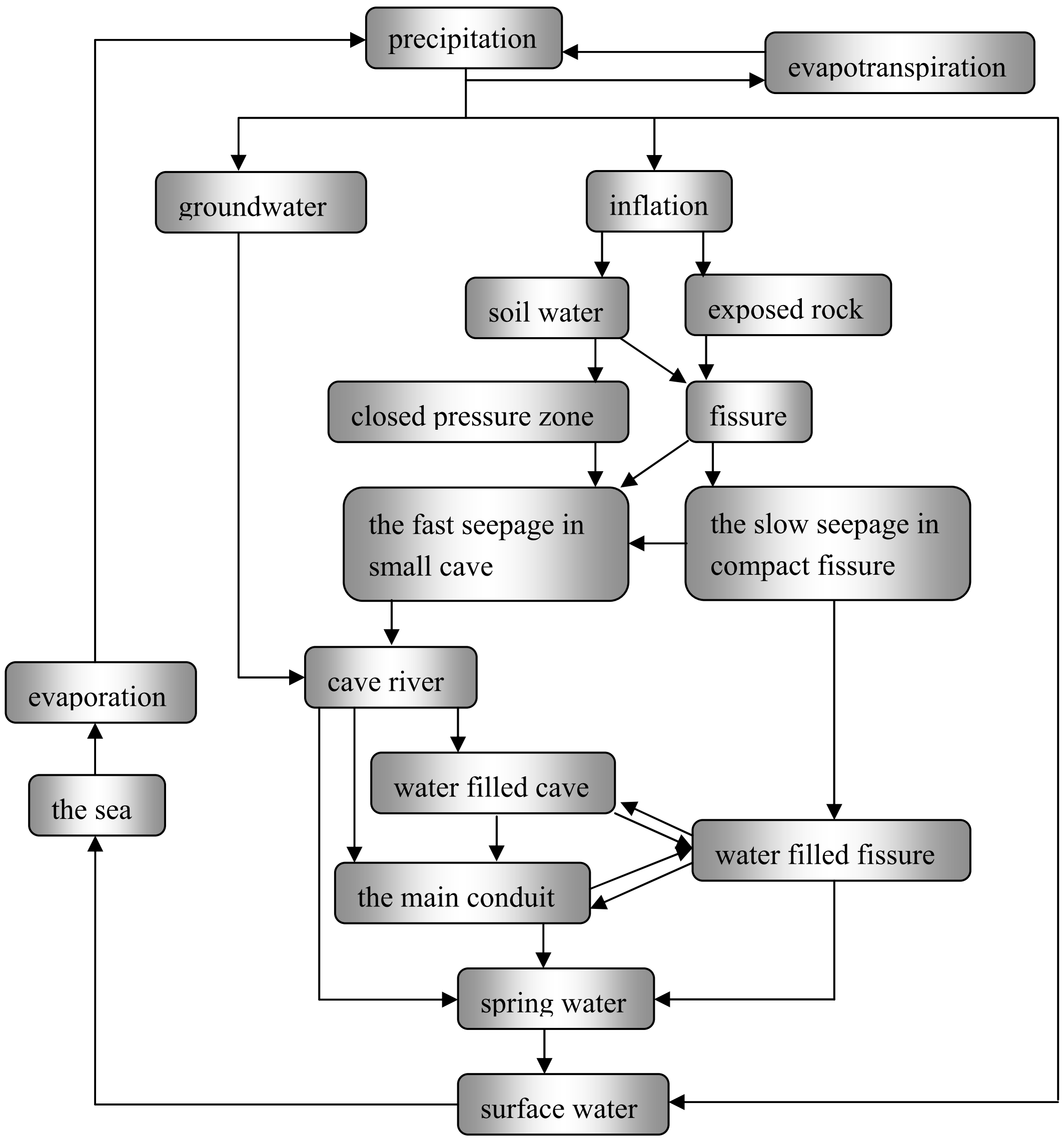

Figure 1-3: Simplistic flowchart of the water cycle in a karst cave system (Smith et al., 1976)

According to the water cycle in a karst cave system (Figure 1-3), the rainwater dissipates in three portions: one runs into the surface water; one recharges the underground water through large conduits sometimes directly into vadose / phreatic zone of a cave system; the remainder penetrates through the soil layer and epikarst percolating slowly downwards. Although the former two portions take up most of the water, the water that passed through, and even stayed in soil and epikarst layers plays a very important role in the water-rock reaction processes and in the regional ecosystem.

Currently, the most popular applications for cave drip water research has related to the geochemical and physical properties of speleothems, which contain palaeohydrological and other climate-related information (Zhang et al., 2004 a, b). Speleothems have been deposited from cave drip waters, therefore, research topics on cave drip water share most environmental indicators with speleothem research, for example: stable isotopes, trace elements and organic matter. In addition, the hydrodynamic conditions, hydrological profiles, and geochemical characteristics of the drip water were also studied in detail (Thrailkill et al., 1981; Baker et al., 2003；Sondag et al., 2003; Tooth and Fairchild, 2003；Musgrove and Banner, 2004; Tatár et al., 2004).

As there is no established standard for cave drip water research, most studies have tried to find general conclusions through comparison. Some research compared the drips in different caves (Yonge et al., 1985; Fairchild et al., 2000; Tooth and Fairchild, 2003); while other focused on different drips within one cave (Baldini et al., 2006; Fairchild et al., 2006). In general, the yearly variations of the environmental indicators should be recorded for the cave drip water studies (Fairchild et al., 2000; Baker and Brunsdon, 2003; Holmgren et al., 2003; Sondag et al., 2003; Tatár et al., 2004, Kogovšek, 2010).

In summary, the main applications of hydrochemical indicators were as follows:

1) Isotopes: Most frequently studied stable isotopes applied in the cave research were oxygen isotope $\delta^{18}O$ and hydrogen isotope $\delta^{2}H$, and some others focused on $\delta^{13}C$. The different hydrological features of the aquifer results in a different lag time in the value of $\delta^{18}O$ and $\delta^{2}H$ from drip to drip, compared with the rain water (Perrin et al., 2003; Cruz et al., 2005). The retention time / residence time of the water in epikarst was the main affect impacts in this different the values of $\delta^{18}O$ and $\delta^{2}H$ in drips, and evaporation also played an important role (Bar-Matthews et al., 1996; Carrasco et al., 2003), otherwise they should equal the yearly average

values of the rain water (Yonge et al., 1985; Caballero et al., 1996; Beynen et al., 2006). The carbon isotope $\delta^{13}C$ was detected as an important indicator for dissolved inorganic carbon (DIC) by Bar-Matthews et al. (1996), as that the faster the drip discharged, the more DIC was dissolved and the lower value of $\delta^{13}C$ was contained in the water. According to Baldini et al. (2005), biomass also affects the value of DIC and $\delta^{13}C$ in drips.

Other rare isotopes were also applied in cave drip water studies. The most extensively used isotope system was the strontium isotopes $^{87}Sr/^{86}Sr$ ratio (Fairchild and Baker, 2012). This composition in cave drip water was applied in order to estimate the potential Sr sources by systematic leaching studies (Tooth, 2000). The magnesium (^{26}Mg) was also widely used, which suggested the speleothem formation and possible environmental impacts (Galy et al., 2002; Buhl et al., 2007). The application of neodinium isotopes ^{143}Nd /^{144}Nd in speleothems as a tracer of dust sources is also in progress (Fairchild and Baker, 2012). The uranium isotopes $^{234}U/^{238}U_0$ ratios were applied in the Soreq Cave, Israel, in order to extract retained palaeohydrological information (Kaufman et al., 1998). Zhou et al. (2005) developed a complex model to account for low $^{234}U/^{238}U_0$ ratios.

2) Trace elements: Techniques for investigating speleothem geochemistry at high resolution are relatively well-advanced, particularly for trace elements (Roberts et al., 1998; Baker et al., 2000; Fairchild et al., 2001; Huang et al., 2001; Baldini et al., 2002; Treble et al., 2003; Johnson et al., 2006). Strontium is one of the most significant elements for cave drip water studies, and the relationship between Sr and Ca (Sr/Ca) was also widely used (Fairchild et al., 2000, 2006; Huang et al., 2001; Tatár et al., 2004; Baldini et al., 2006). The Sr/Ca as well as the Mg/Ca varied closely with the feature of water flow, for example, the drip rate and efficient rain water supplement. However, it is the complex non-linear relationship between climate and hydrochemistry which controls the Sr/Ca and Mg/Ca ratio by four different factors: I) the different dissolved ratio between different lithological characters (dolomite and calcite) and the reaction time in the water-rock system; II)

the calcite precipitated during the flow path, namely the prior calcite precipitation (PCP) (Johnson et al., 2006); III) incongruent dolomite dissolution; IV) selective leaching of Mg and Sr with respect to Ca (Fairchild et al., 2000).

Elements such as Mg, Sr, barium (Ba), U and phosphorus (P) provided valuable additional information on seasonality, paleoaridity and paleomonsoon activity (Roberts et al., 1998; Hellstrom and McCulloch, 2000; Verheyden et al., 2000; Huang et al., 2001; Fleitmann et al., 2003; Treble et al., 2003; Treble et al., 2005; Zhou et al., 2005; Johnson et al., 2006).

3) There are some other environmental impacts and hydrochemical factors which impact on the variation of drip water hydrochemistry. The drip rate, also discussed as the resident time, was recognised as an important impact factor (Genty et al., 2001). The increase in the surface biomass intensified the partial pressure of carbon dioxide (pCO_2) in the soil layer, and furthermore carbonates were dissolved and precipitated (Baldini et al., 2006). The aeration condition controlled the respiration of the subsurface system which consequently impacted on the pCO_2 in cave drip water (Fairchild et al., 2006). Seasonal climate change also affected the pCO_2 in the Obir Caves (Austria) (Spötl et al., 2005). Other environmental parameters, such as air temperature and air pressure (Sondag et al., 2003), organic matter (e.g. fulvic acid) (Beynen et al., 2002; Tatár et al., 2004; Cruz et al., 2005), the dissolved organic matter (DOC) in drip water (Baker et al., 1999; Cruz et al., 2005) were also applied in order to interpret the hydrochemical profile of the drip water.

Dolomite related hydrochemistry has been studied in detail. The main chemical processes in its hydrochemistry are dissolution/precipitation, leaching, surface and sub-surface processes. These processes are evident in dissolution of the dolomite, leaching and ion exchange in the epikarst. Models that describe solution/precipitation and surface chemistry processes, assuming equilibrium, have been developed and are described by Plummer et al. (1991) and Parkhurst (1995). These models will be used in the evaluation of some of the water chemistry results.

Additionally, research on anthropogenic impacts is also rapidly increasing. Land use and land cover change are the most important anthropogenic factors that indicate human influence over the surface of the earth (Lambin et al., 2001). In general, the chemical composition of the water in carbonate-rich rock aquifers is dominated by calcium, magnesium, and bicarbonate, whereas sodium, chloride, and sulfate can be dominant ions in the water that comes from volcanic aquifers or clay minerals (Thomas et al., 1996). Regional groundwater quality is largely determined by both the natural processes (lithology, groundwater velocity, quality of recharge waters, together with interaction with other types of aquifers) and anthropogenic activities (agriculture, industry, urban settlements and increasing exploitation of water resources) (Helena et al., 2000).

A variety of methods and new techniques have been developed and applied in order to analyse cave drip water, including the use of isotopes, GIS, and statistical methods (Ford and Williams, 2007). However, as there is an increasing requirement for high-resolution and short time scale in the palaeohydrological records, it is crucial to interpret the relationship between cave drip water and cave environmental indicators, such as the ecosystem, climate and hydrology within the cave system (Baker and Brundson, 2003; Baldini et al., 2006; Fairchild et al., 2006). Recently, with technological advancement, the high-resolution multi-parameter data logger has been available in order to monitor continuous hydrochemical variations. In this thesis, the detailed karst hydrochemical changes obtained through the new technology, and the comparative differences in the changes under different climate regimes, will be discussed, based on the data collected from the Velika Pasica Cave in central Slovenia.

1.2.4 Thermal conditions in the caves

Heat flow theory can be applied to the development of ground water hydrological science as heat has proven to be a useful tracer in groundwater systems

(Anderson, 2005). While some papers are related to deep aquifers (phreatic zone), which do not directly connect with annual periodical temperature changes from the surface, other papers have primarily focused on geothermal energy sources (Garg and Kassoy, 1981), and mining engineering (Williams et al., 1999). Bundschuh (1993) reported that heat is not an ideal tracer. Nevertheless, Milanovic (2001) considered water temperature as a non-conservative tracer in karst aquifers. In Bundschuh's research (1993), temperature was shown as a parameter in order to indicate the components of different aquifers in spring water. Genthon et al. (2005) used temperature as a marker for karstic water hydrodynamics in La Peyrere Cave (France). Potentially useful information for thermal patterns of karst cave streams was considered for aquifer morphology and recharge studies (Luhmann et al., 2011). Contrary to deep aquifers, fundamental studies on heat transport and temperature gradients for shallow sub-surface karstic cave systems are limited in the literature, especially for cave drip water.

Although the ceiling of the Velika Pasica Cave is thin (in some places only 2 - 5 m), relative thermal isolation from the surface occurs. Generally, at about 1 m below the surface, daily variations in temperature in the soil and rock diminished, although the annual variations in temperature can be observed as deep as 20 - 24 m below surface, depending on the rock and soil types (Thakur and Momoh, 1983). Thus, a shallow cave with an average depth of 10 - 12 m below surface could be a good intermediate window for tracing temperature variation underground. The air movement, ventilation, in the cave was driven by the temperature difference and it also caused the temperature rebalancing.

1.2.5 Eco-hydrology in the cave environment

Northup and Lavoie (2001) stated comprehensively on the geo-microbiology in caves, including the cave microorganisms, the mineral environments and their interaction between each other. Throughout the world, eco-hydrology has recently been developed as a scientific discipline. Several authors have stressed its importance to the progress of hydrology and ecology. The dramatic degradation of global water resources during the 20^{th} and beginning of 21^{st} century has forced environmental and geological scientists to focus and intensify their research on the integration of biological processes with hydrology (Bonacci et al., 2009). The pattern and intensity of hydrological variability significantly influences biotic structure and activity. Alternatively, biotic structures may regulate abiotic features. As a result of these interrelationships, a new concept known as “eco-hydrology” has emerged (Zalewski et al., 1997). During the past two decades, the concept of eco-hydrology has appeared in many scientific books, journals, workshops and conferences dealing with hydrology, hydrogeology, and water resources management (Zalewski et al., 1997). Its rapid development is a consequence of the fact that complex scientific questions, as well as environmental problems, can only be effectively resolved if several scientific disciplines are considered jointly (in this case at least ecology and hydrology). Eco-hydrology can be understood as one branch of ‘‘non-engineering’’ hydrology, which has developed from forest hydrology, wetland hydrology, landscape hydrology and lake hydrology. It seems that an acceptable definition of eco-hydrology would be as follows: ‘‘Eco-hydrology is the science of integrating hydrological processes with biota dynamics over varied spatial and temporal scales’’ (Ognjen et al., 2009). For some authors, eco-hydrology was the coupling of landscape processes with hydrobiology (Bonell, 2002). Due to the particularities of water circulation in karst areas, the coupling of surface water-ground water processes is the most important prerequisite in order to understand constraints on sustainable water resource development.

For its sustainable use and protection, karst as a unique landscape and environment, definitely requires scientific advances in eco-hydrology. Thus karst eco-hydrology was introduced. Karst eco-hydrology intends to integrate not only landscape with groundwater hydrology but also with aquatic biology.

Rouch (1977) stated first that a karst basin is a clearly definable ecosystem with measurable surface inputs from sinking streams and rainfall infiltration, and measurable outputs at the resurgence including biological parameters. Typically, subterranean food webs are truncated at both ends due to the absence of photosynthesis and secondary predation. Karst ecosystems are sensitive to environmental changes (Gibert and Deharveng, 2002). The importance of maintaining biological diversity goes far beyond mere protection of endangered species.

Karst eco-hydrology should be able to answer many important questions dealing with interactions between karst hydrology and karst ecology. The synthesis of ecological and hydrological approaches could increase progress in understanding karst environments and in this way contribute to the development of the karst eco-hydrology concept. Karst eco-hydrology can be understood as a scientific sub discipline concerned with the ecological and hydrological processes in the karst areas (Bonacci et al., 2009). Karst eco-hydrologists should study the effects of hydrological processes on the distribution, structure and function of specific and vulnerable karst biota and ecosystems, and the effects of biotic processes on the elements of water cycle (hydrology). A karst eco-hydrological approach means integrating karst studies into a more general ecological, biological, hydrological, hydro-geological, geo-morphological and geochemical matrix. Studies on karst eco-hydrology bring the diverse perspectives of ecologists and karst hydrologist and hydro-geologists together (Ognjen et al., 2009).

Ecological constraints in subsurface environments, both in fissured and porous aquifers, relate directly to groundwater flow, hydraulic conductivity, interstitial bio-geo-chemistry, pore size, and hydrological linkages to adjacent aquifers and surface ecosystems. Substantial technological advances in the use of tracers and groundwater modelling approaches now make it possible to collate hydrological data on pathways and residence time with ecological variables of water chemistry, faunal composition or microbial activity (Hancock et al., 2009). Living organisms have tended to be applied as ground water indicators, especially through the development of research on groundwater organisms (from meiofauna to bacteria). A particular application to subterranean ecosystem was conducted in order to identify the surface water contamination of groundwater (Hancock et al., 2005). Various forms of groundwater dwelling (geo-micro-) organisms were proposed as indicators of surface – groundwater connections. Ostracods were used to identify wells contaminated with surface water (Malard et al., 1994); Cyclopoida (Copepoda) and Oligochaeta could follow contaminant transport in a fractured limestone aquifer 10 to 40 m deep (Malard et al., 1994). Bacteria, such as fecal bacteria, were used to verify the vulnerability of a karst spring (Butscher et al., 2011); and geo-microbes and bacteriophages also had applications especially in porous aquifers (Griebler, 2001; Bricelj and Čenčur, 2005).

Brancelj (2002) discussed the micro-distribution of micro-crustaceans, copepods (Crustacea, Copepoda), which could reflect the environmental differences at a fine scale, from several centimetres to hundreds of metres. The distribution of different macro-invertebrates (Lancaster and Hildrew, 1993; Graca et al., 1994, Dudgeon, 1996; Lancaster, 1999) and vertebrates (Seehausen and Bouton, 1998; Baumgartner et al., 1999) in groundwater karstic habitats was also studied.

Epikarst harbours a rich fauna of obligate subterranean-dwelling aquatic species, i.e., stygobionts, especially among the Copepoda (Pipan, 2005) and these fauna have a potentially important role in hydrogeology as tracers of water movement in the epikarst without the injection of dyes or other tracers (Pipan and Culver, 2005, 2007). The tracer, mineralized particles, can be mobilized into the water column, thus, so can copepods. According to the Hjulstrom curves (Gordon et al. 1999), as a tracer, it should be easy to mobilize them, and there was a relevant relationship between the flow velocity and the particle size.

1.3 Objectives and structures of the thesis

Hundreds of millions of people worldwide live in karst areas and are supplied by drinking water from karst aquifers. These aquifers include valuable freshwater resources, but are sometimes difficult to exploit and are almost always vulnerable to contamination, due to their specific hydro-geological properties. Therefore, karst aquifers require increased protection and application of specific hydro-geologic methods for their investigation. Other problems frequently encountered in karst areas include: soil erosion and desertification, leakages from channels and reservoirs, collapse of underground cavities, formation of sinkholes, and flooding. Solutions for these problems require the involvement of karst hydrogeological experts.

Although the epikarst zone has a considerable potential storage capability (Perrin et al., 2003), in most occasions, it holds only a small fraction of available fresh water and the water is usually difficult to extract. However, this limited water is of great importance for the resident biota.

1.3.1 The goal of the thesis

In this research my goals were:

A) The analyses of seven years hydro-meteorological data from four permanent drips in the cave that had been collected with high frequency (i.e. every hour). The analyses of this data was carried out on the discharge patterns of different drips, including their relationship with the surface condition, their amount of discharge, their rate, their range of variation and their recession feature, in order to demonstrate the water flow in epikarst, the storage capacity and the probable storing structure. The task established temporal and spatial changes in flow rates of individual flood events and the seasonal variation at different drip sites within the cave.

Hypothesis 1: Different hydrological performance of the four permanent drips in Velika Pasica Cave indicates the structure of the epikarst with different void size, which controls various water flow regimes and different storage capacities.

B) Implementation of the annual hydrochemical monitoring of the drip water at different sites since 2008, and the detailed monitoring at one or two sites according to the rain events from 2011 to 2013, in order to present the difference in the chemical features of the drip water at different sites and the seasonal and rain event variation according to weather changes.

Hypothesis 2: The hydrochemical characteristics of the drip water are affected by the patterns of recharge events in different seasons and the location of the drip sites.

C) A detailed cave thermal dynamic was presented by the air temperature on the surface and in the cave, and the temperature of the drip water. The seasonal temperature variation has been applied in order to investigate and clarify the mechanism of the cave thermal dynamic.

Hypothesis 3: In a shallow and relative closed cave, the thermal variation in the cave is mainly controlled by the heat conduction between the surface and the inside the cave. Additionally, the air convection from the entrance during the cold period and the percolation water also has some limited effect on air and water temperature in the entrance part of the cave.

D) In order to clarify the spatial-temporal relationship between the features of the local aquifer and the habitat-specific groundwater fauna, ecosystem monitoring was conducted in parallel with my research program.

Hypothesis 4: The composition of the aquifer fauna varied at different sites in Velika Pasica Cave over different seasons, and was significantly affected by the hydrological and hydrochemical characterises of the epikarst water.

1.3.2 Independent and original contribution to science

This task was one of the few detailed studies undertaken of a shallow karst aquifer in dolomitized limestone geology. The originality of the study lies in the fact that the data collected on the events in the epikarst zone over a long period of high frequency measurements (at hourly intervals), provided a detailed insight into the dynamics in the transition of water through the area and qualitative changes to its ion content. Measurements in the underground were supported by measurements of weather conditions on the surface, which shed further light on the process dynamics. Preliminary observation of individual flow patterns showed that their rate of flow and flow pattern changed over seven years, which may have resulted from developments in the cracks themselves, but may also be due to changes in their environment, especially in relationship to the location and precipitation volume.

The results from my research will be of interest from a theoretical point of view in order to further understand the hydrological dynamics in the karst system and, concurrently, contribute to an understanding of the ecology of the aquatic fauna specific to an epikarst environment, which for a long time has remained unknown.

With a view to the protection of specific fauna, this research approach is crucial for achieving a better understanding of epikarst hydrology. The results will be a useful tool for understanding the dynamics of underground pollution related to discharge of harmful substances.

1.3.3 The thesis outline

This thesis is comprised of seven chapters. The first chapter provides background information of the study area, including the introduction of epikarst and the related research. The second chapter describes the study site area - the Velika Pasica Cave, central Slovenia. The third chapter focuses on the field and laboratory work undertaken including methodologies that were used and the form of data organization. The fourth and fifth chapters show results of data that were collected, examined and used during this research with a comprehensive discussion of the results, interlinking physical, chemical and biological aspects of the research. Conclusions and recommendations are presented in the sixth chapter. The final chapter includes the literature used during preparation of the thesis.

In order to present the logical structure of this thesis, a flow chart was designed as follows:

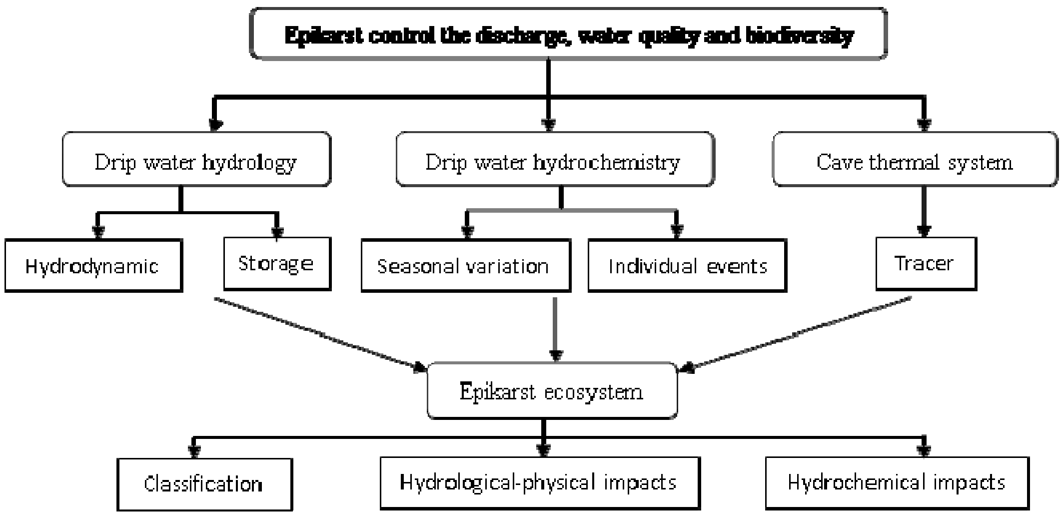

Figure 1-4: The flow chart of the thesis

Chapter 2 Description of the study site

2.1 The location and basic geology in the area of the Velika Pasica Cave

The studied cave, registered as “Velika Pasica” (Kat. No. 75), is located 20 km south of Ljubljana (45º55'14"N, 14º29'41"E), near the village of Gornji Ig, with the cave entrance at an elevation of 662 m a.s.l. (Figure 2-1). The geology is thinly bedded Norian-Retian dolomite from the Upper Triassic period (Pleničar, 1970). Strata inclines to the north at 10-15◦. Three hundred meters south-west of the cave is a hill, known as Črtež (765 m a.s.l.), with approximately 30◦ slopes descending towards the cave. To the north-eastern side of the cave there are less steep slopes and some dolinas, roughly circular karst surface depressions. The area surrounding the cave has no surface water within a radius of 3 - 4 km, apart from a small temporary spring, known as Močile (on average less than 0.1 l/s), and a small pond fed by the spring (Brancelj, 2002). Both are approximately 25 m below the cave entrance and part of the cave water discharge appears there.

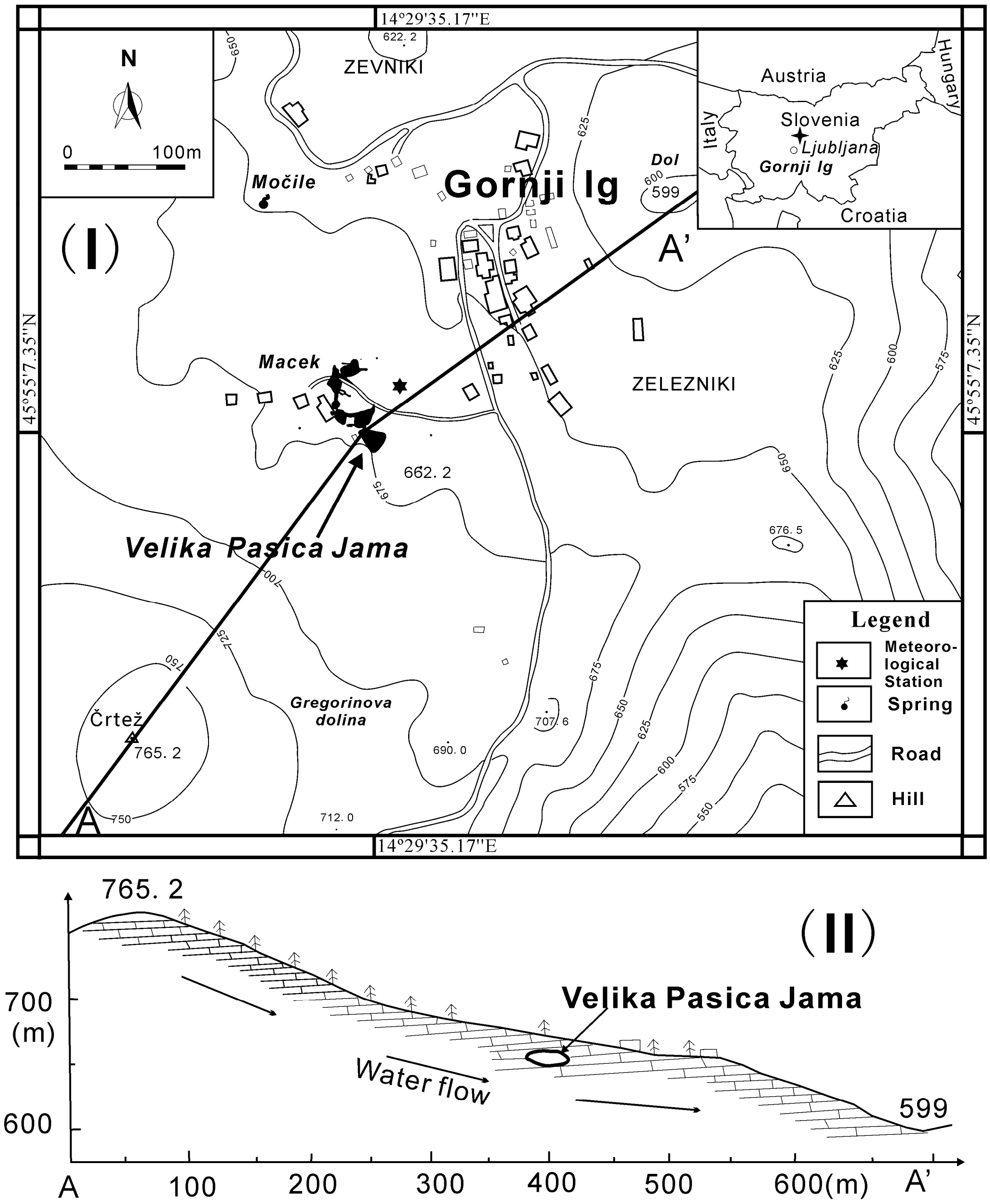

Figure 2-1: (I) Location of the Velika Pasica Cave (Slovenia). The black figure: the Velika Pasica Cave. The main symbols in the map: *: the outside meteorological station; Δ: the highest point of the region - Črtež Hill; : the temporary spring Močile. (II) The geological profile of the cave area.

2.2 Morphology of the Velika Pasica Cave

The interior of the cave is a 126 m long horizontal gallery rich in flowstone decoration (Figure 2-2). The entrance to the cave is located at the bottom of 10 m deep circular depression with a maximum diameter of 15 m. The ceiling of the gallery has a maximum thickness 10 -12 m, however, at some points it is reduced in thickness to 2-5 m (Brancelj, 2002). Thus the cave represents a typical, shallow cave formation (Jeannin et al., 2007). The cave is divided into two sections (Figure 2-2): A) the outer section with two chambers and B) the inner section with an additional two chambers. The outer section and the inner section are connected by a 0.7 × 1.0 meter high passage. Four permanent drips, designated as VP1, VP2, VP3, and VP4, are distributed within the cave; drips VP1 and VP2 are located in the outer section and the other two are in the inner section of the cave.

There is a thin surface layer of soil above the cave, which varies from 0-20 cm in depth. The surface above the cave consists of a patchwork mosaic of deciduous forest, orchard, meadows, a farmhouse and macadam track. At two points rain water with effluent contamination from a dunghill, located adjacent to the farmhouse, enters the cave as a temporary stream at the level of the gallery floor. All water in the cave is exclusively percolating water, entering the cave as permanent or temporary drips from the ceiling or temporary flows (after heavy rain or intensive snow-melt) from the side. During the dry season (mostly summer time), only a few permanent dripping points remain active (the previously listed four above) and these were selected for detailed analysis (Figure 2-2). After prolonged droughts small pools on the clay substrate can dry out and only wet clay remains.

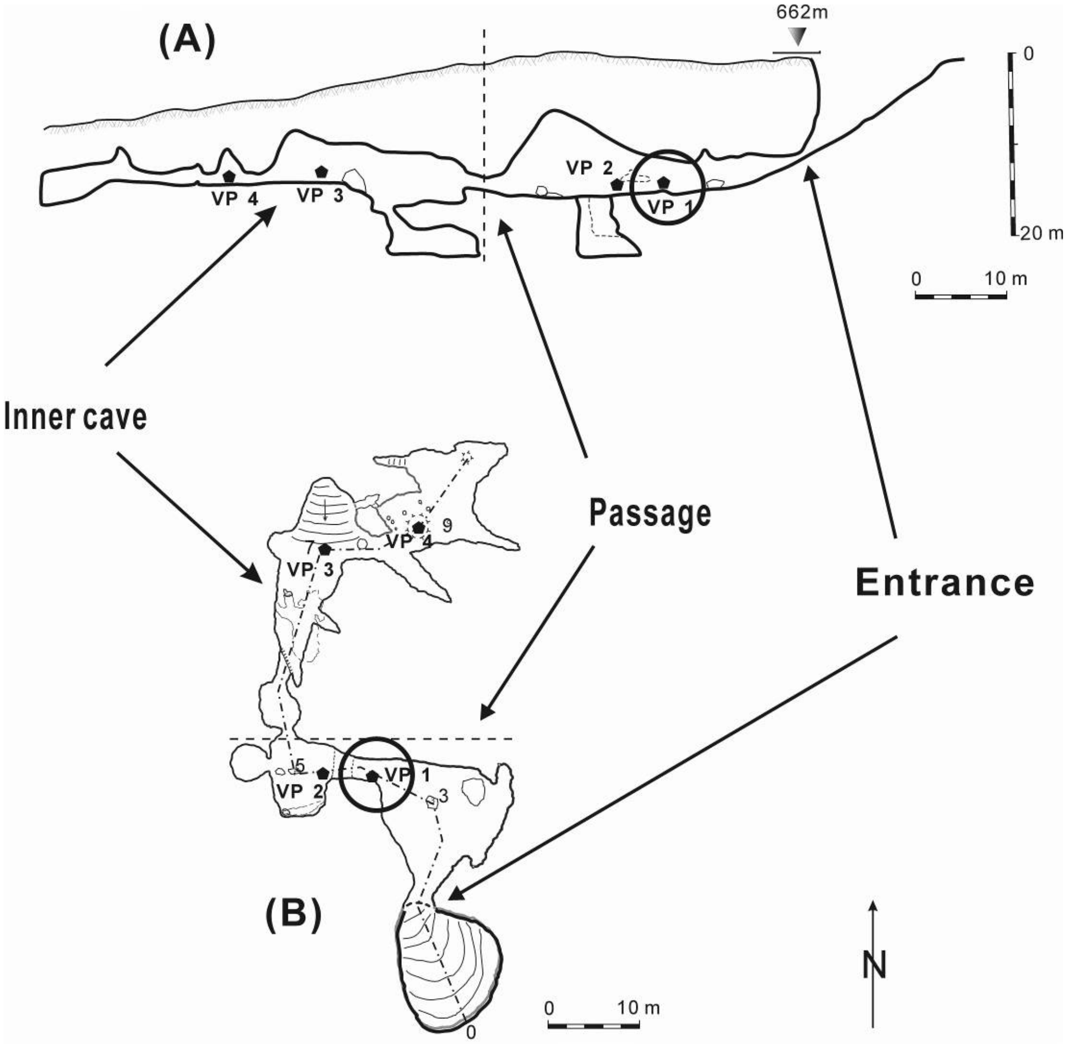

Figure 2-2: Cross-section (A) and ground plan (B) of the Velika Pasica Cave (Slovenia). VP1 – VP4: permanent dripping points. The circle indicates the drip VP1 and the drip VP2 located adjacently which were both analysed in detail in this research. The arrowhead points the cave entrance, the narrow passage for demarcation of the inner cave and the outer cave, and the inner cave.

2.3 The climate of the study site

According to the location, the climate of Ljubljana area dominates with continental characteristics of warm summers and moderately cold winters. Average daily temperatures in July and August are 20.4 °C and 19.8 °C and in January -0.1 °C (www.arso.gov.si). The precipitation is relatively evenly distributed throughout the seasons, although winter and spring tend to be considerably drier than summer and autumn. Yearly precipitation is approximately 1,400 mm (www.arso.gov.si) (Figure 2-3). Storm events are common from May to September and can occasionally fall as heavy precipitation. Snow is common from December to February.

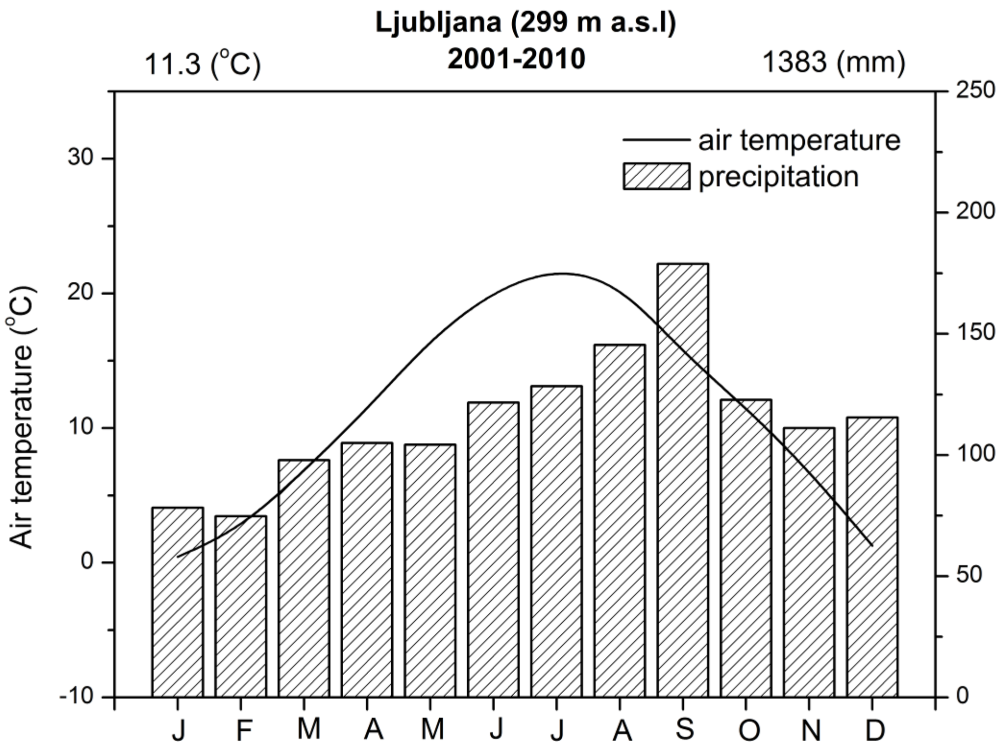

Figure 2-3: The climatic-diagram on mean monthly air temperature and precipitation over a year for the period 2001-2010 for Ljubljana (capital of Slovenia).

Chapter 3 Material and methods

3.1 Continuous recording of hydro-meteorological data

Accuracy and frequency in data collection over a long period were essential parameters undertaken for this research. Systematic data were collected for more than seven years - from June, 2006, in order to obtain detailed hydrological, hydrochemical and thermal process data within the cave. Two data loggers (DL2e, Delta-T Device Company) equipped with several sensors were used for data collection. One Delta-T Data-Logger with sensors for air temperature, precipitation and soil humidity was set on the surface near the entrance of the cave. The other Delta-T Data-Logger with four sets of sensors and rain gauges for air and water temperature, moisture (one sensor) and drip water discharge were set at four drips in the cave. In addition, the biological samples were also collected during this period in combination with the measuring of hydro-meteorological parameters.

3.1.1 The surface meteorological measurement

One of the data-loggers with sensors for air temperature, precipitation, relative humidity and soil moisture was set on the surface, approximately 100 m from the cave entrance (Figure 2-1; Figure 3-1, left). Data from this local meteorological station were mainly used for comparison with the parameters from the cave, such as the drip water discharge and the temperature of the drip water and the cave atmospheric temperature and humidity.

The device was set up as shown in Figure 3-1(left). All the sensors were connected to the data-logger. The amount of precipitation was recorded every hour by a rain gauge (RG1-UM-3, Delta-T Device Company), which recorded the volume in mm (millimetre), with an accuracy and resolution of ± 0.2 mm. The surface air temperature was recorded by an air temperature sensor (resistivity type, digital resolution of 0.05 ºC; probe error ± 0.1 ^{o}C; Delta-T Device Company). Relative humidity (relative humidity sensor RH1; Delta-T Device Company) and soil moisture (Theta Probe ML2x, probe error ± 0.01 m^3/m^3; Delta-T Device Company) were established. The external rain gauge had no heating, thus precipitation during the winter time, when temperatures were below zero were not recorded in accurate amounts and periods, as ice/snow was melted only during warm periods.

Sensors for temperature and precipitation recoded the results once an hour, and were synchronised with the monitoring of temperature and drip water discharge within the cave. Relative humidity and soil moisture was recorded every four hours.

Figure 3-1: Left: the surface meteorological station, a data logger connected with the rain gauge for precipitation monitoring, the moisture and temperature sensors for humidity and atmospheric temperature monitoring, and the soil moisture sensors for soil humidity; **Right:** the drip water collection system at one drip site in the Velika Pasica Cave (Slovenia), composing of a plastic screen for drip water collection, the rain gauge for discharge recording, and the temperature sensors for drip water temperature monitoring and the “Brancelj bottle” for biological sample collection (the sensors and rain gage connect with a data logger).

As technical problems arose from time to time, some data was missed, and for a meteorological reference for the cave area, I consequently used daily precipitation values from a nearby state meteorological station, Pokojišče (part of state meteorological network; http:// www.arso.gov.si), located 8.3 km west of the Velika Pasica Cave at the elevation of 737 m a.s.l., as representative of the precipitation dynamic. Comparison of available data between both meteorological stations during 2010 shows no significant difference in the dynamic and intensity of precipitation on a daily rate.

3.1.2 Hydrological measurement of cave drip waters

In order to determine the hydrological response of the cave drip water to the infiltration events, the storage capability of the epikarst, and the impact of the hydrological impacts on the cave ecosystem, the discharge of four permanent drips at different sites were monitored automatically in the cave, which were synchronized with precipitation monitoring on the surface.

Four permanent drips in the cave were labelled as VP1-VP4 (Figure 2-2). For the drip water discharge, each drip water discharge was measured as a volume of water percolated from the ceiling every hour by the same type of rain gauge (RG1-UM-3, Delta-T Device Company), which recorded the volume in mm (millimetre), with an accuracy and resolution of ± 0.2 mm. These four rain gauges were connected to the second data-logger, which was established in the cave. According to the conversion factor of the rain gauge and the time intervals, the data were later changed into l/s (litre per second) or ml/min (millilitre per minute) in the NIB office for further data analyses. These conversion factors were tested and verified in the field.

At each drip site, most water came from one out point on the ceiling. But the distance between the ceiling and the funnel of rain gauge varied among sampling points and was between 1 and 5 m. In order to collect dispersed jets of water, a plastic screen (2 m x 2m) was placed r to collect it and direct it into the funnel of the rain gauge (Figure 3-1, right).

3.1.3 Cave temperature measurement

In order to interpret the climatic variation of the inner and outer cave environments, both temperatures from the surface (section 3.1.1) and into the cave were monitored. In the cave, four temperature sensors for air temperature and four sensors for water temperature of each permanent drip were established in both the inner section and outer section of the cave (Figure 2-2).

Probes (ST1-05, Delta-T Device Company) (resistivity type with a range of measurement of -25 to +100 ºC and a digital resolution of 0.1 ºC) for water temperature were inserted into the lower section of each rain gauge (Figure 3-1, right). Probes for air temperature were located 50 cm away from the rain gauge and 1 m above the cave floor. Together these eight temperatures probes were connected to the same data-logger as the rain gauge within the cave, and they recorded the results in four hour intervals from the beginning of the monitoring period, and modified to one hour intervals commencing in 2012. These probes were synchronized to the temperature monitoring on the surface. The investigation and interpretation of climate variation within the cave was carried out by monitoring the precipitation, the surface ground temperature ($T_{outside}$), the air temperature inside the cave (T_{air}) and the cave drip water temperature (T_{water}). Furthermore, exploration of the possibility to apply temperature as a natural tracer for hydro-geological research has been considered with a special emphasis on the cave drip water and concurrent ecosystem studies.

In order to determine the correlation and dissimilarity of temperature between the water at the epikarst discharge point and the drip water near the cave floor, two probes were placed at different locations for two weeks in October, 2012. Results showed only a minor difference in water temperature between locations.

On the same data-logger in the cave, there were also two sensors for relative humidity monitoring (with the same type sensors as on the surface). One sensor was installed in the inner cave section and the other was in the outer cave section. Both recorded the results every 24 hours, and were also synchronized to the relative humidity monitoring on the surface.

All the sensors, especially the rain gauges, were regularly maintenance checked and all the data from these two data-loggers were transferred to a computer data base in approximately one-month intervals.

3.2 Field sample collection

Since the precipitation, the discharge of the drip water, and the temperatures of the air and water could be monitored automatically by the sensors with the data-logger, field samples were only taken for water chemistry analyses and aquatic biology analyses.

3.2.1 Hydrochemical sampling

In order to answer the question of the PhD objective on the impact of water quality and climate change on the epikarst fauna, the hydrochemical profile of four permanent drips were monitored within the cave. In addition, water from six water basins in the Velika Pasica Cave was analysed for their physical and chemical parameters, which were required for the year 2000 research survey on the micro-distribution of the Copepoda (Brancelj, 2002).

For the cave drip water analyses, two sampling strategies were conducted.

For the first strategy, in order to investigate the hydrochemical profile, and explain the impact from the hydrochemical difference between four drips to the epikarst ecosystem, during the period 2006-2013, a total of 32 sets of water samples from each of the four drips were taken. Samples were collected according to the faunal collection (biological sampling) regime and supplemented during the intensive rain events of these years. These water samplings were synchronized to the faunal samplings (section 3.2.2). Occasionally, several additional sampling were conjoined during the intensive rain events. The cave drip water samples were collected in a 60 ml PVC bottle. Details on this will be discussed in section 4.3.1.

The second strategy was based on intensive sampling of two drips (VP1 and VP2) in one-hour intervals during the intensive rain and snow melt events in 2012 and 2013. In order to catch the hydrochemical response of drip water to the infiltration events, an automatic water sampler was constructed for sampling (Figure 3-2), which collected a water sample in a 60 ml PVC bottle for 24 hours with one-hour intervals. Each sampling event lasted 3-5 days, due to the rain events. Consistent with the hydrochemical samples, the water temperature and the volume of the discharge of each hour were recorded by the data logger.

Two tests were taken for this time series drip water hydrochemical variation: one test included six intensive rain events in 2011 and 2012 at drip site VP1 and VP2; the other one was from 18th to 22nd of March, 2013.

For the first test, in order to present the different hydrochemical response of drip water at different drip sites to the different rain patterns, six intensive rain events which supplied the drips efficiently, were monitored at drip sites VP1 and VP2. The rain events for VP1 were: from 4th to 9th of August 2011 (hereafter as VP1-AUG); on 19th September 2011 (VP1-SEPT); from 7th to 9th October 2011 (VP1-OCT 1); from 18th to 27th October 2011 (VP1-OCT 2) and from 13th to 18th December 2011 (VP1-DEC). As VP2 showed only weak response to the rain events, a single proper event was selected for comparison, which was from 28th November to 2nd December 2012 (VP2-NOV).

Figure 3-2: 24 hours automatic water sampler for drip water chemistry sampling in the Velika Pasica Cave (Slovenia).

The second test coincided with the end of the long cold, wet winter with some remnant snow melt in March of 2013. Because the local meteorological station could not measure the snow depth, daily snow depth values for this study were used from a nearby meteorological station - Pokojišče (http://www.arso.gov.si). The meteorological data on daily precipitation and snow cover thickness from the Pokojišče station were available from the beginning of January till the beginning of April, 2013. In total, from January 1st to the March 31st, 2013, 595.5 mm of precipitation fell over 56 days, including 329 cm of snow (366.8 mm water depth) in

35 days. In total, there were 63 days with snow cover on the ground. According to the location and the altitude of the Pokojišče station, the data supplied could be supplemented with information from a local meteorological station for the detailed study period from 18th March to 22nd March, as presented in this case research. Details about the time series cave drip water hydrochemical variation will be presented in sections 4.3.2 and 4.3.3.

3.2.2 Biological sampling

In caves, species found in dripping water, or water in the pools on the floor of the galleries, were considered as species living in the unsaturated zone of the karst (epikarst and vadose zone) (Mori and Brancelj, 2008). Thus, the cave drips and the water pools on the floor were the ideal sampling site for epikarst fauna. In the Velika Pasica Cave, four permanent drips (VP1-VP4) were monitored for the hydrological and hydrochemical features of the epikarst water. Synchronized with the hydrological monitoring, the tiny fauna that live in the epikarst water were also collected.

Below each drip, in order to collect dispersed jets of water, a 2m × 2m plastic screen was placed and the collected water was directed into the funnel of the rain gauge. A Brancelj bottle (Brancelj, 2004) (Figure 3-3) was attached at the outlet of the rain gauge, which is specially designed for catching the tiny fauna in the percolating water by filtering with a 60-μm mesh sieve. The lower rims of the holes in the side of container are positioned some centimetres above the bottom, allowing a small poll of water to form in the bottom of the container and enable animals to stay alive for a long time there (Brancelj and Culver, 2005).

The sampling strategy started since May 2006. According to the rain events, climate and fauna activity, the frequency of the sampling was uneven, thus the volume of the drip water varied from site to site and from date to date. Till February 2013, 80 groups of samples were collected. After each sampling, samples were checked immediately in the laboratory with animals alive; afterwards they were transferred into 60 % ethanol until the final identification and further analyses.

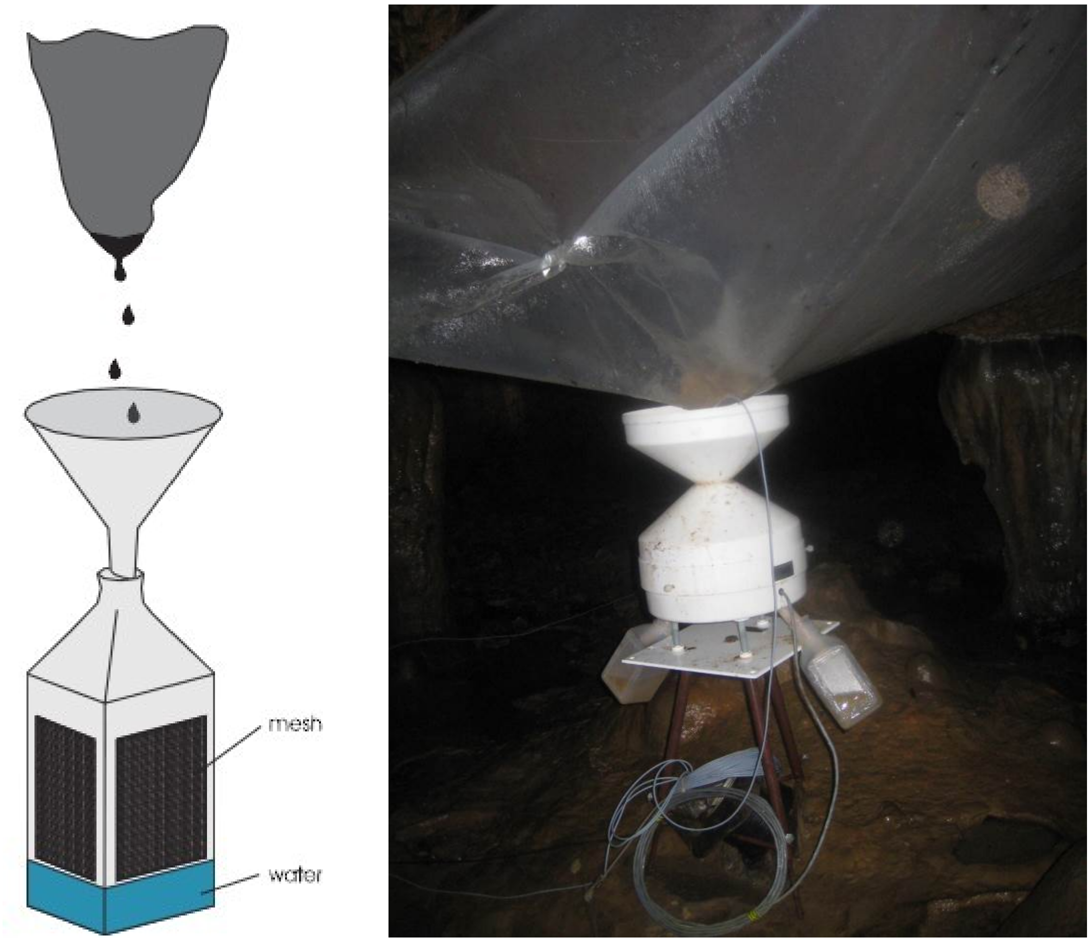

Figure 3-3: Left: A diagrammatic sketch of "Brancelj bottle" - the device for collecting fauna from percolating water (Brancelj and Culver, 2005). **Right:** The practical application of "Brancelj bottle" in the Velika Pasica Cave (Slovenia).

3.3 Laboratory work

3.3.1 Basic water chemistry analyses

Drip water samples were stored fully in the 60 ml PVC bottles and delivered to the laboratory within one hour after the sampling in cold box. In the laboratory all the samples were labelled in sequence according to the date and location of sampling. The electrical conductivity (EC) and pH of the samples were measured immediately by a Multi 340i instrument with an accuracy ±1% and a MultiCal pH-540 meter with accuracy of 0.01. The difference of the EC and pH measure results between in the cave and in the laboratory was checked, and there were no significantly difference. Samples were afterwards stored in a refrigerator at 5 ^oC and analysed within the following 48 hours. All samples were analysed for chemical characteristics by means of ion chromatography (Methrom 761 Compact IC), which included: K^+, Na^+, Ca^{2+}, Mg^{2+}, SO_4^{2-}, Cl^- and NO_3^- ions.

For the first strategic analyses, all 32 sample sets were selected for ion analyses. In the second strategy, due to the high volume of samples, only some samples were selected for IC analyses according to their EC and pH performance, which expressed significant changes in EC in two consecutive samples (i.e. along time series).

3.3.2 Taxa identification

Identification and counting of collected specimens were done only for Copepoda and Ostracoda by taxonomists. For species identification, the most recent taxonomic literature was used. Determination was made by means of a compound microscope (Olympus SZX12) and microscope (Olympus BX50).

3.4 Data analyses

3.4.1 Analyses of hydrological data

For the classification of the flow types of the epikarst water, the monthly discharge data from all the drips during 2010 were applied in this study. The maximum of hourly discharge of all the drips for each month in 2010 and their coefficient of variation (CV) were assessed in order to classify the hydrological characteristics of the cave drip waters (Smart and Friedrich, 1987). During each month, the hourly discharge data (recorded as mm/h) were recalculated into l/s and the maximum discharge values were chosen as the ordinate (Smart and Friedrich, 1987). The CV was calculated as a percentage of discharge and was calculated from the hourly standard deviations of discharge and average monthly discharge following the equation:

$$CV = \frac{\sqrt{\frac{\sum_{i=1}^{n}(R_i - M)^2}{n}}}{M} \times 100\% \qquad (3\text{-}1)$$

R_i: the hourly discharge within each month, in l/s

M: the average discharge of each month, in l/s

n: number of data of each month

The case study from May to June 2010 analysed the response of drips to rain events, presented on an hourly basis. Hour 0 represents the commencement of rain on May 2[nd] (at 3: 00) and hour 1054 represents the end of the observation period on June 14[th] (at 24: 00).

3.4.2 The recession analyses

Graphical approaches have been taken visually and directly, although analytical mathematical models are required to adequately fit the recession segments.

There are some contradictions in the literature (Horton, 1933; Werner and Sundquist, 1951; Hall, 1968; Appleby, 1970; Amit et al., 2002) as to who first derived the simplest and the most widely applied model in theoretical investigations and empirical studies of the recession curve. However, it appears that Boussinesq (1877), Maillet (1905), and Horton (1933) all independently derived the same function around the year 1904 (Nathan and McMahon, 1990):

$$Q_t = Q_0 e^{-at} \quad (3\text{-}2)$$

Q_t : the discharge at time t

t: the time since the recession process starts

Q_0 : the initial discharge

α : constant

Constant α is also known as the cut-off frequency, which represents the ratio of discharge recession and is relevant to the water reservoir medium. As α resulted from the non-homogeneous aqueous medium, its value varies during the recession period. However, the Equation 3-2 is frequently used for the homogeneous or approximately homogeneous aquifer.

The exponential function of the recession is the most frequently used function, which can be written in the alternative form (Tallaksen, 1995; Chapman, 1999; Sujono et al., 2004):

$$Q_t = Q_0 e^{-\frac{t}{C}} \quad (3\text{-}3)$$

$$Q_t = Q_0 k^t \quad (3\text{-}4)$$

Q_t : the discharge at time t

C : a recession period

k : recession constant

C: indicates the residence time of the groundwater system

C is defined as the ratio of storage to flow (Sujono et al., 2004). The term e^{-a} is normally replaced by *k*.

Based on above equations, a relationship between α and *k* is explained in the following forms:

$$k = e^{-a} \quad \text{or} \quad a = -\ln(k) \qquad (3\text{-}5)$$

For recession analyses, 17 rain events in the year 2012 were selected, but not all the drips had clear recession segments for all the events.

(1) The matching strip method

The matching strip method is based on the exponential model (3-2), and plots all the recession on a semi-logarithmic scale. Taking a significantly different approach from the individual recession segment analyses, the recession segments were plotted and shifted until the tail parts of most recessions overlapped in order to form a set of common lines. Following this approach, a mean line through these common lines represents the master recession curve (MRC) (Nathan and McMahon, 1990; Padilla et al., 1994; Tallaksen, 1995).

(2) The correlation method

Rearrangement of the exponential model (3-2), and the recession constant *k* can be expressed as a function of the slope of the correlation line ($\frac{Q}{Q_0}$) and the lag interval t.

$$k = \left(\frac{Q}{Q_0}\right)^{1/t} \qquad (3\text{-}6)$$

Namely, the constant *k* is the slope between the current discharge Q and the previous discharge Qt at the time interval *t* ago (Linsley et al., 1958; Knisel, 1963; Beran and Gustard, 1977; Nathan and McMahon, 1990).

The correlation method plots the all recession segments on natural scales, with the current discharge against the discharge at some fixed time *t* previously. If the equation (3-2) is correct, the plotted data of the recession will form a straight line. The envelope line is drawn as the master recession curve. *k* is a function of the slope of the envelope of the correlation line ($\frac{Q}{Q_0}$) and the lag interval *t*.

(3) The method for dividing the flow sections

Boussinesq's equation also could be modified and represented the discharge Q_t as a sum of the N exponential components:

$$Q_t = \sum_{i=1}^{N} Q_i * k_i^t \text{ (3-7)}$$

Where k_i is the recession constant of the *i*-th component of the recession segment; Q_i is the relevant discharge (Mero, 1964; Forkasiewicz and Paloc, 1967).

(4) Methods for calculating the drip water storage by recession analysis

As the quantitative expression made by Boussinesq (1904), the volume of discharge from drip water also could be presented as:

$$V(t) = \int_0^t Q(t)dt = \int_0^t Q_0 \cdot k^t dt \text{ (3-8)}$$

The total storage volume from t=0 to t=∞ is defined by *V₀*:

$$V_0 = \int_0^\infty Q(t)dt = \int_0^\infty Q_0 \cdot k^t dt \text{ (3-9)}$$

Some researchers have discussed this in relationship to different conditions, such as Amit et al. (2002) and Brenčič (unpublished).

If accumulated, the discharge since the recession started, the total discharge was recorded as V_0 (Equation 3-9).

Thus, the recession equations were presented as:

$$\begin{aligned} Q_{ti} &= Q_1 * k_1^t, [t_0, t_1]; \\ &= Q_2 * k_2^t, (t_1, t_2]; \quad \text{(3-10)} \\ &= Q_3 * k_3^t, (t_2, t_3]. \end{aligned}$$

And the discharge volumes of each component were presented as:

$$V_1 = \int_{t_0}^{t_1} Q_1 \cdot k_1{}^t dt;$$
$$V_2 = \int_{t_1}^{t_2} Q_2 \cdot k_2{}^t dt; (3\text{-}11)$$
$$V_3 = \int_{t_2}^{t_3} Q_3 \cdot k_3{}^t dt.$$

The discharge during the first segment was recorded V_1; the second was V_2; the third was V_3. k_i is the recession coefficient of the recession segment *i*. t_0 was the time the recession started. The irregular points should be eliminated, e.g. the points affected by rain events and draw broken lines for each segment, which represented each recession segment.

3.4.3 Hydrochemical data analyses

After basic chemical analyses in the laboratory, some hydrochemical parameters had to be determined through calculations, such as CO_2 partial pressure (pCO_2) and Saturation Index of Calcite (SIc). Some simple models were built with PHREEQC (Appelo and Postma, 2005).

In order to present the results clearly, the data were mainly organised in Excel. Rock software Aqqa, Grapher 9.0, and Original 8.0 were applied for the figures.

3.4.4 Biological data analyses

The species and their population from each drip were determined from 80 samples which were collected over seven years. In order to classify the fauna, and verify their seasonal and yearly distribution at different drip points, the samples were clustered into seasonal groups and annual groups. The cluster analyses were carried out with the correlation as the similarity measurement by the software PAST (version 2.03) (http://folk.uio.no/ohammer/past/-index.html). The non-metric multidimensional scaling (NMDS) analysis was based on the Euclidean distance measure for investigating the different seasonal microcrustacean species composition at different sites by SPSS 21.0.

Prior to the bio-hydrological analyses, the environmental parameters, such as the drip water discharge pattern, the water temperature, and the drip water hydrochemical profile, were matched for each biological sample. Canonical correspondence analysis (CCA) (ter Braak, 1986) was used in order to assess relationships between data on different species and their abundances and environmental parameters. Altogether, two groups of environmental parameters: the hydrological parameters (the days between two consecutive samplings (days), the amount of drip water discharge (Q), the maximum discharge during the sampling period (Max), the mean discharge (Mean), the coefficient of the discharge variation (CV), the mean drip water temperature (Temp), and the hydrochemical parameters (EC, pH, HCO_3^{2-}, Ca^{2+}, Mg^{2+}, Na^+, K^+, Cl^-, NO_3^- and SO_4^{2-}ions contents) were retained for the statistical analyses. Data on the presence and absence of copepods and two others species *Niphargus stygius* (Schiodte, 1847) (Amphipoda) and *Pseudocandona albicans* (Brady, 1864) (Ostracoda) were used, but rare species (only one individual in the sample) were excluded from the ordination analyses. The statistical significance of environmental variables in CCA was tested by the Monte Carlo permutation test (999 permutations) in forward selection of variables. CCA was run by program CANOCO 4.5 (ter Braak and Smilauer, 2002). In the ordination plots, the coordinates of the sampling sites are the values of the sites on the two best synthetic gradients (axes 1 and 2), and the species are represented by their niche centre along each axis.

Chapter 4 Results

4.1 Hydrological profile of cave drip water

4.1.1 Precipitation and response of the drips in time and maximal discharge

According to the precipitation data from the Pokojišče meteorological station, the amount of rainfall in 2010, its intensity and frequency varied considerably (Figure 4-1). More precipitation was recorded than an "average" year (1383 mm; Figure 2-3) with a total of 2031 mm of rainfall over 178 rainy days. Most precipitation occurred in May, September, November and December. In September 391 mm of rain fell over 17 days with the most intense rain event on 19th September with 112 mm/d. In May and December, there were 21 days in each month with rainfall, 212 mm and 258 mm, respectively. The driest time of the year was in March and April, with 82 mm and 72 mm of precipitation falling over 12 days of each month. During the drier months (March, April, June, July, August and October), the rain mainly came as storms with maximum values close to 16 mm/h (based on data from meteorological station adjacent to the cave).

According to the discharged volume, the four drips could be divided into two groups: drips VP1 and VP3 in one (i.e. significant responding drippings), and drips VP2 and VP4 into another group (i.e. slight responding drippings). Drips VP1 and VP3 reacted relatively fast and with higher discharge, while drips VP2 and VP4 reacted with longer time-delay and lower maximal discharge (Figure 4-1). The discharge from drip VP1 passed 1000 ml/min 18 times with the maximum at 1300 ml/min in 2010 (the highest value recorded was 1320 ml/min in the period 2006 - 2011). After heavy rain, drip VP3 had high peaks as well, but the extremely high discharge occurred only twice, once on September 8th with 815 ml/min, and the other on September 18th with 1160 ml/min, which was also the highest recorded discharge for that drip from 2006 to 2011. At drip VP2, the discharge passed the 250 ml/min level twice (on February 26th and December 24th), with the discharge of 480 ml/min and 500 ml/min, while the maximum discharge in the period 2006 to 2011was 540 ml/min. The discharge from drip VP4 in 2010 was low; there were only two events that passed the 250 ml/min level on September 28th with the maximum discharge 620 ml/min (which is also the highest one recorded in that drip so far). The other was on December 9th with the maximum discharge of 490 ml/min.

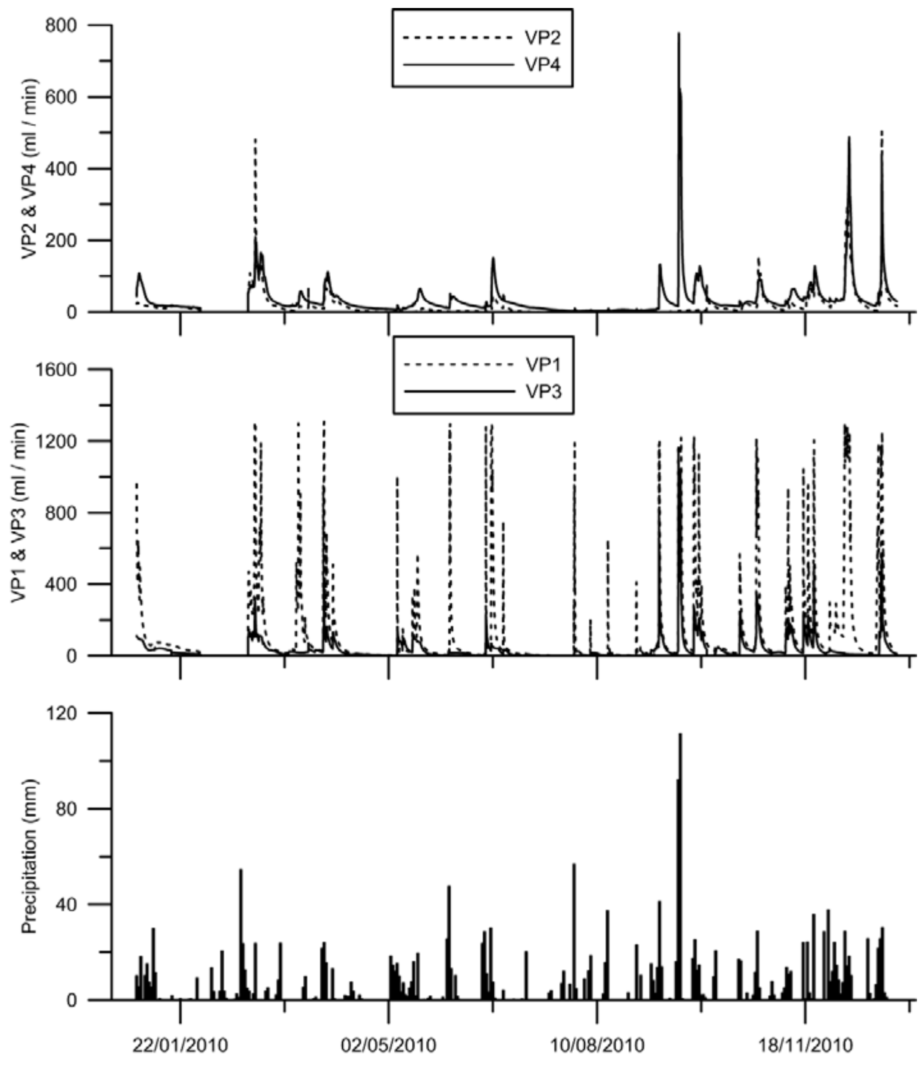

Figure 4-1: Discharge (ml/min) from four drips in the Velika Pasica Cave (Slovenia) in year 2010 (data between 31st January 2010 to 23rd February 2010 are missing) and daily precipitation (mm) recorded in 2010 at the Pokojišče meteorological station (altitude 737 m a.s.l.; 8 km west of the Velika Pasica Cave).

The response sensitivity of drips varied slightly between both groups while both groups had the similar discharge curves to rain rate and intensity. However, there were differences in their reaction times as well as maximum discharge (Figure 4-1). In the spring period, the response time of drip VP1 to rain events varied between 4 - 21 hours, and drip VP3 between 5 - 21 hours but discharge was much greater in VP1. The response time of drip VP2 in the same period was 11 - 47 hours after the rain event, but during the small rain events, which had slight precipitation and short duration, it showed no response. Drip VP4 expressed no response to the small rain events at all, but after persistent and intensive precipitation, the response times were closely related to that of drips VP1 and VP3, varying between 6 - 26 hours.

4.1.2 Classification of the cave drips by seasonal discharge dynamic

Values for average hourly discharge varied significantly based on figures from a one month study period and there were significant differences between different drips (Table 4-1). In order to compare with other analyses, here the unit of the discharge of drip water applied was l/s. Relationships between average hourly discharge and the intra-month variability of discharge for cave drips are site-specific, i.e. each drip has its own dynamic discharge. Drip VP1 had the highest hourly discharge with monthly maxima variation from 7.7×10^{-3} l/s to 1.6×10^{-2} l/s and also significant variation of CV, the highest was in July (552 %; not shown in the Figure 4-2), followed by August and June (343 % and 242 % respectively). The hourly discharge of drip VP2 was lower, with the maximum discharge variation from 2.8×10^{-6} l/s to 6.0×10^{-3} l/s and CV ranged between 31 % and 162 %. Drip VP3 had the second largest hourly discharge most of time (up to 1.4×10^{-2} l/s) and with CV ranged from 71 % to 209 %. Drip VP4 had discharge from 1.0×10^{-4} l/s to 9.3×10^{-3} l/s and CV varied between 28 % and 168 %.

Table 4-1: Monthly discharge for four drips (VP1-VP4) from the Velika Pasica Cave (Slovenia), based on hourly values (Average = mean discharge Q ($\times 10^{-5}$ l/s), Max = maximal discharge of the period ($\times 10^{-5}$ l/s); CV = coefficient of variation (%); n = number of data). **: Sections of data from February are missing (for details see Figure 4-1)*

	January				February				March			
	Average	Max	CV	n	Average	Max	CV	n*	Average	Max	CV	n
VP1	106.16	1148.52	133	736	544.51	1556.70	64	133	159.74	1565.14	162	744
VP2	16.42	31.25	31	736	144.23	575.10	66	133	24.71	151.73	123	744
VP3	38.20	132.87	77	736	153,84	385.37	36	133	36.68	519.93	108	744
VP4	30.96	129.49	88	736	120.27	249.97	44	133	45.32	196.77	87	744
	April				May				June			
	Average	Max	CV	n	Average	Max	CV	n	Average	Max	CV	n
VP1	80.47	1376.54	195	719	80.76	1549.66	222	744	102.01	1545.44	242	720
VP2	20.34	124.99	135	719	3.41	12.10	100	744	9.03	51.51	133	720
VP3	31.46	307.40	146	719	36.62	191.98	114	744	25.80	283.19	127	720
VP4	33.20	133.43	90	719	24.08	77.13	069	744	39.19	180.16	81	720
	July				August				September			
	Average	Max	CV	n	Average	Max	CV	n	Average	Max	CV	n
VP1	16.14	1421.58	552	744	15.75	774.97	343	741	237.95	1470.84	162	720
VP2	0.88	5.35	117	744	0.08	0.28	162	741	2.63	7.04	101	720
VP3	3.38	33.50	209	744	10.35	28.71	71	394	122.61	1392.02	179	720
VP4	11.49	27.87	58	744	5.33	10.42	28	741	83.78	929.51	168	720
	October				November				December			
	Average	Max	CV	n	Average	Max	CV	n	Average	Max	CV	n
VP1	120.83	1460.99	187	744	173.65	1438.47	126	721	306.54	1551.07	138	744
VP2	26.36	186.07	110	744	31.07	132.02	120	721	72.71	601.85	127	744
VP3	54.10	423.94	139	744	75.72	598.19	105	721	38.49	664.06	209	744
VP4	36.66	108.10	58	744	52.41	152.01	70	721	91.06	582.71	119	744

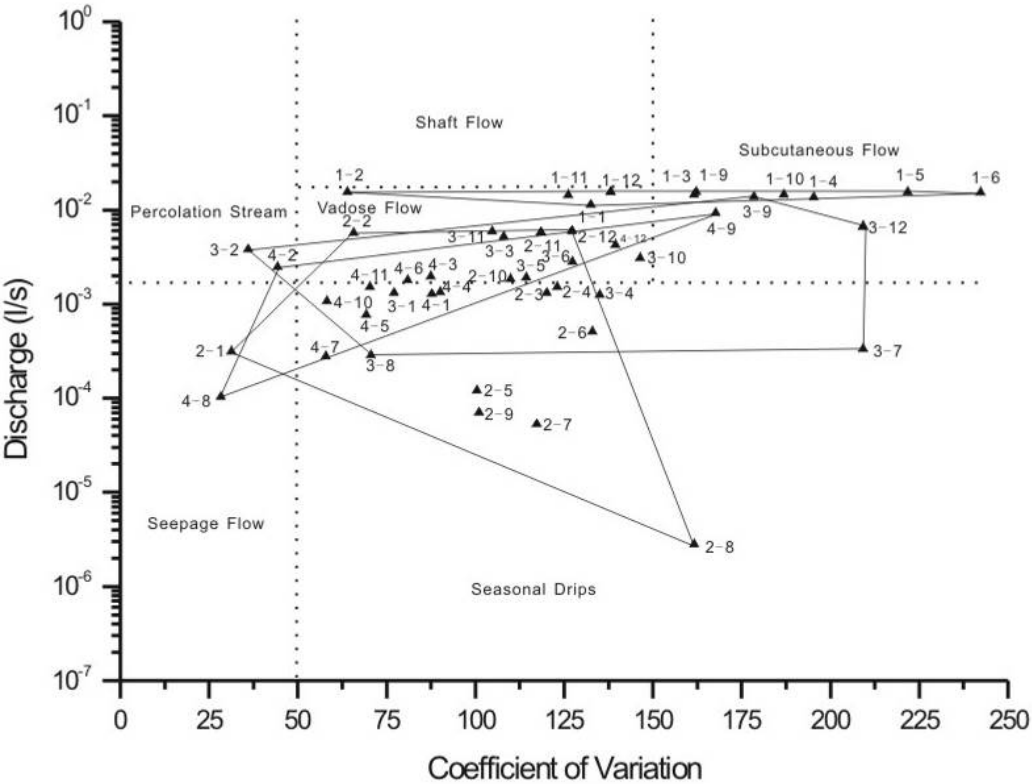

Figure 4-2: Relationship between the maximum discharge and the intra-month variability of discharge for four cave drips in the Velika Pasica Cave (Slovenia). Each plot is based on the hourly maximum discharge for each month (l/s) versus the inter-monthly variability measured as the coefficient of variation (%) within the karst water classification scheme (Smart and Friedrich, 1987). The first number in a plot is referred to the drip (VP1 – VP4) and the second number referred to the months.

Within the classification scheme for cave drip water, all the drips in the Velika Pasica Cave frequently had a low drip rate, thus most of them fall into the seasonal drip type, followed by the vadose flow (Figure 4-2). The exception is drip VP1, which is characterised by the very distinct vadose / subcutaneous flow, with a rather high and constant maximal discharge and with seasonally variable CV. Drip VP2 was characterised by vadose and seasonal flow with significant variability in monthly maximum discharge and CV. Drip VP3 was characterised by a combination of seasonal, subcutaneous and vadose flow, with the lower discharge in summer and the maximum discharge in autumn. Drip VP4 was located in the sector of the seasonal / vadose flow but in some summer months seepage flow prevailed.

4.1.3 Response of the drips to rain events (case study in May and June 2010)

Two rain events occurred in May and at the beginning of June 2010 which affected the activities of the drips in the cave. The first rainfall commenced on May 2nd (at 3:00; indicated as hour 0) with relatively low intensity, but continued gently until May 15th (at 22:00; hour 332). Over that period 101.6 mm of precipitation fell. The second event was short but more intensive and lasted from May 29th (at 15:00; hour 661) to June 4th (at 2:00; hour 792), when 81 mm rain fell (in the shadow part of Figure 4-3). Before the second event, there was only a slight shower on May 21st, (2.8 mm of rain in 15 hours; from hour 454 to hour 468). The analysed period finished on June 14th (at 24:00; hour 1053) (Figure 4-3).

Before this event, a long period (about 320 hours) with no or slight precipitation (several small rain events occurred (0.2 - 4 mm/h)), which did not feed drip efficiently. Since the first rain commenced on May 2 at 3:00 (= hour 0), it took more than 90 hours before the drips started to respond inside the cave. The first response of drips to the rain event occurred 92 hours since the first rain started, when drip VP3 commenced to rise. Within the following hour, drip VP1 started to respond (at hour 93), followed by drip VP4 at hour 94. At hours 92 and 94, heavy rain arrived at two peaks (3.6 mm/h and 8.4 mm/h respectively). Drip VP2 responded gently and with considerable delay on May 13th (in hour 262).

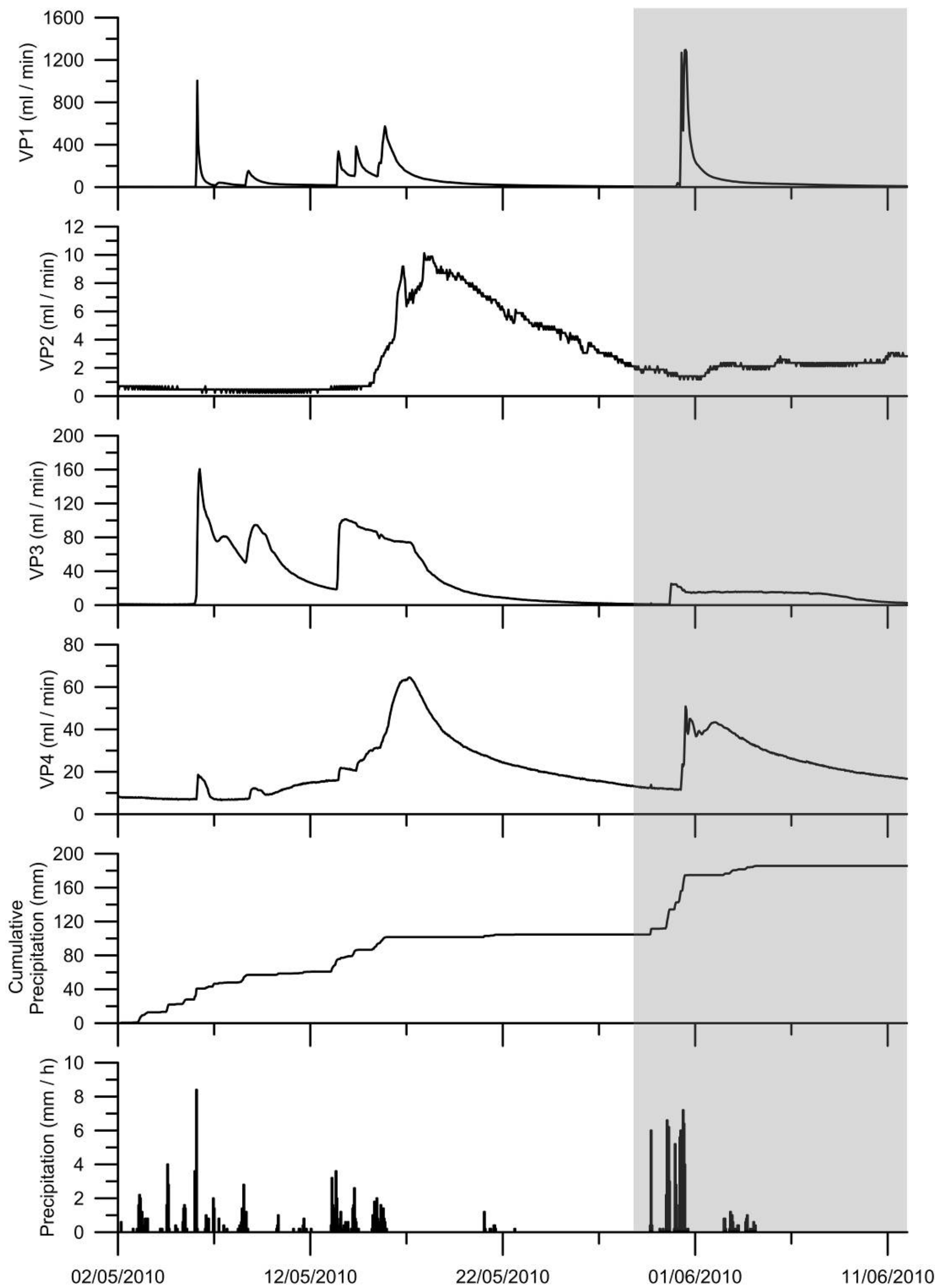

Figure 4-3: Responses of four permanent drips in the Velika Pasica Cave (Slovenia) according to the precipitation in May and June 2010 (duration of studied period = 1054 hours). The shadow part indicates the second rain event.

After the drips started to respond, each drip had a different response time to achieve its "local" maximum discharge. For the first rain events, the first peak of discharge in drip VP1 arrived within two hours after it started to respond (from the minimum 2 ml/min to the maximum 721 ml/min at hour 95). Some slower increase was in drip VP3, which took five hours to arrive at its peak (from the minimum 2 ml/min to the maximum 115 ml/min at hour 98). The first peak of drip VP4 came as rapidly as in drip VP1 although the discharge was much lower (from the minimum 5 ml/min to the maximum 13 ml/min at hour 97). The extreme was drip VP2 which was belated, and also with a small volume (from the minimum 0.3 ml/min at hour 262 to the maximum 6.6 ml/min at hour 351).

During the second rain event (the shadow part in Figure 4-3), drip VP1 responded within 21 hours after rain commenced (in hour 693) and with a higher maximal discharge (930 ml/min; at hour 699) in comparison to the first event. Drip VP3 reacted almost concurrently with drip VP1 but with lower maximum discharge (18 ml/min; also lower compared to the first event). Drip VP4 reacted during the second rain event almost concurrently with drips VP1 and VP3. Compared to the first event it had slightly lower maximum discharge (36.5 ml/min/) but with a long "tail" afterwards. Drip VP2 reacted to the second rain event by a slight rise in discharge without any distinguished peak.

In order to assess the intensity and duration of the drip's discharge, the average discharge values were compared to the discharge distribution curves (DDC) (Figure 4-4).The discharge distribution curves for a period between May 2nd and June 14th (i.e. in total of 1054 hours) compared with average hourly discharge values revealed that in drip VP1 hourly discharge was above the average value (61.2 ml/min) for 217 hours (20.6 % of total observed time) (Figure 4-4). In drip VP2 it was for 321 hours (30.5 % of total observed time) above the average discharge (2.8 ml/min), in drip VP3 it was for 288 hours (27.3 % of total observed time) above the average discharge (26.3 ml/min) and in drip VP4 it was for 401 hours (38.0 % of total observed time) above the average discharge (22.3 ml/min).

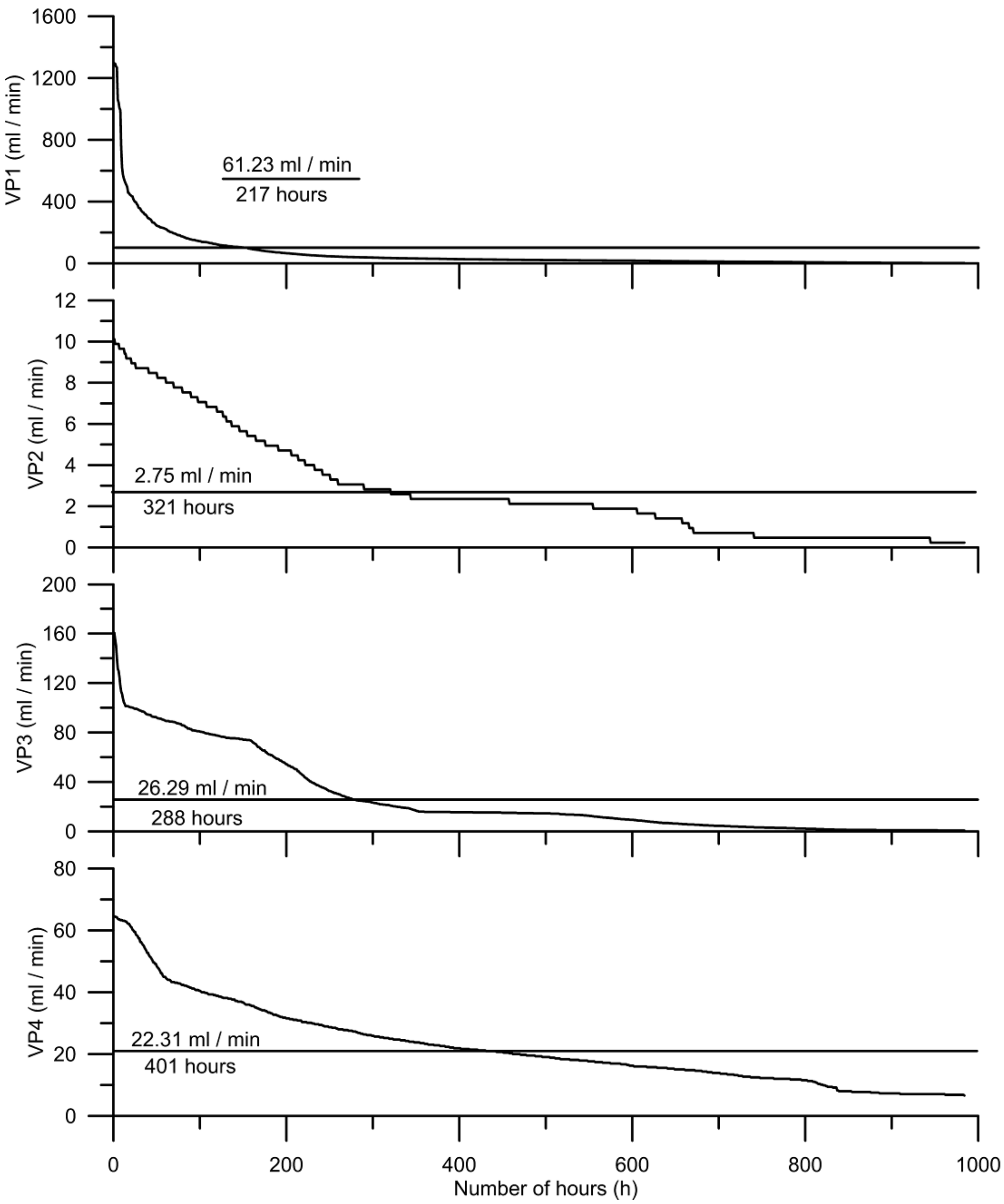

Figure 4-4: Discharge distribution curves of four permanent drips in the Velika Pasica Cave (Slovenia) for May and June, 2010 (duration of studied period = 1054 hours). The horizontal line was the average discharge for studied period which was indicated above the line; value below the horizontal line was the duration of discharge larger average discharge

4.2 The regulation and storage capacity of epikarst

4.2.1 Hydrology of the cave drip water

According to the drips response speed and their discharge intensity of the four permanent drips in the cave in response to the precipitation, also discussed in section 4.1, each drip could be described as: “rapid response with high intensity discharge” (VP1); “fast response with moderate discharge” (VP3); “rapid response with congest discharge” (VP4) and “slow response with congest discharge” (VP2). VP1 had rapid response to the precipitation, with high fast discharge flow followed by a subsiding period. There was no apparent response from VP2 to the event. VP3 responded fast while it had gentle rise and prolonged recession process. The discharge from VP4 was very low. An example of different hydrological performance of drips to a precipitation at the beginning of January is illustrated, with total amount of 25.6 mm rainfall fell in 28 hours, from 2nd to 3rd January, 2012 (Figure 4-5).

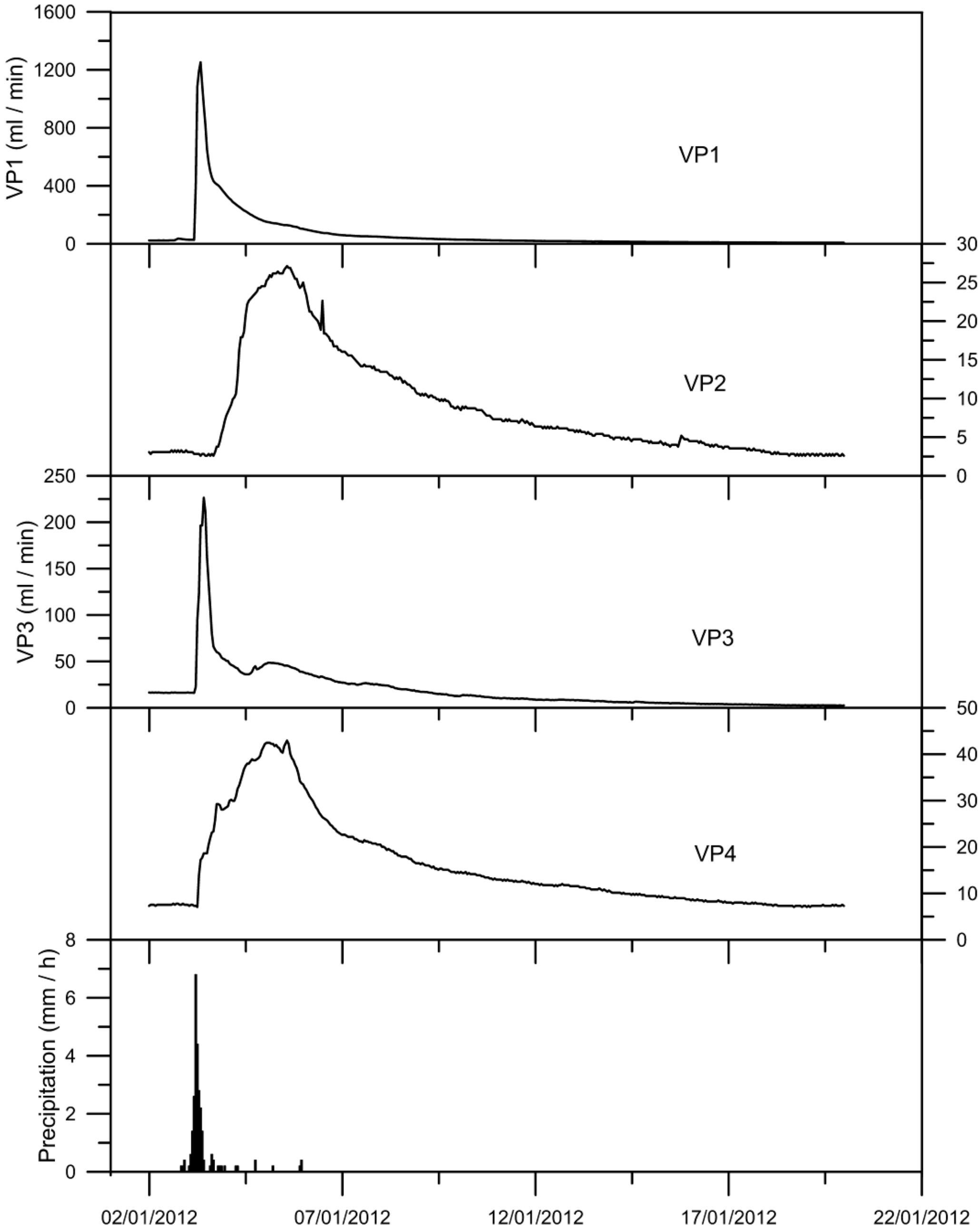

Figure 4-5: The hydrological response of four drips in the Velika Pasica Cave (Slovenia) to the rain event from 2nd to 3rd January, 2012.

4.2.2 Recession analyses

4.2.2.1 Individual recession segments in different rain events

Average recession characteristics can be summarized from all the recession curves. The values of the recession coefficient k for each 17 rain events in 2012 are given in Table 4-2. Based on this data, the average recession coefficient k was obtained. According to the discharge performance of each drip, the recession coefficient k were presented respectively, which decreased from 0.992 (VP4) to 0.988 (VP2), 0.980 (VP1), 0.975 (VP3). The k of each individual event varied significantly between different drips.

According to the hydrological characteristics of the different drips, they had distinctive performance to each rain event. VP1 responded most to the rain events (16 times) with recession segments, while VP2 skipped 8 events. The dry weather was one of the factors which affected the failure in lack of recession segments.

Implied from the Equation 3-2, the recession should be plotted in a straight line on the semi-logarithmic plots. However, in plotting the individual recession segments of the discharge of four drips to rain events directly on the semi-logarithmic plots, usually they did not result in straight lines, which could be explained by the different flow components, namely fast flow and slow flow, while different segments with different flows had their own recession coefficient k. Comparison between different drips indicated this clearly (Figure 4-6). VP 2 matched much better than VP1 in a straight line.

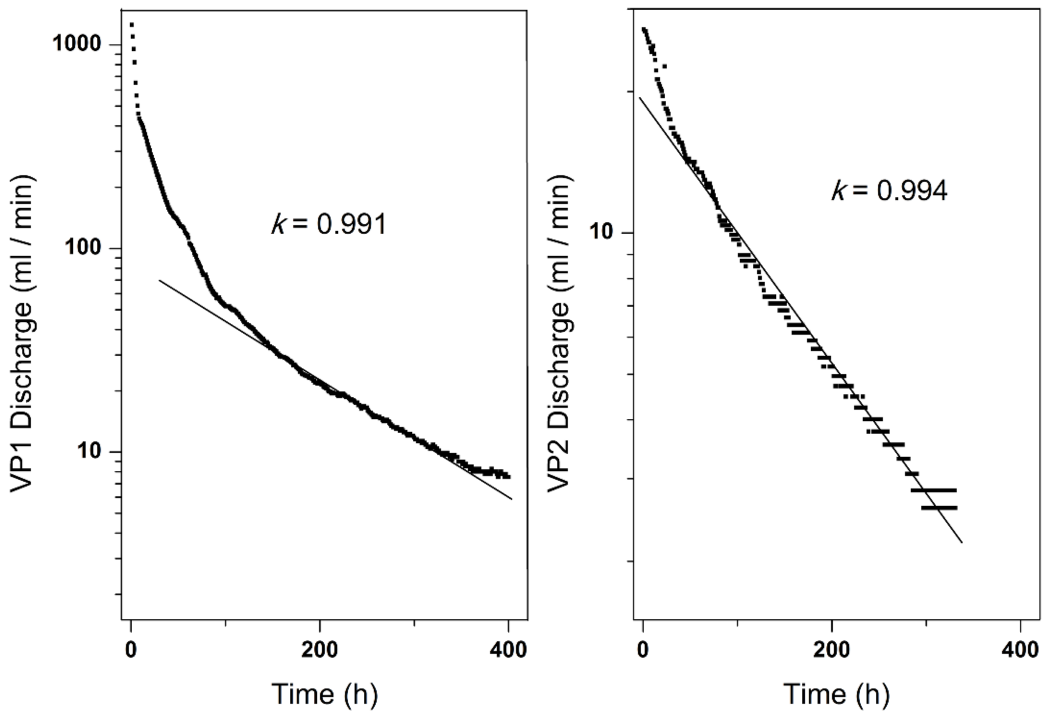

Figure 4-6: Example of individual recession segment analysis for estimating the recession constant *k* in semi-logarithmic plot at drip VP1 and VP2 sites in the Velika Pasica Cave (Slovenia), during the rain event on 3.1.2012.

4.2.2.2 Master recession

Affected by the weather conditions, the recession behaviour of individual events varied significantly in the drips, thus it was hard to determine a *k* for a particular catchment. Thus, the master recession methods were applied to overcome the problem, which were defined as an envelope of the individual recession curves. Two most commonly used graphical methods have been used to construct the master recession curve: the matching strip (Snyder, 1939) and the correlation method (Langbein, 1938).

1) Matching strip method

The Master recession curves (MRC) of VP1 and VP2 were calculated by the matching strip method and are presented in Figure 4-7. Meanwhile, all the results of the recession constant *k* are presented in Table 4-2.

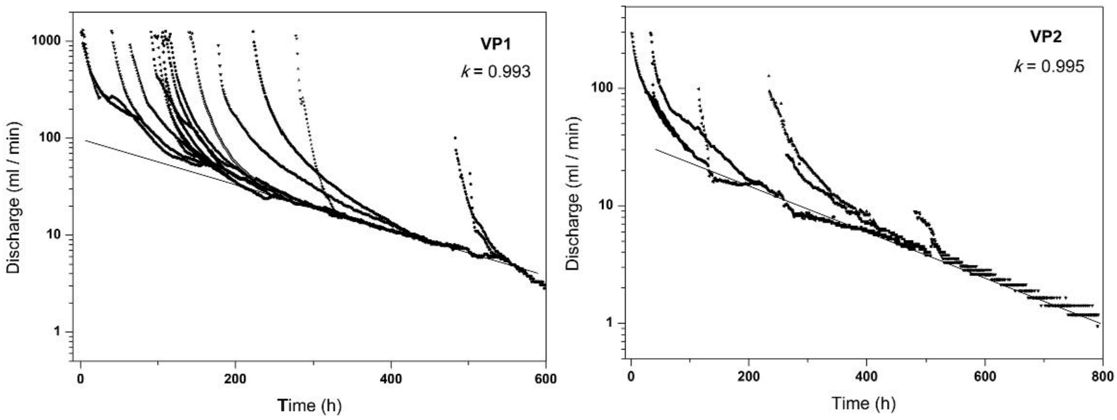

Figure 4-7: Example of the matching strip method for estimating the recession constant *k* at drip VP 1 and VP2 in the Velika Pasica Cave (Slovenia) for the year 2012.

2) Correlation Method

According to the correlation method, analyses of VP1 and VP2 in the interval two hours and five hours were plotted in Figures 4-8 and 4-9, and all the results of recession constant *k* are presented in Table 4-2.

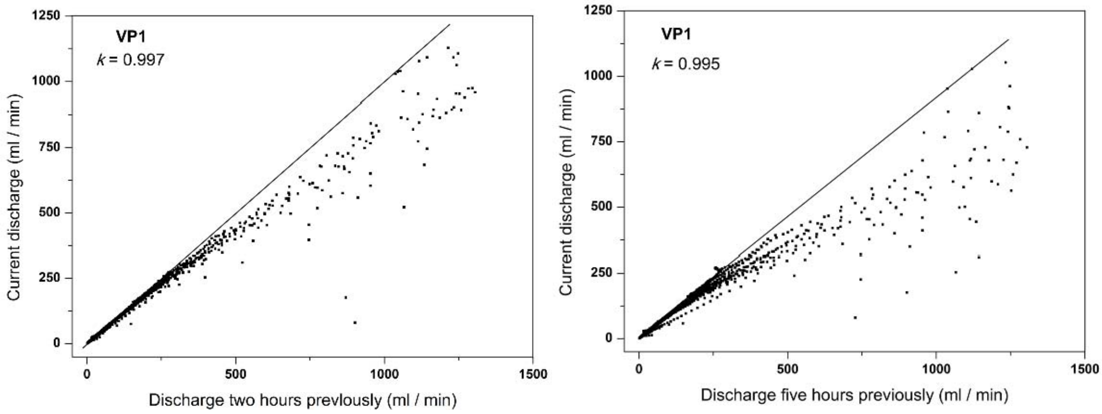

Figure 4-8: Example of the correlation method for estimation of the recession constant k with two hours (left) and five hours (right) difference at site VP1 in the Velika Pasica Cave (Slovenia).

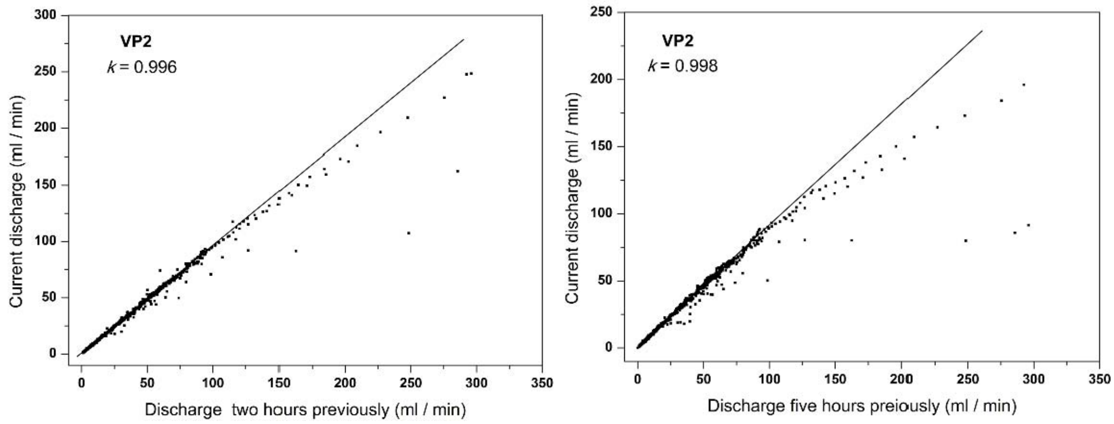

Figure 4-9: Example of the correlation method for estimation of the recession constant k with two hours (left) and five hours (right) difference at site VP2 in the Velika Pasica Cave (Slovenia).

Table 4-2: Recession constants *k* of four drips in the Velika Pasica Cave (Slovenia) estimated by different methods

Event	VP1				VP2				VP3				VP4			
		Master recession				Master recession				Master recession				Master recession		
			Correlation				Correlation				Correlation				Correlation	
	IN	MS	2 h	5 h	IN	MS	2 h	5 h	IN	MS	2 h	5 h	IN	MS	2 h	5 h
2012/1/3	0.991				0.994				0.991				0.996			
2012/3/19	0.979															
2012/4/15	0.990								0.987							
2012/4/22	0.988				0.997				0.987				0.995			
2012/5/13	0.958								0.974							
2012/5/16	0.986								0.983				0.997			
2012/6/4	0.972								0.980							
2012/6/12	0.982				0.987				0.936				0.990			
2012/7/11	0.986								0.951				0.998			
2012/9/1	0.970															
2012/9/13	0.974								0.960				0.982			
2012/9/20	0.993				0.994				0.975				0.996			
2012/10/15	0.986				0.993				0.984				0.991			
2012/10/28	0.978				0.977				0.977				0.976			
2012/11/1	0.970				0.978				0.976							
2012/11/5	0.979				0.986				0.981							
2012/11/28	0.983				0.988				0.976				0.996			
average	0.980	0.993	0.997	0.995	0.988	0.995	0.996	0.998	0.975	0.990	0.996	0.998	0.992	0.997	0.997	0.998
CV	0.009				0.007				0.015				0.007			

IN: individual; MS: matching strip.

4.2.3 The division of the flow sections

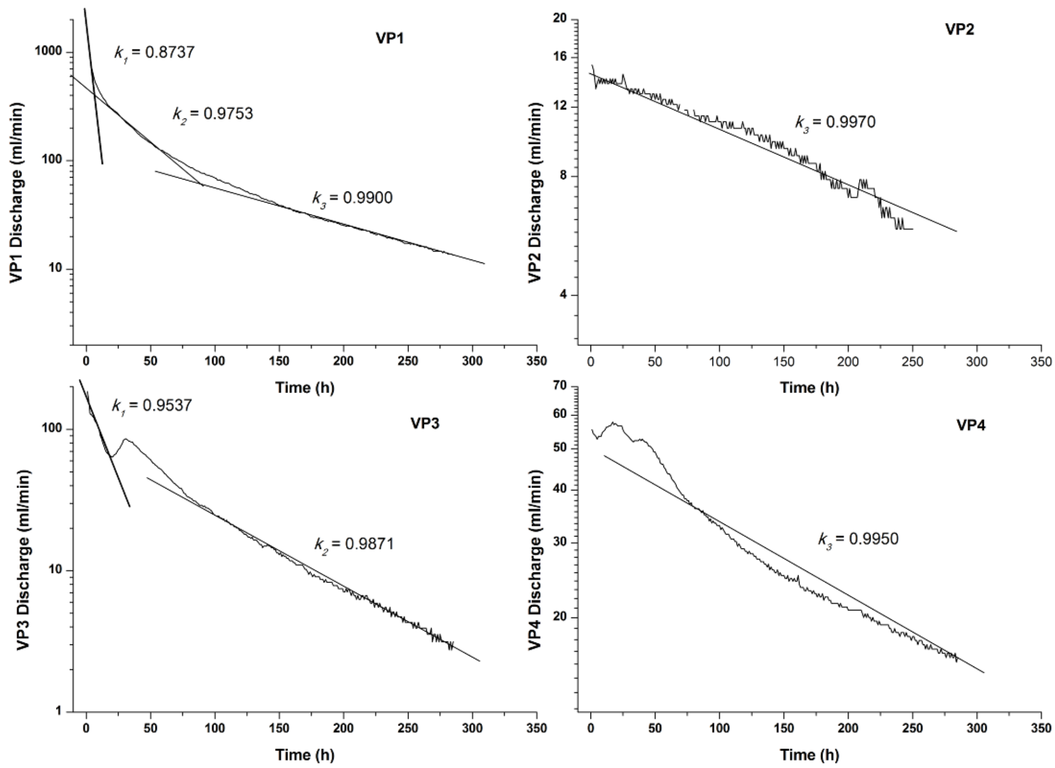

Figure 4-10: example of the division of the recession segment of four drips in the Velika Pasica Cave (Slovenia) in the event in April 2012.

The recession processes at different drips to the same recharge event performed distinctively different (Figure 4-10). The recession curve of VP1 could be divided into three segments, and two segments for VP3, while one for each VP2 and VP4. Different segments could be indicated by their different recession coefficient *k*. The values of the recession parameter *k* for each component are presented in Table 4-3. In total, 17 events were selected, but the drips did not respond to the full progresses. At sites VP2 and VP4, the recession segments in some events were missed. Albeit, VP1 was the most active drip, and it contained the fast flow and intermediate flow almost all times, while the slow flow occurred less frequently, i.e. 13 times. VP3 also was an active drip (Figure 4-5), but the most common water flow there was the intermediate flow and the slow flow was rare. The slow flow and intermediate flow were predominent at sites VP2 and VP4. The results from the recession analyses are in accordance with the hydological curves in Figure 4-5.

Table 4-3: The average values and range of the recession coefficients for each component flow of the recession segment of four drips in the Velika Pasica Cave (Slovenia). N: the number of each component flow of the recession segment.

	VP1			VP2		
	Fast	Intermediate	Slow	Fast	Intermediate	Slow
Average	0.8959	0.9742	0.9900	0.9282	0.9803	0.9939
Range	0.8201-0.9405	0.9615-0.9828	0.9831-0.9949	0.9276-0.9288	0.9709-0.9872	0.9897-0.9973
N	16	16	13	2	7	7
	VP3			VP4		
	Fast	Intermediate	Slow	Fast	Intermediate	Slow
Average	0.9465	0.9814	0.9913	0.9236	0.9700	0.9952
Range	0.9270-0.9601	0.9714-0.9872	0.9908-0.9917	0.9179-0.9293	0.9518-0.9882	0.9911-0.9984
N	9	12	2	2	8	13

4.2.4 The calculation of the storage (an example)

In order to estimate the water storage in epikarst, and the volume of different water flow, the Equation 3-11 was figured out. The rain event in April, 2012, presented in Figure 4-10, was taken as an example for the calculation. Combined the Equation 3-11 and Figure 4-10, the epikarst flow was divided into three periods: the fast flow, the intermediate flow and the slow flow. For each period was determined the initial flow rate, the recession coefficient and the duration of the water flow. The parameters are presented in the Table 4-4.

Table 4-4: The recession parameters of different flow periods of the event in April, 2012, Velika Pasica Cave (Slovenia). The parameters includes the initial flow rate, the recession coefficient, and the duration of three different periods of the recession.

	Fast			Intermediate			Slow		
	Q1 (ml/min)	k1	Δt1 (hour)	Q2 (ml/min)	k2	Δt2 (hour)	Q3 (ml/min)	k3	Δt3 (hour)
VP1	1518.61	0.8737	25	259.46	0.9753	166	19.26	0.9900	61
VP2	-	-	-	-	-	-	15.33	0.9970	250
VP3	185.16	0.9537	85	23.59	0.9871	191	-	-	-
VP4	-	-	-	-	-	-	56.61	0.9950	262

After calculation from the Equation 3-11, all the volumes of different recession periods are figured out in Table 4-5. Meanwhile, really discharge from each drip, which was monitored by the data-logger, was presented in the Table 4-5 for comparison.

Table 4-5: Comparison between the results of the recession calculation and the measured discharge, and their difference from the rain event in April, 2012. V(1): the calculated result; V'(1): the measured discharge; δ: the difference between them. Values in litres (l).

	Fast			Intermediate			Slow			Total		
	V1(l)	V1'(l)	δ1(%)	V2(l)	V2' (l)	δ2(%)	V3(l)	V3' (l)	δ3(%)	V(l)	V' (l)	δ(%)
VP1	11.23	12.56	-10.60	12.24	14.70	-16.73	0.81	0.95	14.73	24.28	28.21	-13.93
VP2	-	-	-	-	-	-	2.69	2.54	5.91	2.69	2.54	5.91
VP3	3.84	4.92	-21.95	1.76	1.77	-0.56	-	-	-	5.6	6.69	-16.69
VP4	-	-	-	-	-	-	7.34	7.48	-1.87	7.34	7.48	-1.87

4.3 The hydrochemical response of cave drip waters to seasonal climate variability

4.3.1 Hydrochemical characteristics

4.3.1.1 Major ions

For the first strategy (section 3.2.1), a total of 32 sets of drip water samples from four drips were taken during the period 2006-2013. Five sets from the year 2009 and 2010 are presented in Table 4-6. The Piper diagram and the Schoeller diagram (Figures 4-11 and 4-12) present the entire 32 sets of water samples. Both the table and figures indicated that Ca^{2+}, Mg^{2+} and HCO_3^- ions were the main components of the water chemistry. Figure 4-11 shows that all the drips have similar water types to those in the cave. The dipping waters are mostly characterised as Ca-HCO_3, and some as Mg-HCO_3, e.g. VP4. From the anion results, bicarbonate was relative high in all the samples, followed by sulphate and chloride (Figure 4-12); while among the cations, Ca^{2+} and Mg^{2+} were the main ions, although Mg^{2+} concentration was higher than that of Ca^{2+} in some samples.

However, the concentrations of different ions varied from drip to drip with VP4 being the most extreme. With the exception of samples from VP4, most samples were characterised by Ca-HCO_3 waters, with low TDS and electrical conductivity (EC). Waters samples from VP4 were mostly of Mg-HCO_3 type with high TDS and electrical conductivity (Table 4-6). The main ions, Mg^{2+} and HCO_3^-, had similar variation. They were much higher at VP4 and slightly higher at VP2 than those at VP1 and VP3. Concurrently, these differences were also mirrored by minor ions, such as NO_3^-, SO_4^{2-} and K^+ were higher at VP4, Na^+ and Cl^- were abundant at VP3. Due to the high Mg^{2+} concentration at VP4, the ion concentration indicator, EC was relatively higher than in other drips (Table 4-6).

Table 4-6: Chemical analyses for five sets of dripping water samples in the Velika Pasica Cave (Slovenia) in 2009 and 2010. EC: electrical conductivity (μS/cm (25 °C)). TDS: total dissolved solid (mg/l), calculated by Rockware AqQA. Highest values are marked in bold.

Sites	Date	Cl^-	NO_3^-	HCO_3^-	SO_4^{2-}	Na^+	K^+	Ca^{2+}	Mg^{2+}	EC	TDS	Water type
		mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	μS/cm (25 °C)	mg/l	
VP1	2009/12/23	0.23	0.49	178.59	1.39	0.43	0.16	33.93	15.02	240	229.75	Ca-HCO_3
VP2	2009/12/23	0.26	1.06	328.53	2.93	0.69	0.11	58.35	30.25	403	421.12	Ca-HCO_3
VP3	2009/12/23	**2.02**	0.41	286.54	1.38	**4.36**	0.26	**58.85**	19.81	345	373.22	Ca-HCO_3
VP4	2009/12/23	0.57	**41.42**	**738.01**	**6.19**	0.86	**0.64**	53.39	**122.26**	**747**	**921.92**	Mg-HCO_3
VP1	2010/1/17	0.12	0.65	253.52	1.64	0.46	0.18	45.94	22.59	328	324.45	Ca-HCO_3
VP2	2010/1/17	0.23	0.43	296.65	2.18	0.64	0.19	46.45	30.8	377	377.14	Mg-HCO_3
VP3	2010/1/17	**6.85**	0.86	291.38	1.58	**4.05**	0.18	**55.75**	24.58	399	384.37	Ca-HCO_3
VP4	2010/1/17	0.51	**37.14**	**592.01**	**6.56**	1.02	**0.58**	39.07	**101.31**	**633**	**741.06**	Mg-HCO_3
VP1	2010/2/23	0.14	0.56	220.21	1.67	0.61	0.08	40.75	19.1	289	282.56	Ca-HCO_3
VP2	2010/2/23	0.18	0.46	302.09	2.55	0.64	0.12	51.24	29.1	378	385.92	Ca-HCO_3
VP3	2010/2/23	**5.44**	0.52	271.47	1.66	**2.77**	0.12	**52.41**	22.83	363	356.7	Ca-HCO_3
VP4	2010/2/23	0.67	**27.81**	**577.19**	**5.73**	0.98	**0.56**	49.49	**90.21**	**621**	**724.83**	Mg-HCO_3
VP1	2010/8/16	0.1	0.997	508.61	1.35	0.56	0.41	**92.6**	44.64	484	648.27	Ca-HCO_3
VP2	2010/8/16	0.14	PMD	359.44	2.58	0.62	PMD	62.88	33.35	437	459.01	Ca-HCO_3
VP3	2010/8/16	**2.01**	2.05	387.07	0.79	**3.44**	**1.24**	51.77	44.18	630	490.53	Mg-HCO_3
VP4	2010/8/16	0.41	**18.87**	**678.94**	**5.84**	1.04	0.7	56.69	**104.04**	**679**	**847.66**	Mg-HCO_3
VP1	2010/9/02	0.11	1.17	486.22	1.44	0.53	0.39	84.66	45.08	553	618.43	Ca-HCO_3
VP2	2010/9/02	0.12	1.17	490.98	1.46	0.52	0.47	84.87	45.88	436	624.3	Ca-HCO_3
VP3	2010/9/02	**1.06**	0.86	488.30	0.77	**2.74**	0.23	**91.36**	40.46	606	624.92	Ca-HCO_3
VP4	2010/9/02	0.33	**21.32**	**584.69**	**6.36**	0.93	**0.61**	111.91	**53.03**	**693**	**757.86**	Ca-HCO_3

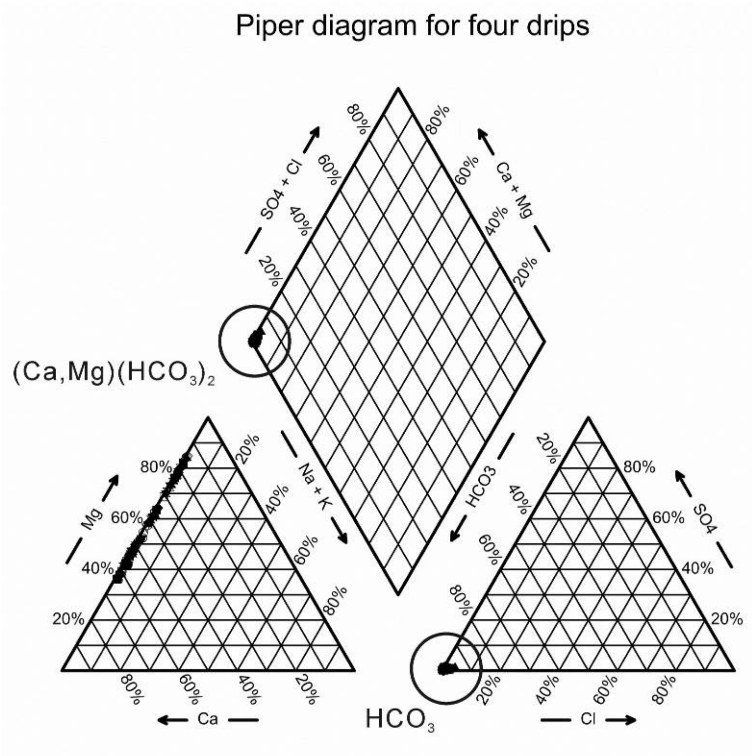

Figure 4-11: Piper Diagram showing hydrochemistry of all 32 sets of drip water samples during the period 2006-2013 from four drip sites in the Velika Pasica Cave (Slovenia).

These differences were observed not only between different locations, but also among different seasons of the hydrological year (Table 4-6).

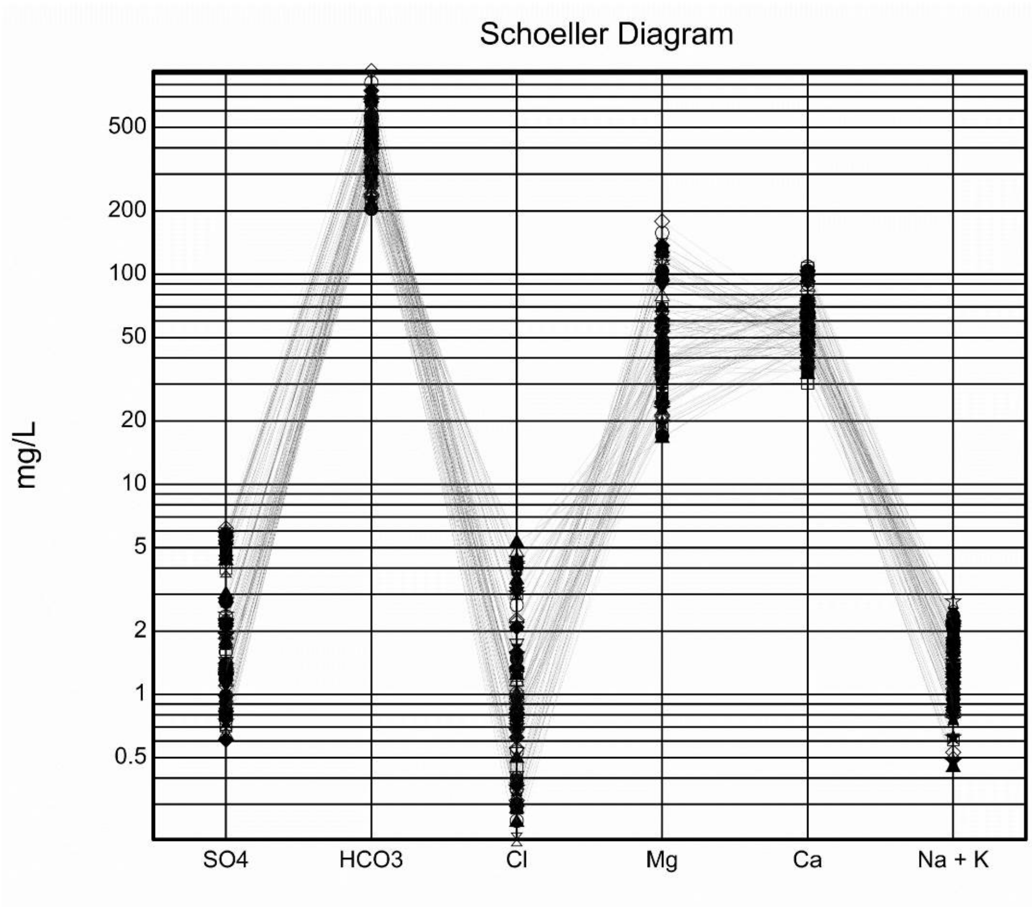

Figure 4-12: Schoeller diagram with concentrations of main ions for all 32 sets of drip water samples during the period 2006-2013 from four drip sites in the Velika Pasica Cave (Slovenia).

4.3.1.2 The seasonal variation of ions between drips

Considering the continuity of the sampling regime, we choose the period from October 2011 to December 2012, and 23 sets of the group samples for analyses.

The hydrochemical feature of the cave drip water exhibited some yearly variations on a seasonal base. The dominant ions, Ca^{2+} and Mg^{2+} ions, had higher concentrations during the summer season, while lower concentrations in the colder season (Table 4-6; Figure 4-13). The variations were detected within different drips. The minor ion, Na^{+}, K^{+}, Cl^{-} and SO_4^{2-}, had less seasonal variations (Figure 4-14).

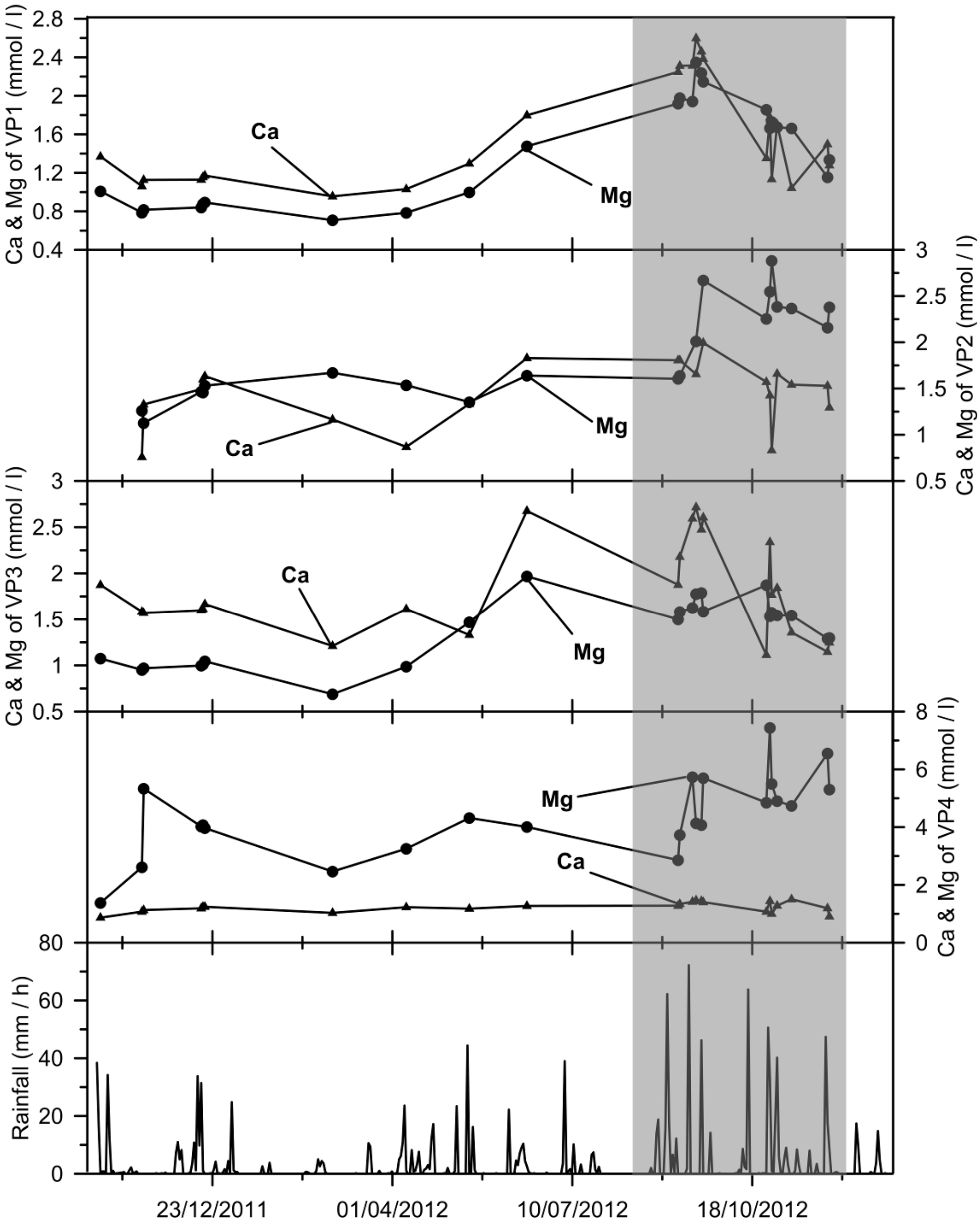

Figure 4-13: Variations in major ions, Ca^{2+} and Mg^{2+} (in m mol/l) from four drips from October 2011 to December 2012 in the Velika Pasica Cave (Slovenia). The gray band indicates the intensive infiltration period.

The most obvious variations were driven by Ca^{2+} and Mg^{2+} ions at the four different drip sites (Figure 4-13). The drips were affected significantly by the infiltration events particularly during the cold period. At the VP1 site, both ions varied synchronously during the even rainfall period, but when the intensive rainfall period started, they varied significantly. The drip VP 3 had a similar pattern in variation as VP1, while it reacted more visually to the rain event. Different from the drips VP1 and VP3, Mg^{2+} ions normally kept higher than Ca^{2+} at the drip sites VP2 and VP4 .Frequently, Mg^{2+} ions were slightly higher than Ca^{2+} at VP2, while at VP4, the Mg^{2+} ions concentration was much higher than the Ca^{2+}. This reading was the highest among all the drips. Mg^{2+} ions had an obvious increase during the intensive rainfall period at both VP2 and VP4 sites, while Ca^{2+} remained low.

During the same period, the minor ions oscillated even more obviously from drip to drip (Figure 4-14). The most distinctive feature between the drips was the Cl^- at VP2 and the SO_4^{2-} ions at VP4, and both were significantly higher than at other sites. Regarding the low ions concentration, they retained slight variation, but they still maintained some annual variation patterns. The Cl^- ions generally had slightly higher concentration during the lower rainfall period, while Na^+ and K^+ ions slightly decreased during the intensive rainfall period. However, the SO_4^{2-} ions presented low value and low variation throughout the year at the other three drips, with the exception of VP4.

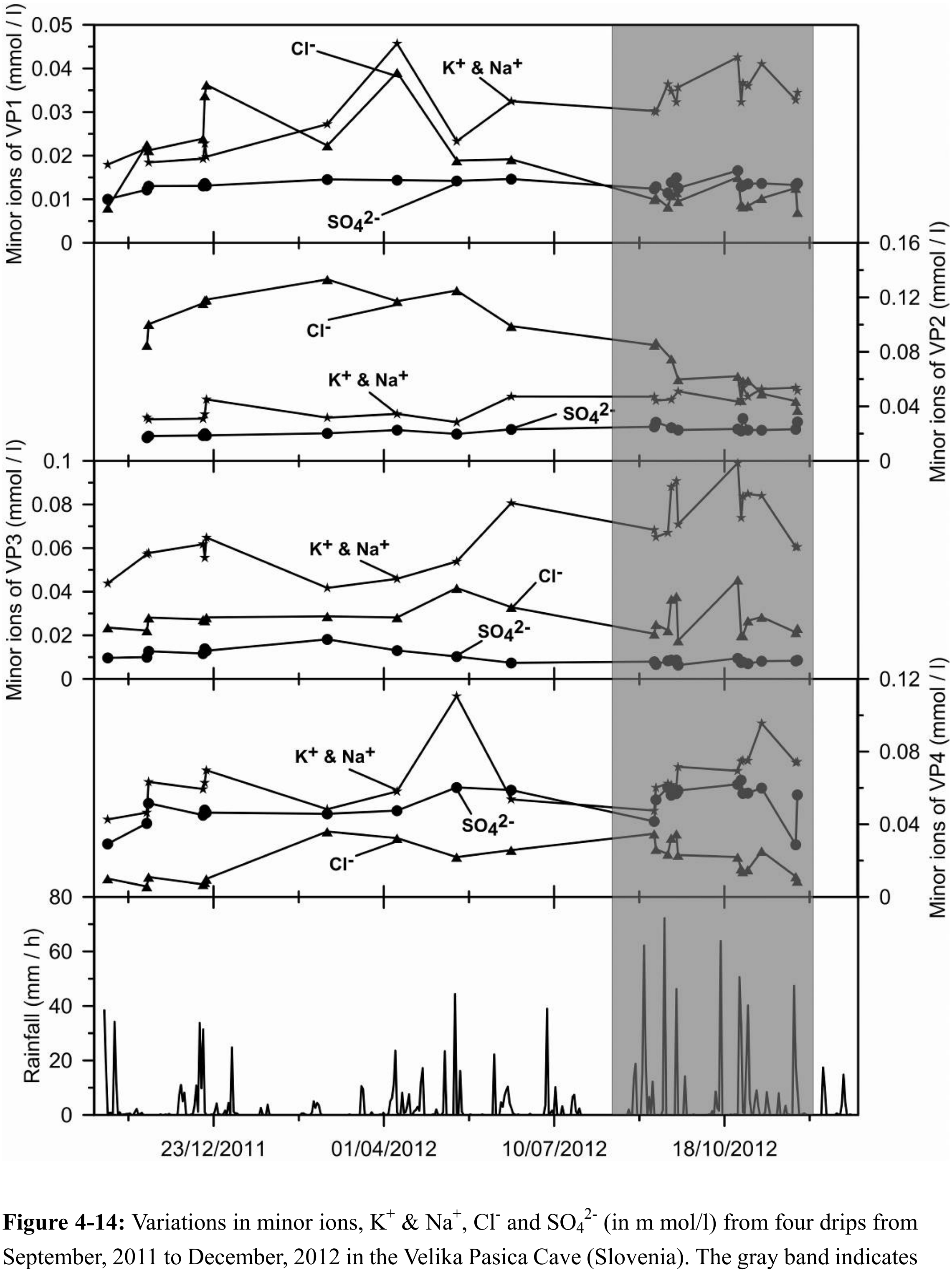

Figure 4-14: Variations in minor ions, K^+ & Na^+, Cl^- and SO_4^{2-} (in m mol/l) from four drips from September, 2011 to December, 2012 in the Velika Pasica Cave (Slovenia). The gray band indicates the intensive infiltration period.

4.3.1.3 Correlations of chemical parameters

According to the ion concentrations (Figure 4-12), they can be divided into to three groups: a) HCO_3^- was the most abundant ion; b) Ca^{2+} and Mg^{2+}were the major cations; c) SO_4^{2-}, Cl^-, Na^+ and K^+ were the minor ions. Their concentrations were affected by the location and seasons (Figures 4-13 and 4-14).

Table 4-7: The Pearson correlation between the ions and electrical conductivity (EC) at four drips (VP1-VP4) in the Velika Pasica Cave (Slovenia). **. Correlation is significant at the 0.01 level (2-tailed).*. Correlation is significant at the 0.05 level (2-tailed).

	EC-HCO3	EC-Ca	EC-Mg	HCO3-Ca	HCO3-Mg	Ca-Mg	Mg-SO4
VP1(23)	0.979**	0.908**	0.971**	0.959**	0.961**	0.844**	0.100
VP2(20)	0.872**	0.286	0.897**	0.591**	0.867**	0.114	0.625**
VP3(23)	0.899**	0.666**	0.964**	0.915**	0.834**	0.543**	-0.788**
VP4(23)	0.980**	0.417*	0.979**	0.462*	0.993**	0.359	0.498*
ALL(89)	0.954**	0.197	0.873**	0.186	0.930**	-0.185	0.866**

Correlations between the ions and EC, based on data the data from the 23 sets of water samples from all four drips (89 samples) from October, 2011 to December, 2012 are presented in Table 4-7. In the cave region, Mg^{2+} and HCO_3^- represented a strong correlation with EC (Figure 4-15, Left). HCO_3^- was the major anion in the water of this area, and thus it significantly determines the conductivity of the water. Overall concentration of HCO_3^- and Mg^{2+} ions were linearly related to specific conductance (Figure 4-15, Right), which can be expressed by equations:

Best linear fit: $[HCO_3^-] = 0.994213\ EC - 78.2402$, $r^2 = 0.954$;

Best linear fit: $[Mg^{2+}] = 0.224633\ EC - 56.1236$, $r^2 = 0.873$;

Best linear fit: $[Ca^{2+}] = 0.171815\ EC - 20.5922,\ r^2 = 0.197$.

Where parentheses denote species concentration in mg/l and EC is corrected for 25 °C.

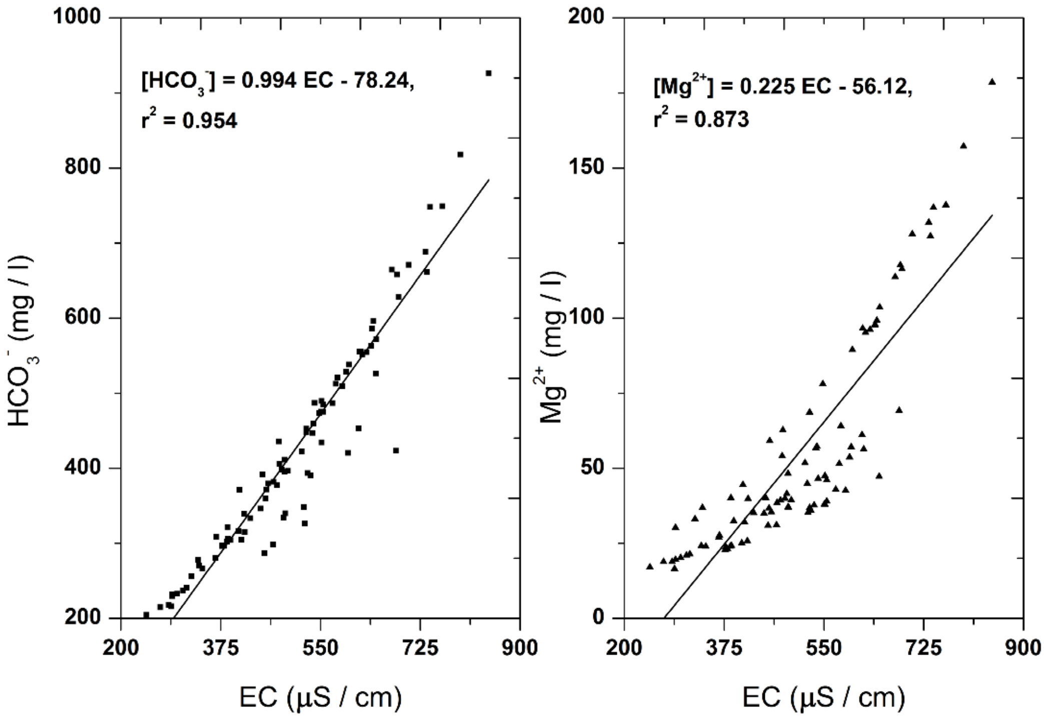

Figure 4-15: Left: Correlation between HCO_3^- ions and conductivity; **Right:** Correlation between Mg^{2+} ions and conductivity. This figure is based on the 23 sets of samples (89 samples) from October, 2011 to December, 2012 from four drips in the Velika Pasica Cave (Slovenia).

However, at different drip sites, their relationships had specific dissimilarities. Ca^{2+} as one of the major ions preformed distinctively at different sites, and was strongly related to EC and HCO_3^- ions, even Mg^{2+} at VP1. However, the relationships between EC and Ca^{2+} ions were much weaker at VP2 and VP4. This is also the reason why the EC of the cave drip water at VP1 was mainly monitored for the time series analyses in the following two sections. Concurrently, the specific variation of Ca^{2+} ions at different sites also acted in relationship with the hydrological profiles of different drips.

In addition, SO_4^{2-} ions had high concentration in VP4 and strong correlation with Mg^{2+}, although the concentration of Mg^{2+} ions was much higher.

4.3.2 The hydrochemical response of cave drip waters to different rain patterns

4.3.2.1 The distribution of studied rain events

In the study area, August is the hottest time of the year and December is usually cold and wet. In August, with high evapotranspiration from high temperature and low humidity and temperate surface run-off, discharge from the drips was very low. During this period, the precipitation commonly came as short but intense storms, which are the so called "concentrated rain" events. On the contrary, in a period of colder conditions (e.g. December), the rainfall fell more lightly but frequently. The study of VP1 was carried out in the period when the outside temperature declined (Figure 4-16). As a result of different temperature and precipitation performance, the study period could be divided into two parts. Prior to the rain event VP1-OCT1, the precipitation fell as a short intensive storm, namely concentrated rainfall. Most of these rain events were insufficiently intensive for the efficient recharge of the underground system (Figure 4-16). While after event VP1-OCT1, the diffuse rains fell gently and were sustained over time, which recharged the epikarst efficiently (Figure 4-16).

Several intensive rain events occurred over the study period of VP1, but only five of them supplied the drips efficiently: from 4th to 9th of August, 2011 with 42.8 mm rainfall (hereafter as VP1-AUG), on 19th September, 2011 with 47.4 mm (VP1-SEPT), from 7th to 9th October, 2011 with 42.8 mm (VP1-OCT 1), from 18th to 27th October, 2011 with 105 mm (VP1-OCT 2) and from 13th to 18th December, 2011 with 92 mm (VP1-DEC). As VP2 showed only weak response to the rain events, a single significant event was selected for analysis, which was from 28th November to 2nd December, 2012 with 74.2mm (VP2-NOV).

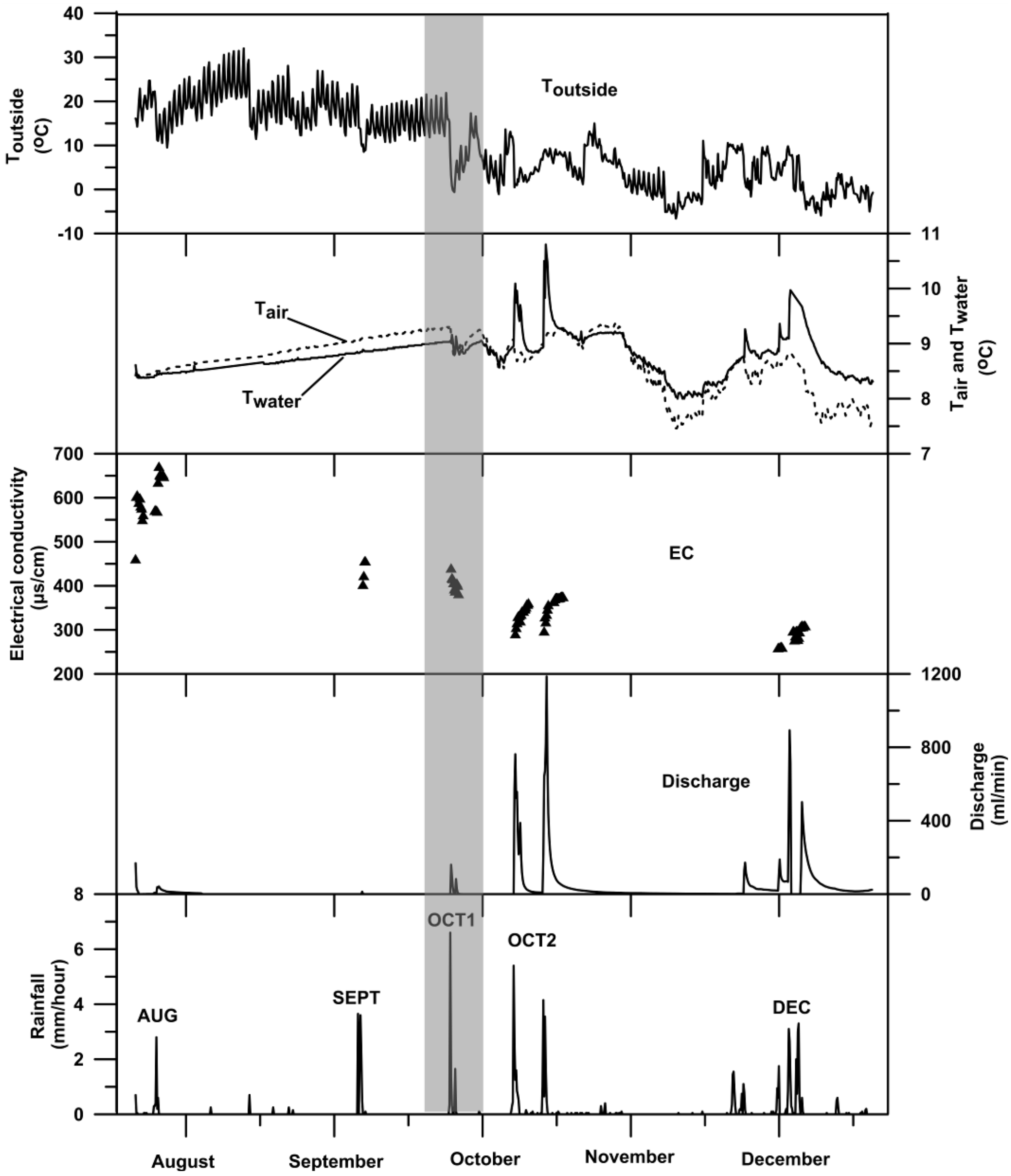

Figure 4-16: Air temperature at the surface ($T_{outside}$) and near drip VP1 (T_{air}), temperature (T_{water}), electrical conductivity (EC) and discharge of the drip water (VP1), and rainfall for the entire study period (August 4th to December 31st 2011). The shadow band indicates the division of intensive and diffuse recharge in the study period.

4.3.2.2 The response of four drips to a rain event (a rain case study in October, 2011)

The four permanent drips in the cave showed different hydrological performances to the same rain event. An example of drip reaction to precipitation, a slight rainfall event at the end of October is illustrated, with a total amount of 46.4 mm rainfall fallen from 26th to 27th , October, 2011 (Figure 4-17). According to the drips response speed and their discharge intensity in response to the precipitation, drips could be described as: "rapid response with high intensity discharge" (VP1); "rapid response with moderate discharge" (VP3); "rapid response with congest discharge" (VP4) and "slow response with congest discharge" (VP2). VP1 had rapid response to the precipitation, with a high fast discharge flow followed by a long subsiding period. There was no apparent response from VP2 to the event. VP3 and VP4 responded rapidly while they had relatively lower discharges, compared with VP1.

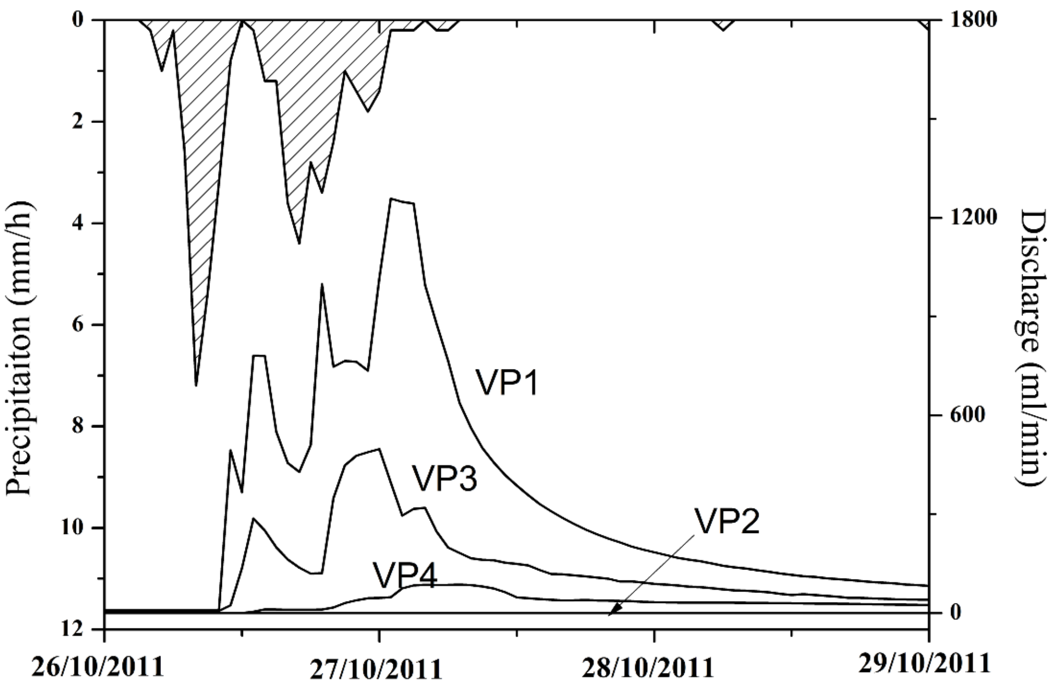

Figure 4-17: Different responses of each drip to a rain event (in grey) from 26th to 29th, October, 2011 in the Velika Pasica Cave (Slovenia).

4.3.2.3 Responses in EC for drip waters of VP1 and VP2 to rain events

The main ions in the drip water from both sites were Ca^{2+}, Mg^{2+}, and HCO_3^-

ions. As the outside temperature became cooler, they also decreased and synchronized downward with EC. From August to December, the EC decreased gradually, from 589 µs/cm to 294 µs/cm (VP1, Table 4-8).

Accompanied by the variation in discharge as a response to rain events, the EC also showed a relevant response. Before VP1-OCT1 (Figure 4-16), the drips decreased when the rainfall ceased. With regard to the variation in EC, when the discharge increased to the highest value, a fall in EC was synchronous. Following the fastest flow the EC increased rapidly to its maximum, then it decreased slowly until the drip water ceased. Such response was observed in VP1-AUG, VP1-SEPT and VP1-OCT1, although the event VP1-SEPT was too short to present its peak.

After entering the diffuse rain period (the time after VP1-OCT2, Figure 4-16), the drip water always maintained a detectable flow, resulting in the different response in EC (Figure 4-18). Similar to the previous period, EC decreased immediately after the discharge peaks. However, after the trough, the EC rose gradually until it arrived at a stable value. Such responses were observed in VP1-OCT2, and in VP1-DEC (Figure 4-18).

A small amount of fast flow resulted in the low EC at the beginning of the rain event at VP2, while it rose up rapidly as the main flow came. Subsequently, as the discharge decreased, EC also declined into a stable value (VP2-NOV, Figure 4-18), which was different from drip VP1.

Table 4-8: Chemical and physical data on drip water VP1 from five rain events in 2011 and VP2 in 2012. *: number of samples; EC: electrical conductivity; σ: standard deviation.

Rain event	Sample type	EC (μs/cm) 25℃	pH	T (°C)	pCO_2 (log10)	Cl^- (mg/l)	NO_3^- (mg/l)	SO_4^{2-} (mg/l)	Na^+ (mg/l)	K^+ (mg/l)	Ca^{2+} (mg/l)	Mg^{2+} (mg/l)	HCO_3^- (mg/l)	SIc	Mg/Ca (molar)
VP1-AUG(10*)	Average	589.33	8.33	8.43	-2.78	0.43	1.01	1.17	0.54	0.31	73.88	50.15	478.98	1.08	1.23
	σ	62.17	0.02	0.10	0.05	0.14	0.44	0.24	0.11	0.14	19.69	6.87	65.71	0.17	0.47
	Max	671	8.35	8.58	-2.73	0.81	1.84	1.77	0.86	0.68	101.59	61.12	585.59	1.32	2.67
	Min	462	8.30	8.38	-2.86	0.31	0.33	0.96	0.47	0.20	42.03	36.38	405.74	0.83	0.85
VP1-SEPT(4)	Average	415.00	8.36	8.86	-2.94	1.47	3.14	2.21	0.44	0.48	66.56	29.60	347.47	0.99	0.74
	σ	14.94	0.01	0.00	0.02	0.04	1.62	0.08	0.04	0.20	3.69	1.20	18.72	0.04	0.01
	Max	429	8.36	8.86	-2.92	1.52	5.55	2.33	0.48	0.69	70.68	30.73	367.66	1.03	0.76
	Min	398	8.35	8.86	-2.96	1.43	2.06	2.15	0.38	0.28	63.00	28.48	329.50	0.95	0.72
VP1-OCT 1(13)	Average	399.54	8.38	8.98	-2.97	0.55	2.70	1.43	0.43	0.22	62.12	31.23	344.64	0.98	0.84
	σ	17.59	0.01	0.14	0.02	0.25	1.65	0.39	0.03	0.19	4.29	1.66	15.32	0.04	0.07
	Max	441	8.39	9.14	-2.93	1.25	7.46	2.59	0.48	0.84	69.43	33.29	367.29	1.03	0.95
	Min	374	8.37	8.81	-3.01	0.32	1.24	1.09	0.39	0.12	55.16	27.74	321.56	0.91	0.75

VP1-OCT 2(21)	Average	337.57	8.37	9.59	-3.04	0.44	1.14	1.02	0.37	0.15	52.69	24.16	281.64	0.84	0.76
	σ	30.26	0.06	0.51	0.06	0.18	0.41	0.13	0.05	0.07	5.08	3.05	30.10	0.10	0.04
	Max	378	8.44	10.70	-2.93	0.74	1.65	1.21	0.44	0.31	59.42	28.67	321.35	0.99	0.87
	Min	289	8.24	8.84	-3.13	0.26	0.40	0.74	0.29	0.09	44.86	19.23	233.91	0.59	0.71
VP1-DEC(15)	Average	294.53	8.35	9.98	-3.10	0.84	1.11	1.31	0.37	0.17	40.72	21.97	232.87	0.64	0.75
	σ	17.19	0.06	0.51	0.07	0.29	0.45	0.09	0.05	0.10	5.12	4.50	15.30	0.07	0.01
	Max	315	8.42	9.67	-2.92	1.33	1.83	1.50	0.44	0.47	46.78	29.34	249.14	0.76	0.77
	Min	260	8.20	8.68	-3.18	0.47	0.50	1.21	0.29	0.09	32.30	17.23	203.79	0.41	0.73
VP2-NOV(8)	Average	538.75	8.17	9.73	-2.56	1.34	0.40	2.30	0.87	0.43	62.73	54.14	463.88	0.93	2.26
	σ	38.35	0.07	0.27	0.09	0.20	0.10	0.24	0.11	0.08	10.13	2.18	38.90	0.10	0.09
	Max	594	8.28	10.14	-2.42	1.81	0.60	2.80	1.11	0.55	76.18	57.88	523.65	1.06	2.41
	Min	502	8.06	9.33	-2.70	1.19	0.31	2.08	0.76	0.33	45.88	51.54	404.55	0.80	2.15

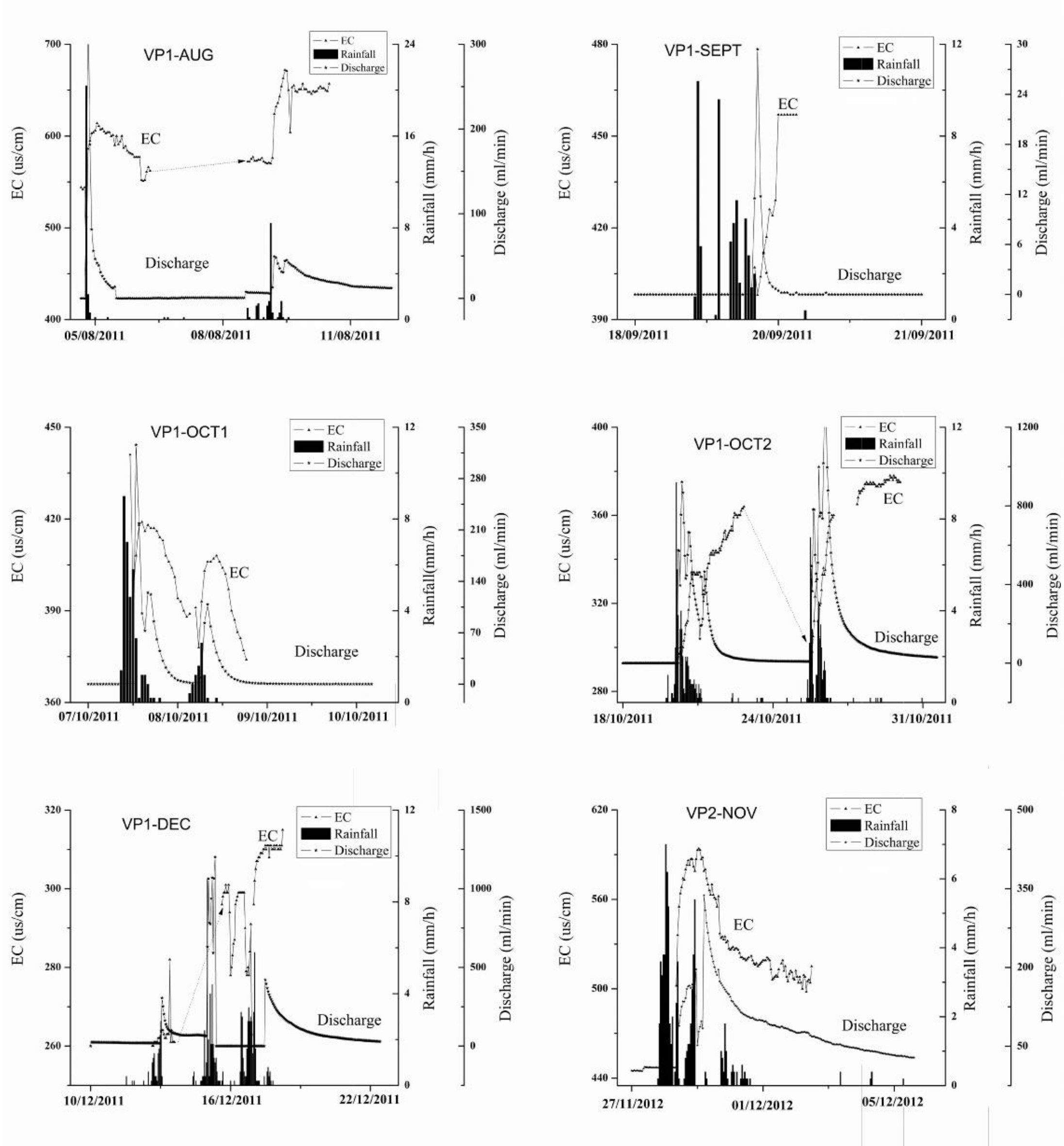

Figure 4-18: The precipitation and the relevant discharge and electrical conductivity of drip VP1 during the five main rain events in 2011 and drip VP2 in 2012 in the Velika Pasica Cave (Slovenia).

4.3.2.4 The Mg/Ca ratio as a response to rain events

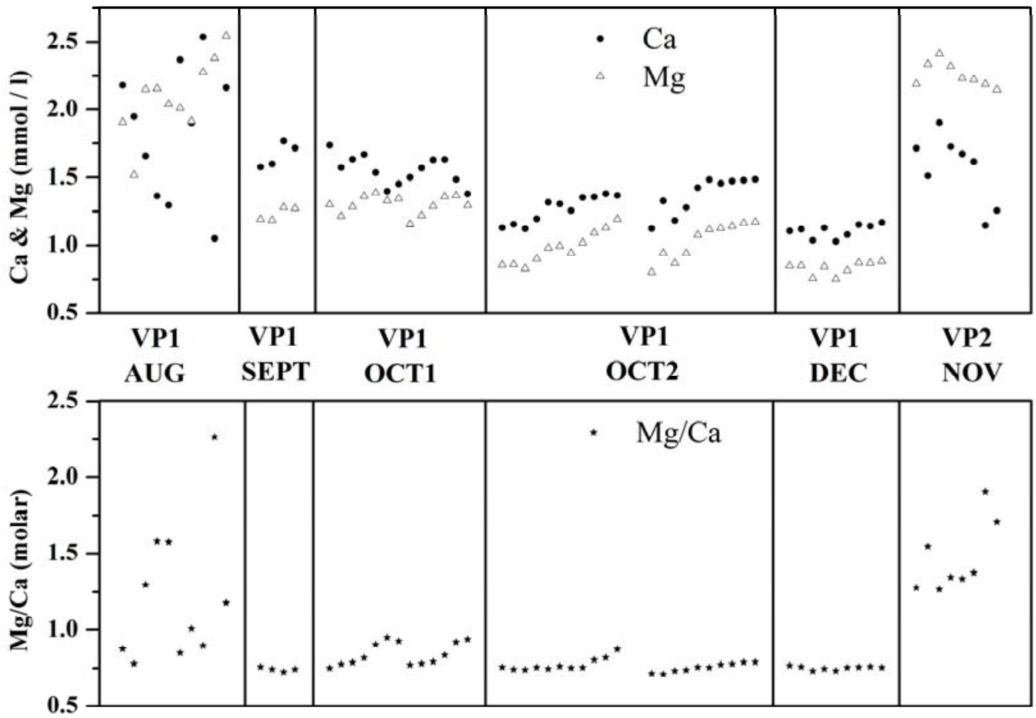

Figure 4-19: Concentration of Ca^{2+} and Mg^{2+} ions (upper graph) and the Mg/Ca ratio (lower graph) in the drip water of VP1 and VP2 in the Velika Pasica Cave (Slovenia) from August to November 2011.

The Mg/Ca ratio of drip water had distinct seasonal variation reflecting different rain patterns (Figure 4-19). Both Ca^{2+} and Mg^{2+} ions concentrations have a similar variation pattern as the Mg/Ca ratio, while they decreased as the season changed. During August, the Mg/Ca ratio varied randomly, and with a high value (range from 0.85 to 2.27). Subsequently, the variation of Mg/Ca ratio smoothed out. During the concentrated rainfall period, the Mg/Ca ratio was low when the rain commenced while it increased slightly at the end of each storm (Figure 4-19). After entering the diffuse rain period, the concentration of Ca^{2+} and Mg^{2+} ions slightly increased at the end of each storm, but their ratio remained stable. The Mg/Ca ratio kept a low and stable value which was prolonged into VP1-DEC, with Mg/Ca ratio at about 0.75.

However, the ratio at VP2 was much higher and more random than at VP1 during the diffuse rain period (November).

4.3.3 Hydrochemical response of cave drip water to snowmelt water

The daily precipitation and daily snow depth at the Pokojišče meteorological station from the beginning of January to the beginning of April, 2013, are presented in Figure 4-20, which indicated the weather conditions during the study period. There were two rain events during the study period, from 18th March to 22nd March, 2013: one was on March 18th -19th , with 41.4 mm rain falling in 20 hours, and the other one was less intensive, from March 20th - 21st, with 7.2 mm of rain over 14 hours (data from a local meteorological station). The surface temperature maintained the regular daily oscillations with the exception of March 19th when heavy rainfall occurred (Figures 4-20 and 4-21). Meanwhile, the rate of snow melt followed the surface temperature variation, but the rain water accelerated it significantly, as indicated by the increase of drip water discharge. Consequently, the snow melt was controlled by two impacts: the regular daily oscillations of temperature and rain fall, which resulted in two intensive percolation events. The first occurred following an intensive rain event, with rapid and significant response in the drip discharge. The drip started to respond in one hour after the rain event commence, and it rose to its peak at 1250 ml/min in three hours. The second resulted from a slight rainfall, with a lower, sluggish discharge. It took eight hours for the drip to rise to its peak at 800 ml/min. The warmth of the daytime melted the snow simultaneously and the rainfall accelerated it significantly to cause the high discharge (Figure 4-21).

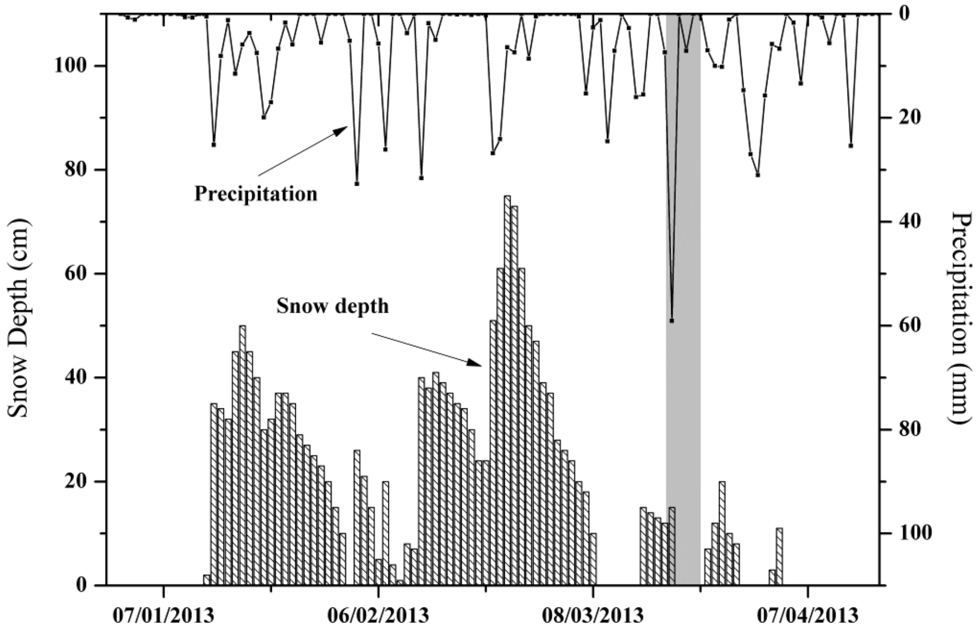

Figure 4-20: The daily precipitation and daily snow depth at the Pokojišče meteorological station (SW of Ljubljana, Slovenia) from the beginning of January to the beginning of April, 2013; the gray band is the studied period discussed in this section (for details see Figure 4-21).

Consequently, the drip discharge affected the hydrochemical features. The EC reflected the amount of ions (Table 4-9), showed a reverse variation with the discharge (Figure 4-21), but the EC varied sensitively following the discharge, which was also indicated by the significant correlation between each other ($r = -0.915$, $p \leq 0.01$, two-tailed) (Table 4-10). The dominant ions at drip site VP1 were Ca^{2+}, Mg^{2+} and HCO_3^- (Table 4-9). All indicated relatively low variability, with the coefficient of variation (CV) = 10%, 12% and 11%, respectively, compared with the minor ions, such as Na^+ ions with CV = 30%, K^+ with CV = 26%. The main components, Ca^{2+} and Mg^{2+} ions and the Mg/Ca molar ratio followed the EC variation pattern closely and they varied according to the discharge variation (Figure 4-21). The Mg/Ca molar ratio was relatively stable with a mean molar value of 0.75 and with CV = 3% (Table 4-9). Stable ratio between both ions was indicated with a significant correlation between them ($r = 0.981$, $p \leq 0.01$, two-tailed) (Table 4-10). It was also valid for Ca^{2+} ions *vs*. Mg/Ca ratio ($r = 0.856$, $p \leq 0.01$ two-tailed).

Table 4-9: The mean value and variations in chemical composition of the drip water in the Velika Pasica Cave (Slovenia) in a period 18th to 22nd March, 2013 (n= 19). EC (electrical conductivity); pCO_2 (partial pressure of CO_2); SIc (saturation index of calcite); Mg/Ca (molar ratio between Mg^{2+} and Ca^{2+} ions).

Statistic	EC µS/cm (25℃)	pH	T (℃)	Cl^- (mg/l)	NO_3^- (mg/l)	SO_4^{2+} (mg/l)	HCO_3^- (mg/l)	Na^+ (mg/l)	K^+ (mg/l)	Ca^{2+} (mg/l)	Mg^{2+} (mg/l)	pCO_2 (log10)	SIc	Mg/Ca (molar)
Mean	282.53	8.3	7.07	0.15	0.31	1.21	244.34	0.50	0.21	45.92	20.60	-3.00	0.60	0.75
C.V.	0.10	0.01	0.02	0.16	0.22	0.12	0.11	0.30	0.26	0.10	0.12	0.01	0.20	0.03
Max	318	8.3	7.25	0.21	0.47	1.50	281.84	0.85	0.35	51.81	24.39	-2.94	0.76	0.78
Min	215	8.2	6.80	0.11	0.22	0.93	182.78	0.36	0.14	35.27	14.81	-3.07	0.33	0.70

Regarding the minor ions: K^+, Na^+, SO_4^{2-}, Cl^- and NO_3^-, their concentrations were low but their CVs were higher than in the dominant ions (Table 4-9). Meanwhile, they had a low correlation coefficient with the discharge as do the dominant ions (Table 4-10). The pCO_2 maintained stability at around -3.00, with CV = 1% (Table 4-9), but it was insignificant in relationship with other parameters, such as, Ca^{2+} ions (r = 0.393) (Table 4-10). The drip water temperature acted as a special indicator for the drip discharge, correlated closely with the discharge rate (r = -0.976, $p \leq 0.01$, two-tailed). However, its variation range during the observation period was quite narrow, with CV = 2%.

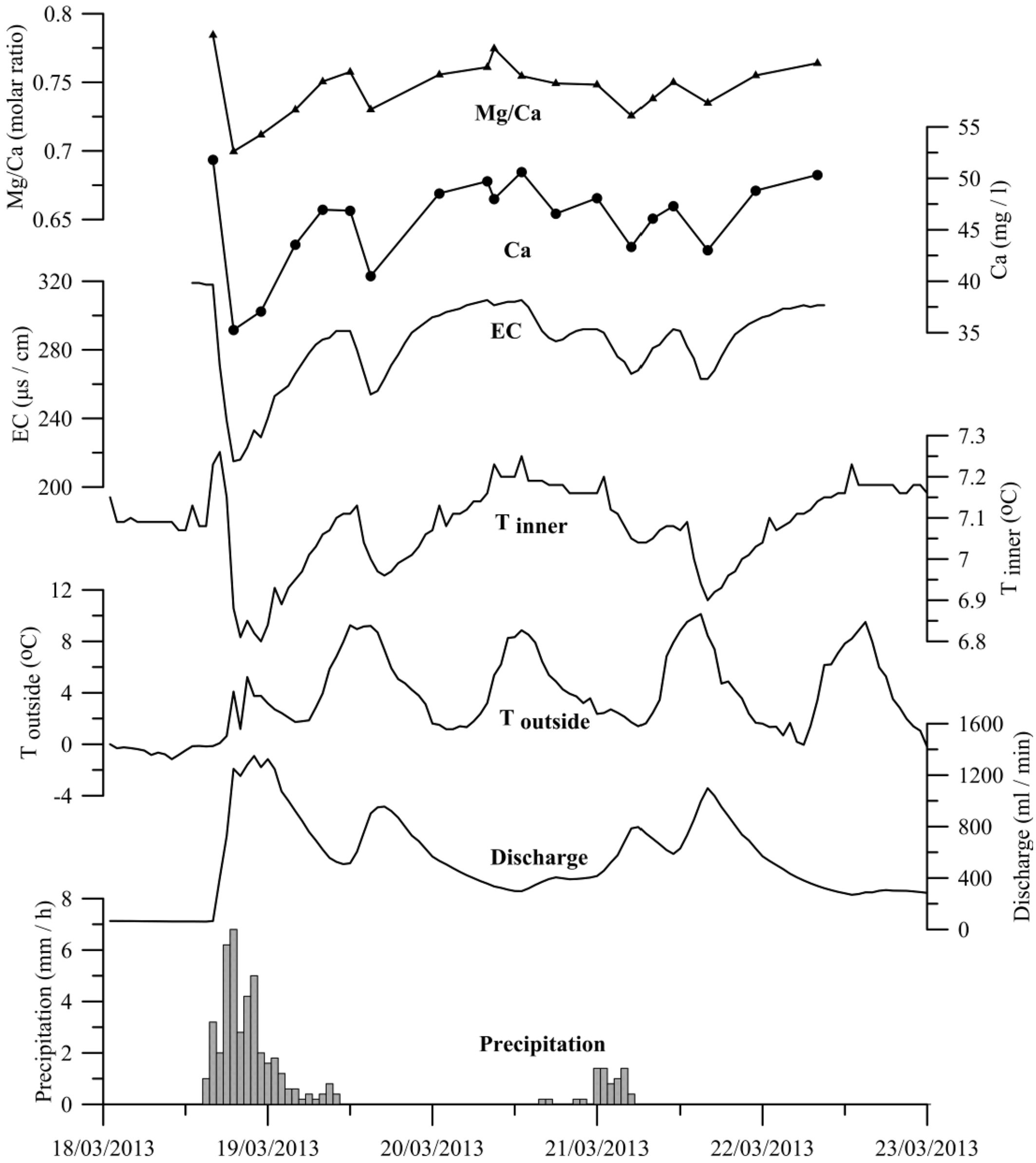

Figure 4-21: The hourly variation of the precipitation, the discharge from drip VP1, the surface temperature ($T_{outside}$), the temperature of drip water (T_{inner}), electric conductivity (EC), Ca^{2+} ions concentration and Mg/Ca ration of the drip water during the period 18th to 22nd March, 2013 in the Velika Pasica Cave (Slovenia).

In order to present the different response to the two flood events, samples were divided into two groups (Figure 4-22). The variations of the main hydrochemical and hydrological parameters of the drip water presented similar and a strong correlation between each other during these two events, e.g. in Figure 4-22, II, the fitting lines of the two events between Ca^{2+} ions and EC overlapped. However, variation ranges for the parameters of the first flood event were larger than those of the second flood, which indicated that the higher discharge caused a lower ion concentration and the slower flow, the higher concentration. The higher discharge of the first flood corresponded to the lower Ca^{2+}, Mg^{2+} ions, EC, and Mg/Ca values (Figure 4-22).

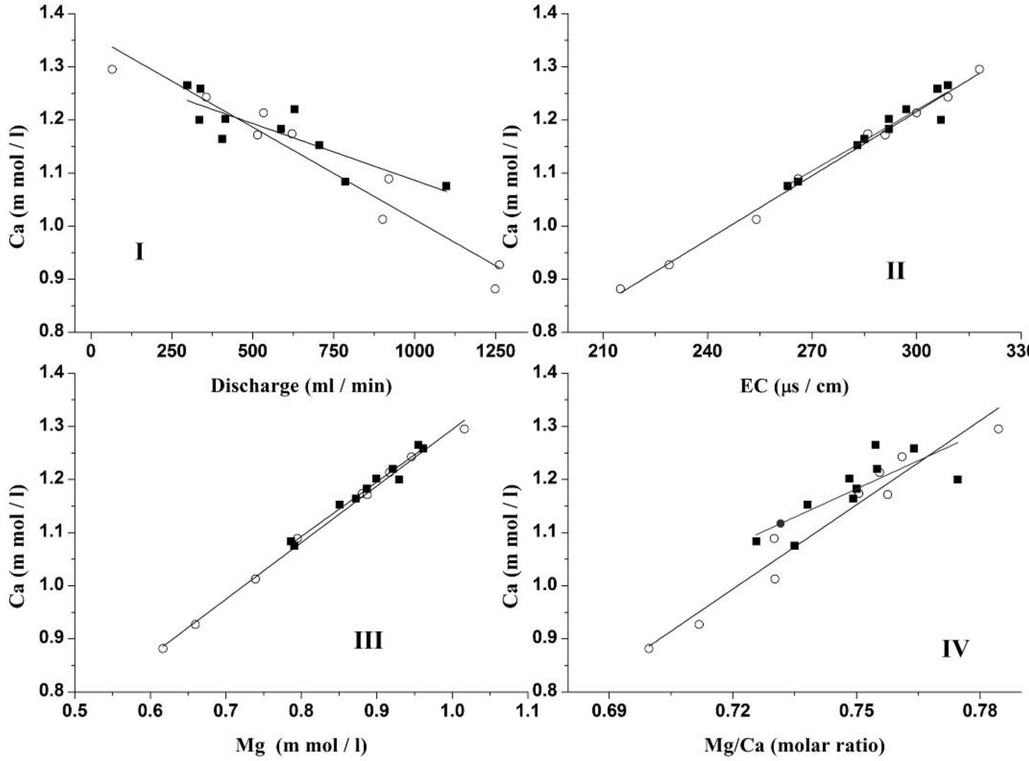

Figure 4-22: Cross plots for the main hydrochemical and hydrological parameters of the drip water from the Velika Pasica Cave (Slovenia): (I) Ca^{2+}ions concentration *vs*. discharge of drip water; (II) Ca^{2+} ions concentration *vs*. electrical conductivity (EC); (III) Ca^{2+} ions concentration *vs*. Mg^{2+} ions concentration; (IV) Ca^{2+} ions concentration *vs*. Mg/Ca (molar ratio). The samples were divided into two sets according to two flood events: white circles represented the first flood event and the solid squares represented the second flood event.

Table 4-10: The Spearman correlation coefficients of the main hydrological and hydrochemical parameters of the cave drip water: the drip water temperature (T: ^{o}C); discharge of drip water (Q: ml/min); electric conductivity (EC: μm/cm); the ions, Cl^-, NO_3^-, SO_4^{2-}, Na^+, K^+, Ca^{2+}, Mg^{2+} and HCO_3^- (mg/l), CO_2 partial pressure (pCO_2) (log10) and Mg/Ca (m molar ratio) (n=19). * correlation is significant at the 0.05 level (2-tailed). ** correlation is significant at the 0.01 level (2-tailed).

	T	Q	EC	Cl	NO_3	SO_4	Na	K	Ca	Mg	HCO_3	pCO_2
Q	-0.976**											
EC	0.857**	-0.915**										
Cl	-0.317	0.310	-0.290									
NO_3	-0.250	0.251	-0.171	0.667**								
SO_4	0.740**	-0.799**	0.885**	0.066	0.132							
Na	-0.147	0.066	0.063	0.536*	0.575**	0.208						
K	0.502*	-0.466*	0.392	-0.548*	-0.597**	0.123	-0.276					
Ca	0.801**	-0.874**	0.972**	-0.349	-0.240	0.828**	0.047	0.418				
Mg	0.823**	-0.907**	0.981**	-0.327	-0.221	0.862**	0.055	0.366	0.981**			
HCO_3	0.805**	-0.888**	0.979**	-0.332	-0.240	0.844**	0.085	0.417	0.993**	0.991**		
pCO_2	0.193	-0.214	0.365	0.036	0.227	0.466*	0.419	0.240	0.393	0.368	0.393	
Mg/Ca	0.762**	-0.845**	0.901**	-0.120	-0.095	0.908**	0.035	0.182	0.856**	0.908**	0.885**	0.244

4.4 A study of temperature characteristics in the cave

4.4.1 The environmental temperature and precipitation

Seasonal micro-climates apparently varied in the cave area (Figure 4-23), which have been monitored since 2006. During the observation period, from 20th June, 2006 to 22nd March, 2008, July and August were the hottest months and the highest temperature outside was 32 °C on July 23rd in 2006. December and January were the coldest months and the lowest temperature recorded was on December 22nd, 2007, at -11.35 °C (Table 4-11).

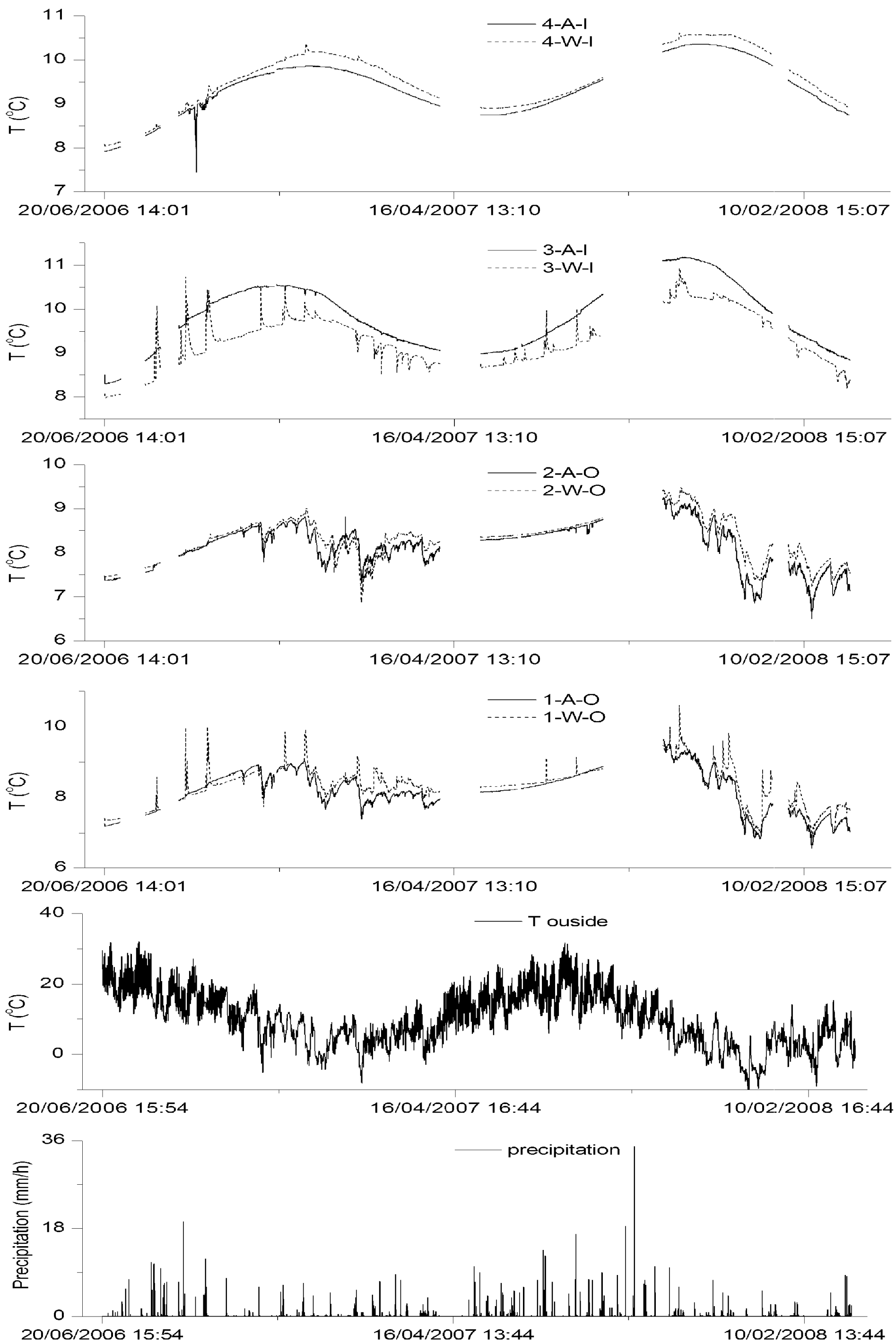

Figure 4-23: The temperature (°C), precipitation (mm/hour) from outside the cave, the water temperatures of four drips (°C) and adjacent air temperature of each drip (°C) recorded from 20th June, 2006 to 22nd March, 2008. The number of the legend indicates the drip site number; "A" indicates the air temperature; "W" is for the water temperature; "O" is for the outer section of the cave and "I" is for the inner section of the cave.

On the surface, the temperature differences between day and night were frequently over 10°C, shown as the SD (standard deviation) as high as 7.76 (Table 4-11). On 23rd July, 2006, the difference was approximately 13°C. The intensity of the rainfall in spring (April and May) was not high, but it was frequent; while in summer, the frequency of rain events decreased but several heavy storms occurred; the strongest one on 20th June, 2010 (44mm of rain in 24hours).

Table 4-11: The variation range and average temperatures inside and outside the Velika Pasica Cave (Slovenia) from 20th June, 2006 to 22nd March, 2008. X-A/W-O/I indicates: the air / water temperature near Drip X from outer or inner section of the cave; $T_{outside}$: the surface air temperature. SD: standard deviation.

	1-A-O (°C)	2-A-O (°C)	3-A-I (°C)	4-A-I (°C)	$T_{outside}$ (°C)	1-W-O (°C)	2-W-O (°C)	3-W-I (°C)	4-W-I (°C)
max	9.65	9.26	11.18	10.35	32.01	10.62	9.48	10.93	10.61
min	6.55	6.50	8.30	7.45	-11.35	6.85	6.87	7.98	7.52
average	8.20	8.15	9.86	9.41	9.80	8.36	8.30	9.34	9.60
SD	0.58	0.50	0.71	0.57	7.76	0.53	0.47	0.59	0.62

4.4.2 The temperature variation inside the cave

The Velika Pasica Cave is divided into two parts: the outer section (close to entrance) and the inner section (far from entrance) (Figure 2-2).

Inside the cave, the temperature was more constant in comparison with the surface temperature. The variation range was smaller and the standard deviation was much lower (Table 4-11, Figure 4-24). The temperature inside the cave (both of air and dripping water), showed a similar trend with distinct seasonal variations: rising during summer and autumn, and dropping in winter and spring (Figure 4-23).

However, there was a time difference in the variation trend between outside and inside the cave during the observation period, from 20th June, 2006 to 22nd March, 2008 (Figure 4-24). In a short period of this time, on the surface the temperature increased from the lowest point of 2006, -4.4 ^{o}C at the end of December 2006, until the middle of July 2007, when the highest temperature recorded for 2007 reached 31.7 ^{o}C. Within the cave, the temperature of the drips reached the highest recorded peak in November 2006, which was 10.5 ^{o}C in the inner section of the cave (as averaged from both air temperature sensors at VP3 and VP4) and 9.5 ^{o}C in the outer section (as averaged from both air temperature sensors at VP1 and VP2). Thereafter, the temperature in the cave started to drop until the beginning of May 2007, which was the coldest period in the cave (Figure 4-24). In additional, although the surface was much hotter than the cave interior during summer, the variation of all the air temperature inside the cave was between 6.5 ^{o}C and 11.0 ^{o}C. The internal temperature did not response immediately when the surface temperature dropped to a lower level than inside, but based on the air temperature variation at VP3 in 2006 it still increased for an additional 49 days before it started to decline.

There were considerable differences also in the environments between the two sections within the cave. Both inner and outer sections had apparent seasonal variation in temperature and the overall trend showed a similar pattern. The outer section was generally cooler than the inner parts all the year round, and the average temperature was more than 1^{o}C lower than that in the inner part (Figure 4-23; Table 4-11). The outer section had an immediate connection with the surface environment as a result of the cave entrance morphology. The temperatures in the outer section varied more abruptly and irregularly, especially during cold weather, which commenced from late August.

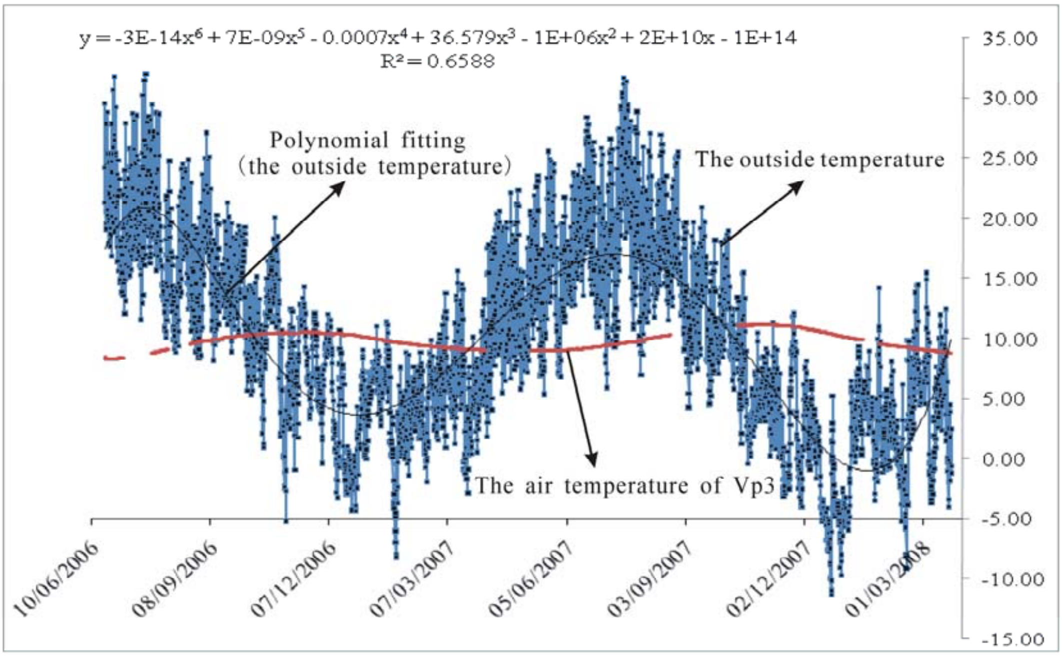

Figure 4-24: The temperature (°C) outside the cave, and the air temperatures near drip VP3 (°C) recorded from 20th June, 2006 to 22nd March, 2008 at the Velika Pasica Cave (Slovenia). The equation represents the fitted line for the outside temperature variation.

4.4.3 Response to the rain events signal

Precipitation is the only replenishment source for the cave drip water in the Velika Pasica Cave area. A rain event in September 2006 is presented here as an example of the impact of a rain event on the cave's climate (Figure 4-25). Two storms occurred during August and September, 2006 with different patterns: the first on 29th August 2006, came as a short but heavy rain event (47.4 mm in 7 hours); while the other lasted 84 hours, from 15th September 2006, with 96.4 mm of precipitation.

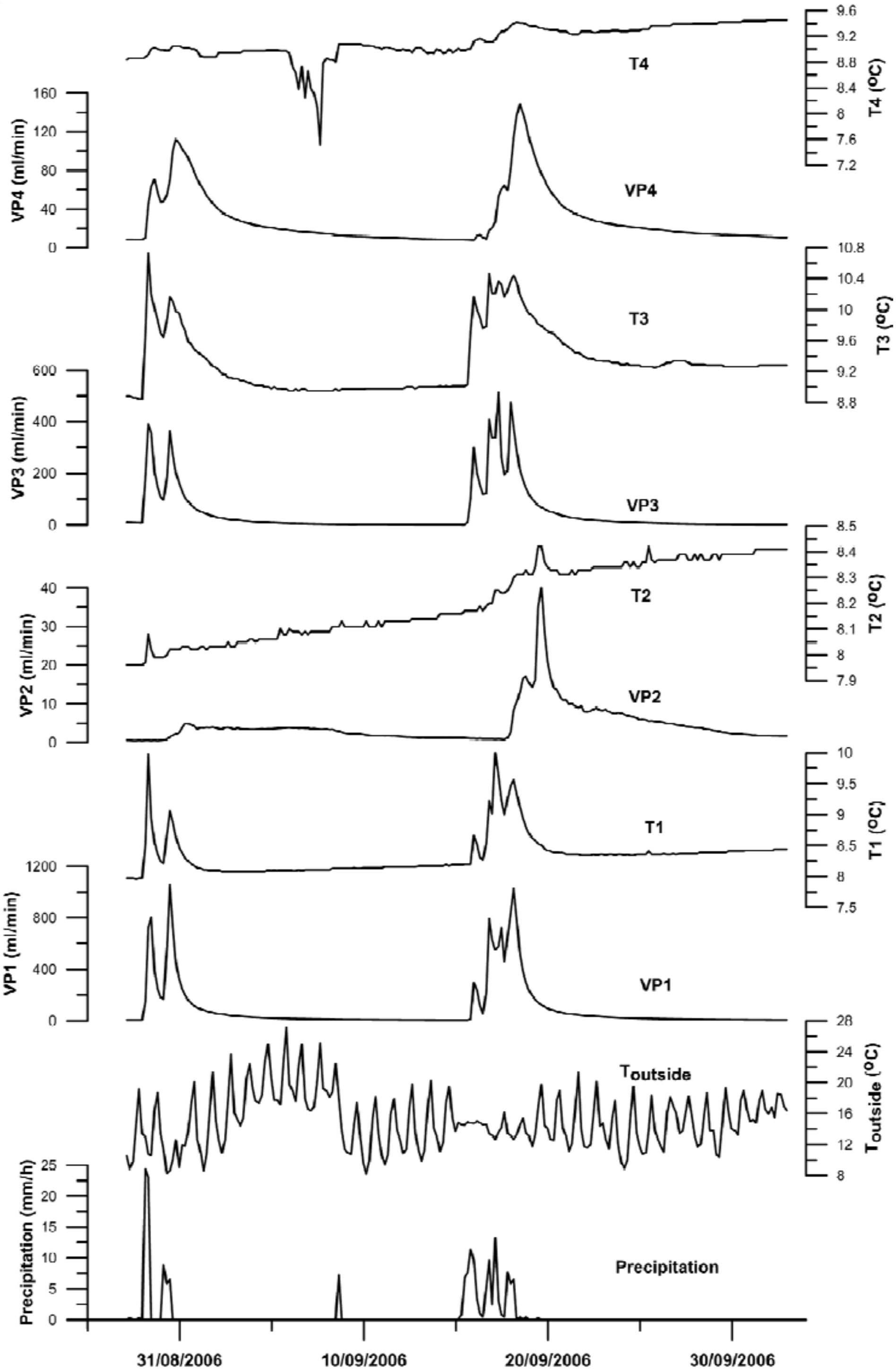

Figure 4-25: The response of the discharge and the water temperature of the four drip waters to the rain events in the Velika Pasica Cave (Slovenia) in the summer 2006 (from 28th August to 2nd October). $T_{outside}$: the air temperature on the surface; VP1: the discharge of drip site VP1; T1: the drip water temperature.

The temperature of the drip water reflected a strong relationship with the amount of discharge (Figure 4-25). The temperature of drip water of VP1 and VP3 showed a more instantaneous and apparent response. In both drips, the larger discharge indicated higher efficiency and speed of water flow. However, the drips VP2 and VP4 had less discharge and consequently smaller variation in drip water temperature.

4.5 Epikarst control of the cave biodiversity

4.5.1 Micro-crustacean assemblages

4.5.1.1 Taxonomic composition of four drip sites

In total, 80 sample sets were collected from the four permanent drip sites in the Velika Pasica Cave from March 2006 to February 2013. Twelve aquatic species (ten stygobionts and two stygophiles) were identified, ten of which belong to the Crustacea Copepoda (Table 4-12), the two others were *Niphargus stygius* (Schiodte, 1847) (Amphipoda) and *Pseudocandona albicans* (Brady, 1864) (Ostracoda, stygophyle). Representatives of Protista Rotatoria, and Nematoda and Oligochaeta belonging to different ecological categories (stygoxenes, stygophyiles, stygobionts), collected during the faunal sampling were not included in the analyses due to taxonomic impediments (Brancelj, pers. comm.). The most numerous specimens belonged to *Morariopsis dumonti* Brancelj, 2000, representing nearly a half of the population of all stygobionts (829 out of 1740 specimens). However, representatives of some species were quite rare in the cave: *Elaphoidella tarmani* Brancelj, 2008, *Phyllognathopus viguieri* (Maupas, 1892), *Parastenocaris nolli alpina* Kiefer, 1969 and the amphipod *N. stygius* were represented by only a few specimens.

The abundance of stygobionts differed from site to site. VP2 showed the highest abundances, with 712 specimens (710 belonged to the Copepoda), while VP4 seemed an undesired habitat for most faunal species, and only *Moraria varica* (Graeter, 1910) prefer for this location with 240 specimens. Although the number of specimens at VP1 was almost the same as at site VP3, the faunal composition was quite different. For example, 379 specimens were caught at VP1 190 of which were copepods, while at VP3 389 individuals were copepods out of a total of 398 specimens.

No site provided an optimum habitat for the entire suite of known cave species from the Copepoda, Ostracoda and Amphipoda genera already known from the cave. The sites with highest biodiversity (i.e. number of different stygobiotic species) were drips VP1 and VP3, with nine species respectively.

However, the species list richness and abundance differed significantly from site to site. *Pseudocandona albicans* was most abundant at site VP1 with 186 specimens (49.1 % of the total population at VP1), and the second was *Speocycops infernus* (Kiefer, 1930) with 130 specimens (34.3 % of the total population at VP1). The most abundant species at VP2 was *M. dumonti* which represented 88.8 % of the stygobiotic assemblage at VP2. At VP3, the most common species were *M. dumonti* and *Bryocamptus pyrenaicus* (Chappuis, 1923) with 36.9 % and 35.2 % of representatives, respectively. At VP4, *M. varica* was the most abundant species (95.6 % of the population at VP4) and was unique to this drip location. Additionally, such as *M. varica* was exclusively found in VP4, there were several other site specific species: *P. nolli alpina* was found only at VP1 and *E. tarmani* only at VP3.

Correlation similarity clusters based on the abundance and distribution of all the faunal specimens, were constructed in order to classify the species from the four drips (Figure 4-26). The cluster analysis recognized four groups. *M. varica* was exclusively located at site VP4. The population there strongly related with specific chemical profile of the VP4. A second cluster assembled *P. nolli alpina*, *S. infernus*, *N. stygius* and *P. albicans* all found atVP1. The third group included: *Bryocamptus pyrenaicus* (Chappuis, 1923) and *E. millennii*, predominantly found in VP3, and additionally exclusive specie for the site: *E. tarmani*. Representatives of *M. dumonti* were found in all the drips with the largest population at VP2. VP2 was the major habitat site for *Bryocamptus typhlops* (Mrazek, 1893) and *Moraria poppei* (Mrazek, 1893). *Phyllognathopus viguieri* was rare in the cave, only appearing at VP1, VP2, and VP3 once.

Table 4-12: List of stygobiotic species from four drips from the Velika Pasica Cave (Slovenia) in the period from March, 2006 to February, 2013 collected on 80 sampling expeditions. Two non-Copepoda micro species were included: # - Ostracoda and * - Amphipoda.

Species	VP 1		VP 2		VP 3		VP 4		sum
	No.	Proportion (%)	No.	Proportion (%)	No.	Proportion (%)	No.	Proportion (%)	
Phylognathopus viguieri (Maupas, 1892)	1	0.26	1	0.14	1	0.25			3
Bryocamptus typhlops (Mrazek, 1893)	1	0.26	52	7.30	1	0.25	1	0.40	55
Bryocamptus pyrenaicus (Chappuis, 1923)	3	0.79	3	0.42	140	35.18			146
Elaphoidella millennii Brancelj, 2008	3	0.79			35	8.79	1	0.40	39
Elaphoidella tarmani Brancelj, 2008					2	0.50			2
Morariopsis dumonti Brancelj, 2000	48	12.66	632	88.76	147	36.93	2	0.80	829
Parastenocaris nolli alpina Kiefer, 1969	4	1.06							4
Speocycops infernus (Kiefer, 1930)	130	34.30	15	2.11	61	15.33	6	2.39	212
Moraria poppei (Mrazek, 1893)			7	0.98	2	0.50			9
Moraria varica (Graeter, 1910)							240	95.62	240
**Niphargus stygius* (Schiodte, 1847)	3	0.79					1	0.40	4
#*Pseudocandona albicans* (Brady, 1864)	186	49.08	2	0.28	9	2.26			197
Total No. of stygobiotic species	9		7		9		6		31
Total No. of copepods	190		710		389		250		1539
Total No. of stygobionts	379		712		398		251		1740

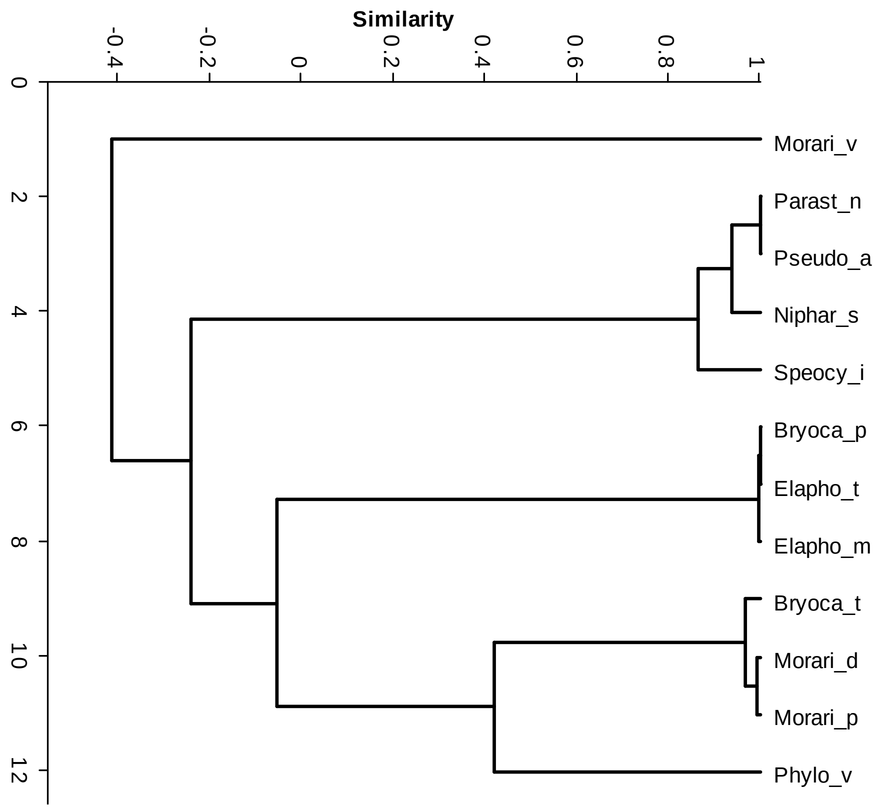

Figure 4-26: The cluster of the stygobiotic species constructed on the frequency of occurrence and abundances of the species at four drips (VP1-VP4) in the Velika Pasica Cave (Slovenia).

4.5.1.2 The seasonal fauna distribution variation

Seven years data on the seasonal abundance and composition of the fauna at each drip site from 2006 to 2012 indicated that they were clustered into several groups (Figure 4-27).

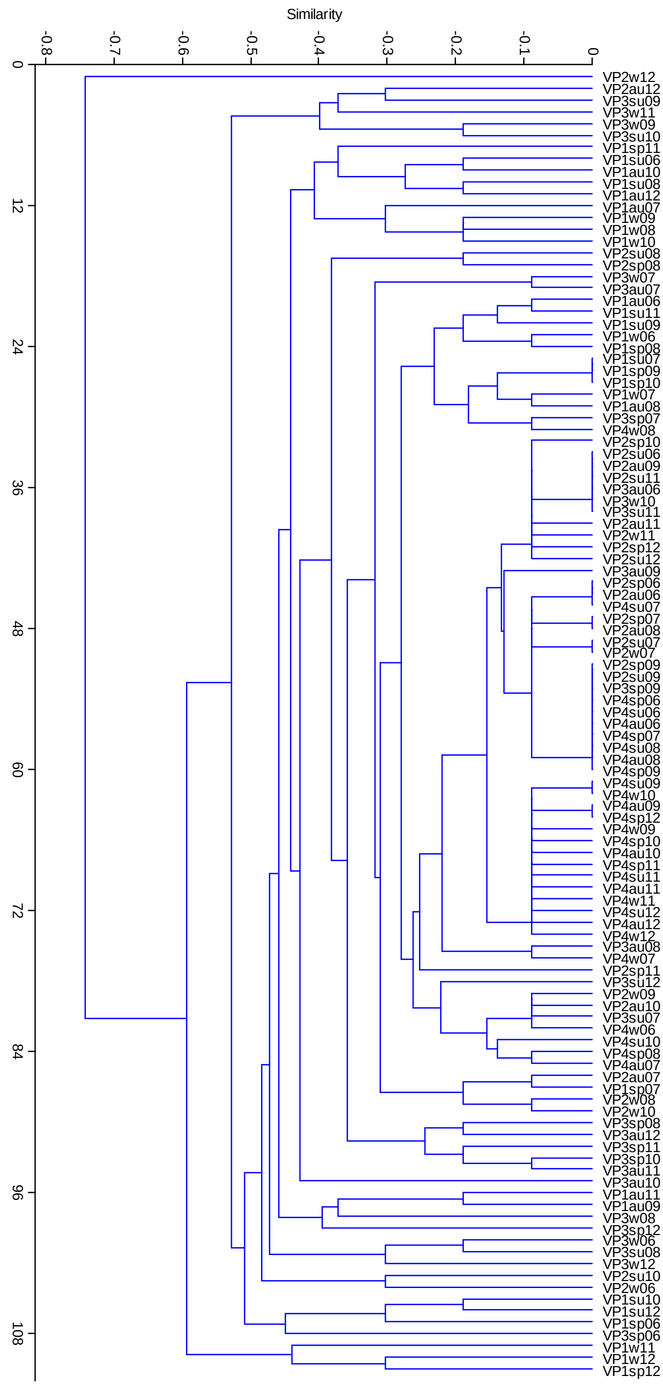

Figure 4-27: The cluster of the stygobiotic species constructed on the abundances of different seasons at four sites in the Velika Pasica Cave (Slovenia) from 2006 to 2012. The samples label presented as VP1sp06 means the spring of 2006 at site VP1; au = autumn, sp = spring, su = summer, w = winter.

4.5.2 Relationship between hydrological characteristics and the epikarst invertebrate community

Some hydrological characteristics were related to species composition from four drips, such as the days between two consecutive samplings (days), the amount of drip water discharge between two consecutive samplings (Q), the maximum discharge during the sampling period (Max), the mean discharge (Mean), the coefficient of the discharge variation (CV) and the mean drip water temperature (Temp). The results of the canonical correspondence analysis (CCA) of VP1-VP3 are presented in this section. Due to the poor taxonomic diversity found at VP4 (Table 4-12), this site and its faunal composition were excluded from the analysis.

4.5.2.1 The canonical correspondence analysis on the data from drip site VP1

In order to explain the relationship between hydrological characteristics and the epikarst invertebrate assemblage at VP1, the first four axes and the eigenvalues of the canonical correspondence analysis on the data from drip site VP1 (Table 4-13 and Figure 4-28), are presented. The CCA on the data at VP1 accounted for 27.5 % of the total variance in the species data. The first axis explained 16.4 % of the variance (inertia) in the species data, and the remaining three represented 4.5 %, 3.7 % and 1.8 %, respectively. With respect to the environmental variables, 59.6 % of the species variance was explained based on the first axis. Meanwhile, the first axis had the strongest correlation with the environmental factors ($r = 0.781$), and the remaining three had lower, with $r = 0.598$, 0.565, 0.279, respectively.

Table 4-13: A summary of the canonical correspondence analysis (CCA) for the relationship between epikarst invertebrates and hydrological parameters at drip site VP1 in the Velika Pasica Cave (Slovenia).

Axes	1	2	3	4	Total inertia
Eigenvalues:	0.237	0.065	0.052	0.026	1.442
Species-environment correlations:	0.781	0.598	0.565	0.279	
Cumulative percentage variance					
of species data:	16.4	20.9	24.6	26.4	
of species-environment relation:	59.6	76	89.3	95.8	
Sum of all eigenvalues					1.442
Sum of all canonical eigenvalues					0.397

The canonical correspondence analysis (CCA) triplot for VP1 was constructed on the first two axes (Figure 4-28). From the length of the environmental factors, the main environmental parameters affecting species distribution in the VP1 site are: the maximum discharge rate (Max) and the amount of the discharge (Q). The drip water temperature (Temp) had the lowest impact. The first canonical axis was in negative correlation with all the factors, and only the coefficient of variation for the discharge rate (CV), the drip water temperature (Temp) and the amount of the discharge (Q) were positively correlated with the second axis. Significances of these hydrological variables in CCA were tested by the Monte Carlo permutation test.

Taxa with different affinities or tolerance to the hydrological parameters were identified (Figure 4-28). The species *P. nolli alpina* was only found at VP1 and it was positively correlated with the amount of the discharge (Q) and the coefficient of the discharge variation (CV). The most abundant species, *P. albicans* was positively correlated with the hydrological parameters: Q, Mean and Max. Most other species presented low or negative relationships with the analyzed hydrological parameters.

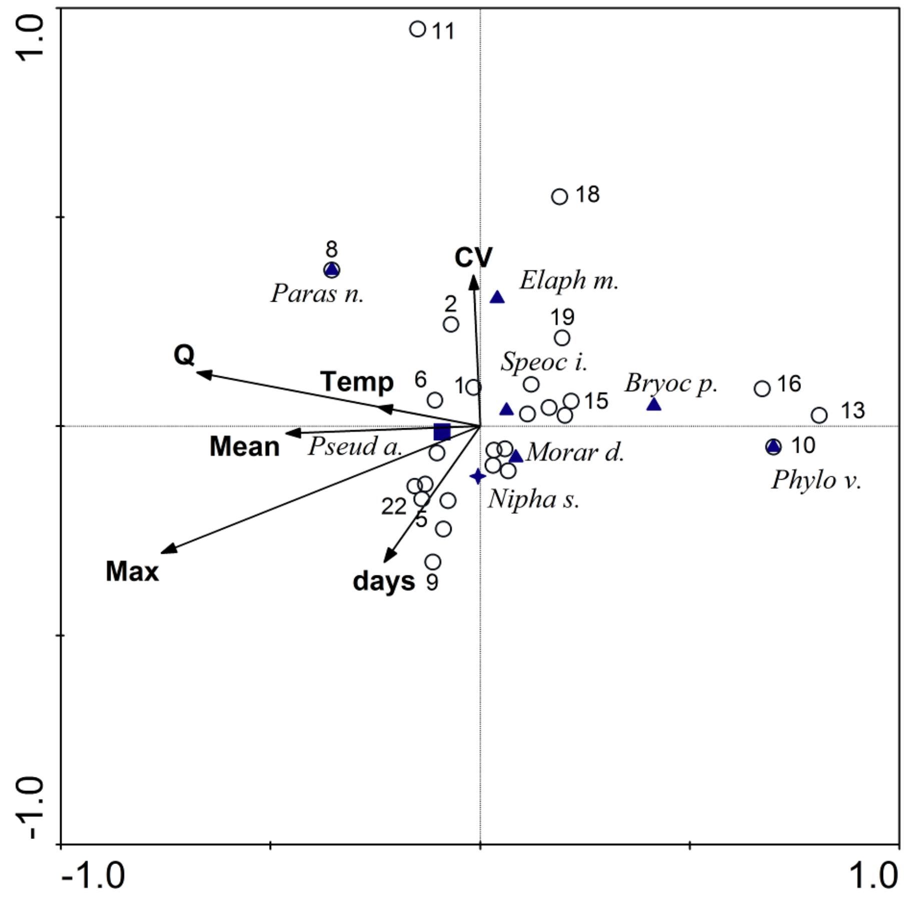

Figure 4-28: Canonical correspondence analysis (CCA) triplot of 26 samples from the drip site VP1 in the Velika Pasica Cave (Slovenia) shows the relationship between the epikarst invertebrate and the six hydrological parameters. The arrow displayed the hydrological factors; Triangle for Copepoda; asterisk for Amphipoda; square for Ostracoda; open circles for samples (with the sample numbers next to the circles), each sample includes its fauna composition and its hydrological characteristics . Days: the days between two consecutive samplings; Q: the amount of drip water discharge between two consecutive samplings; Max: the maximum discharge during the sampling period; Mean: the mean discharge; CV: the coefficient of the discharge variation; Temp: the mean drip water temperature.

4.5.2.2 The canonical correspondence analysis on the data from drip site VP2

The CCA on the data for VP2 represented 19.9% of the total variance in the species data (Table 4-14). The first two axes explained 16.7 % of the total variance of species data and 83.5 % of the species variance to the environmental variables. The first axis had a higher relationship with the environmental parameter (r = 0.568), while the other three were lower.

Table 4-14: A summary of the canonical correspondence analysis (CCA) for relationships between epikarst invertebrates and hydrological parameters at site VP2 in the Velika Pasica Cave (Slovenia).

Axes	1	2	3	4	Total inertia
Eigenvalues:	0.066	0.036	0.014	0.004	0.612
Species-environment correlations:	0.568	0.422	0.387	0.223	
Cumulative percentage variance					
of species data :	10.8	16.7	19	19.6	
of species-environment relation:	54.1	83.5	95.1	98.1	
Sum of all eigenvalues					0.612
Sum of all canonical eigenvalues					0.122

The mean drip water temperature (Temp) had the main impact on site VP2 (Figure 4-29), followed by the variation of discharge (CV). The others parameters had lower impacts, such as the days between two consecutive samplings (Days), the maximum discharge (Max), the mean discharge (Mean) and the amount of discharge (Q).

The first canonical axis was positively correlated with the drip water temperature (Temp) and the discharge variation (CV), while negatively correlated with the amount of discharge (Q). The second canonical axis was negatively correlated with the drip water temperature (Temp), the mean discharge (Mean) and the maximum discharge (Max), while positively correlated with the days between two consecutive samplings (Days).

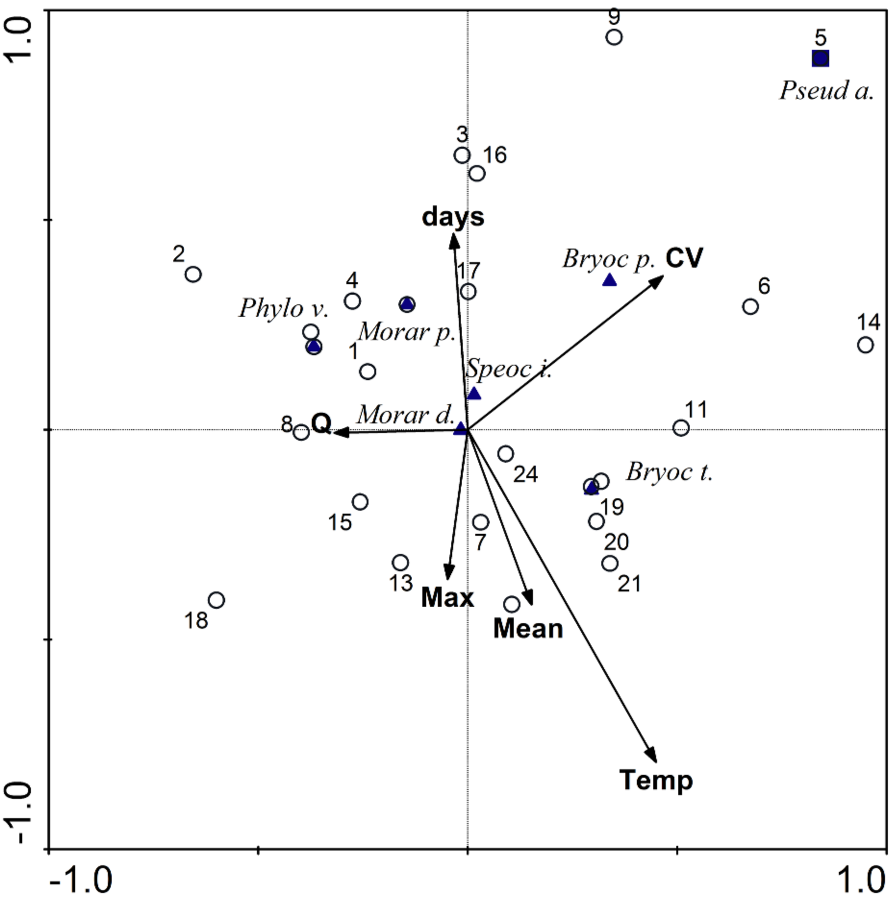

Figure 4-29: Canonical correspondence analysis (CCA) triplot of 26 samples from the drip site VP2 in the Velika Pasica Cave (Slovenia) shows the relationship between the epikarst invertebrates and the six hydrological parameters. The arrow displayed the hydrological factors; Triangle for the Copepoda; square for Ostracoda; open circles for samples (with the sample numbers next to the circles), each sample includes its fauna composition and its hydrological characteristics. Days: the days between two consecutive samplings; Q: the amount of drip water discharge; Max: the maximum discharge during the sampling period; Mean: the mean discharge; CV: the coefficient of the discharge variation; Temp: the mean drip water temperature.

At this site, *P. albicans*, *B. pyrenaicus* and *B. typhlops* demonstrated positive correlation with the discharge variation (CV). But the other parameters were distributed homogeneously in the triplot.

4.5.2.3 The canonical correspondence analysis on the data from drip site VP3

The CCA on the data at VP3 represented 38.7 % of the total variance in the species data (Table 4-15). The first two axes explained 36.7 % of the total variance of species data and 94.9 % of the species variance to the environmental variables. The first two axis had a tighter relationship with the environmental parameter (r = 0.893 and r = 0.588), while the other two were quite low.

Table 4-15: A summary of the canonical correspondence analysis (CCA) for the relationship between epikarst invertebrates and hydrological parameters at drip site VP3 in the Velika Pasica Cave (Slovenia).

Axes	1	2	3	4	Total inertia
Eigenvalues:	0.358	0.093	0.019	0.004	1.227
Species-environment correlations:	0.893	0.588	0.311	0.182	
Cumulative percentage variance					
of species data:	29.2	36.7	38.3	38.6	
of species-environment relation:	75.4	94.9	99	99.8	
Sum of all eigenvalues					1.227
Sum of all canonical eigenvalues					0.475

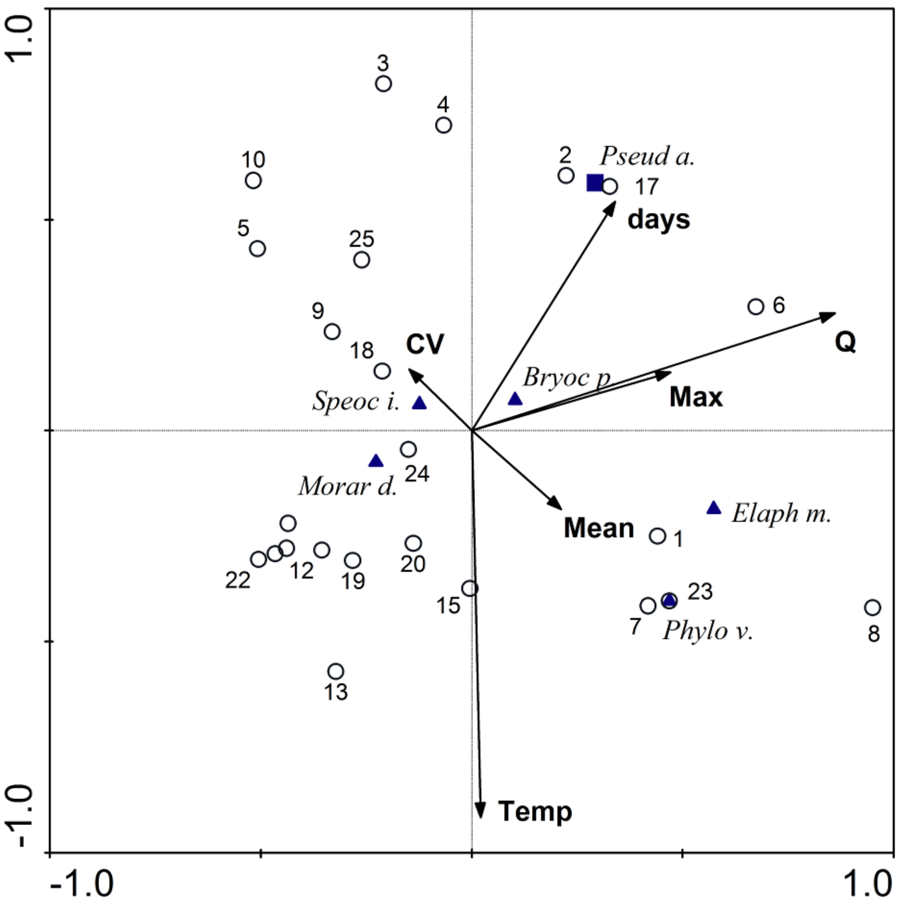

Figure 4-30: Canonical correspondence analysis (CCA) triplot of 26 samples from the drip site VP3 in the Velika Pasica Cave (Slovenia) shows the relationship between the epikarst invertebrates and the six hydrological parameters. The arrow displayed the hydrological factors; Triangle for the Copepoda; square for Ostracoda; open circles for samples (with the sample numbers next to the circles), each sample includes its fauna composition and its hydrological characteristics. Days: the days between two consecutive samplings; Q: the amount of drip water discharge between two consecutive samplings; Max: the maximum discharge during the sampling period; Mean: the mean discharge; CV: the coefficient of the discharge variation; Temp: the mean drip water temperature.

The mean drip water temperature (Temp) also impacted significantly at site VP3, from Figure 4-30, meanwhile, the impact of the discharge volume (Q) was more remarkable than the maximum discharge (Max), the mean discharge (Mean) and the variation of the discharge (CV).

The first canonical axis was positively correlated with the amount of discharge (Q), the maximum discharge (Max) and the mean discharge (Mean), but negatively correlated with the variation of the discharge (CV). The second canonical axis was negatively correlated with the drip water temperature (Temp), but positively with the days of the monitoring period (Days).

At this site, *P. albicans* was positively correlated with the days between two consecutive samplings (Days). *E. millennii* and *P. viguieri* were slightly positively correlated with the mean discharge (Mean).

4.5.2.4 The Spearman's rank correlation coefficients between the hydrological factors and the epikarst invertebrate community

Spearman's rank correlation coefficients between six hydrological factors and ten stygobiotic epikarst invertebrates are presented in Table 4-16. *Elaphoidella tarmani* was omitted from the table, due to its rare occurrence. In combination with the Table 4-12, the abundance of different species affected the results of the correlation analyses, such as *P. albicans* at VP1 (n = 186), *M. dumonti* at VP2 (n = 632) and *M. varica* at VP4 (n = 240). However, not all the high abundance species correlated closely with these factors, such as *M. dumonti* (n = 147) and *B. pyrenaicus* (n = 140) at VP3.

Table 4-16: Spearman's rank correlation coefficient between six hydrological factors and eleven epikarst invertebrates. Days: the sampling period; Temp: the drip water temperature; Q: the amount of the discharge; Max: the maximum discharge; Mean: the mean discharge; CV: the variation of the discharge. *. Correlation is significant at the 0.05 level (2-tailed). **. Correlation is significant at the 0.01 level (2-tailed).

		Pseud a.	Bryoc t.	Bryoc p.	Elaph m.	Morar d.	Paras n.	Speoc i.	Morar p.	Morar v.	Nipha s.	Phylo v.
VP1	Days	0.28		-0.18	0.04	0.15	0.23	0.25			0.23	0.17
	Temp	0.22		0.12	-0.01	-0.07	-0.04	-0.06			0.06	-0.20

	Q	0.59**		-0.32	-0.02	0.21	0.33	0.30			0.25	-0.25
	Max	0.35		-0.32	-0.21	-0.02	0.23	-0.07			0.18	-0.28
	Mean	0.43*		-0.18	-0.06	0.06	0.25	0.15			0.07	-0.28
	CV	0.08		-0.16	0.27	-0.15	-0.17	0.00			-0.12	-0.23
	Days	0.28	0.04	0.00		-0.10		-0.11	0			0.17
	Temp	-0.17	0.46*	-0.01		0.16		0.22	-0.15			-0.20
VP2	Q	-0.01	0.26	0.15		0.58**		0.51**	0.15			-0.17
	Max	-0.09	0.43*	0.07		0.55**		0.44*	-0.04			-0.17
	Mean	-0.07	0.34	0.20		0.69**		0.60**	0.09			-0.17
	CV	0.28	0.01	-0.02		-0.37		-0.34	-0.09			-0.28
	Days	0.21		0.02	0.32	-0.28		0.16				-0.11
	Temp	-0.33		0.09	0.16	0.20		-0.08				0.28
VP3	Q	0.35		0.28	0.42*	-0.32		0.11				0.25
	Max	0.19		0.27	0.08	0.03		0.06				0.23
	Mean	0.14		0.25	0.25	-0.09		0.01				0.25
	CV	-0.01		0.04	-0.07	0.06		-0.03				-0.14
	Days							0.20		0.23		
	Temp							-0.15		0.23		
VP4	Q							0.28		-0.18		
	Max							0.33		-0.25		
	Mean							0.17		-0.46*		
	CV							0.28		0.46*		

4.5.3 Relationship between hydrochemical features and the epikarst invertebrate community

4.5.3.1 The canonical correspondence analyses on the hydrochemical data from drip site VP1

The CCA analyses of the relationship between the main hydrochemical parameters and the epikarst invertebrate species at site VP1 is indicated by the first four axes and the eigenvalues in Table 4-17. The data for CCA analysis at VP1 accounted for 71.7 % of the total variance in the species data. The first two axes explained 41.2 % and 15.2 % of the variance in the species data, respectively. For the species-environment relationship, the first two axes explained 57.3 % and 21.3 %, respectively. These two axes had a very strong correlation with the environmental factors, r = 0.964 and r = 0.850.

Table 4-17: A summary of the canonical correspondence analysis (CCA) for the relationship between epikarst invertebrates and hydrochemical parameters at drip site VP1 in the Velika Pasica Cave (Slovenia).

Axes	1	2	3	4	Total inertia
Eigenvalues:	0.257	0.095	0.066	0.02	0.623
Species-environment correlations:	0.964	0.85	0.787	0.551	
Cumulative percentage variance					
of species data:	41.2	56.4	67.1	70.2	
of species-environment relation:	57.3	78.6	93.4	97.8	
Sum of all eigenvalues					0.623
Sum of all canonical eigenvalues					0.447

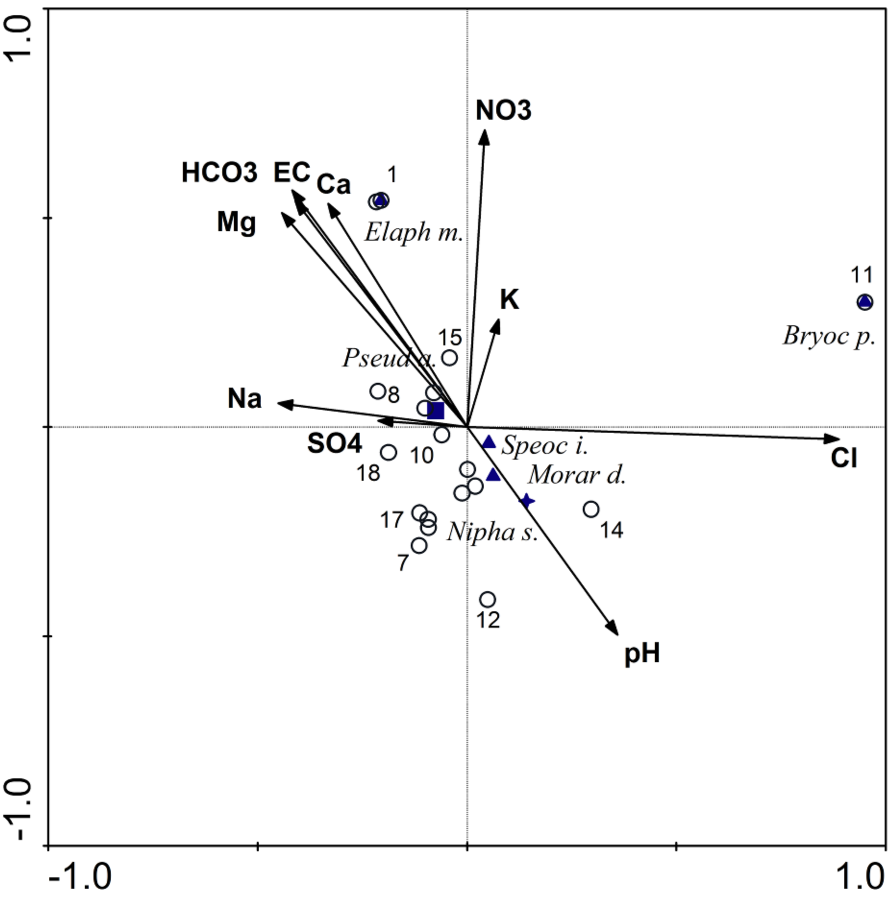

Figure 4-31: Canonical correspondence analysis (CCA) triplot of 20 samples from the drip site VP1 in the Velika Pasica Cave (Slovenia) shows the relationship of the epikarst invertebrate, the ten hydrochemical parameters. The arrow displayed the hydrochemical parameters; Triangle for Copepoda; asterisk for Amphipoda; square for Ostracoda; open circles for samples (with the sample numbers next to the circles), each sample includes its fauna composition and its hydrochemical characteristics. EC: the electrical conductivity; Cl^-, NO_3^-, SO_4^{2-}, HCO_3^-, Na^+, K^+, $Ca^{2+}$and Mg^{2+} : the main ions of the water samples.

The CCA triplot of the relationships from the drip site VP1 was constructed in the first two axes (Figure 4-31). Most hydrochemical factors had significant impact on the invertebrate assemblage composition at VP1 including the major ions, such as Ca^{2+}, Mg^{2+} and HCO_3^- ions, EC, pH and even the minor ions, Cl^- and NO_3^-. The first canonical axis positively correlated with the Cl^- and pH, but negatively with most major ions and EC. Most of the hydrochemical factors were in positive correlation with the second axis with the exception of the pH.

In the CCA, according to the canonical axis, the species *B. pyrenaicus* responded positively in correlation with the Cl^-, but insignificantly with other factors. *E. millennii*, was in positive correlation with the major ions, EC and even the NO_3^- ions, while in negative correlation with the pH.

4.5.3.2 The canonical correspondence analysis on the hydrochemical data from drip site VP2

For the hydrochemical factors, the CCA on the data at VP2 accounted for up to 50.2 % of the total variance in the species data (Table 4-18). The first two canonical axes explained 46.6 % of the total variance in species data, and 92.9 % of the species variance to the environmental variables. The first two axes had a strong relationship with the environmental parameters: r = 0.810 and r = 0.645, respectively.

Table 4-18: A summary of the canonical correspondence analysis for the relationship between epikarst invertebrates and hydrochemical parameters at drip site VP2 in the Velika Pasica Cave (Slovenia).

Axes	1	2	3	4	Total inertia
Eigenvalues:	0.175	0.104	0.018	0.003	0.598
Species-environment correlations:	0.81	0.645	0.481	0.955	
Cumulative percentage variance					
of species data:	29.2	46.6	49.6	50.1	
of species-environment relation:	58.3	92.9	98.9	100	
Sum of all eigenvalues					0.598
Sum of all canonical eigenvalues					0.3

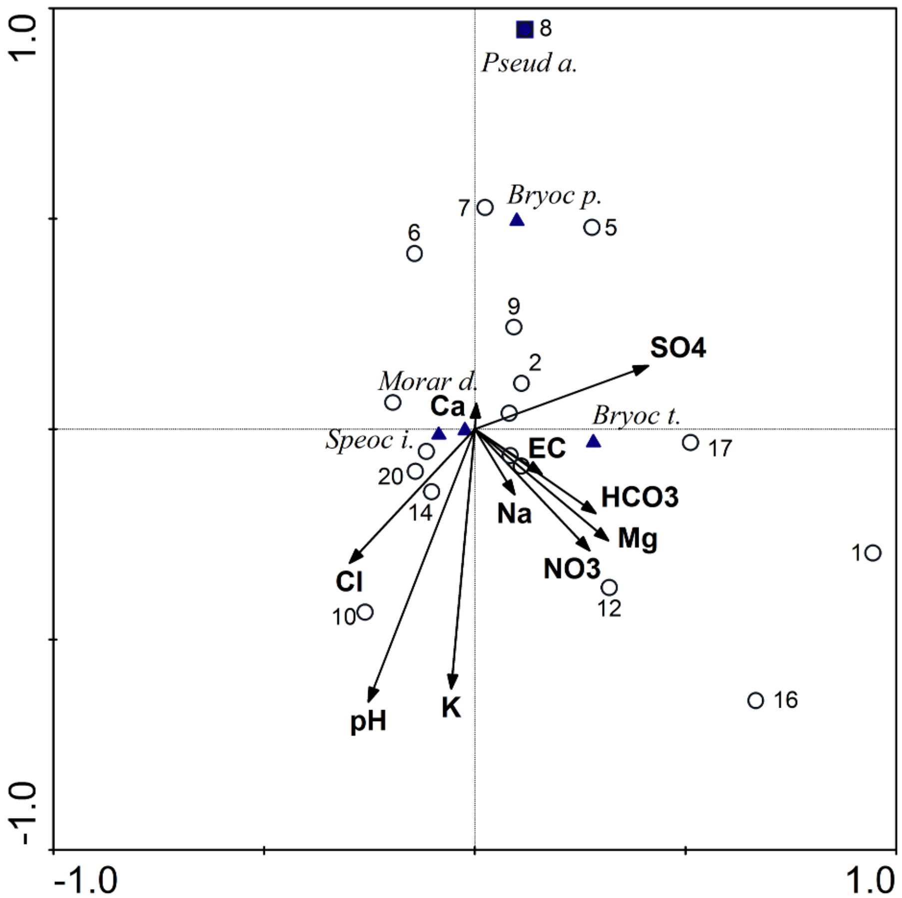

Figure 4-32: Canonical correspondence analysis (CCA) triplot of 20 samples from the drip site VP2 in the Velika Pasica Cave (Slovenia) shows the relationship of the epikarst invertebrate, the ten hydrochemical parameters. The arrow displayed the hydrochemical parameters; Triangle for Copepoda; square for Ostracoda; open circles for samples (with the sample numbers next to the circles), each sample includes its fauna composition and its hydrochemical characteristics. EC: the electrical conductivity of the water samples; Cl^-, NO_3^-, SO_4^{2-}, HCO_3^-, Na^+, K^+, $Ca^{2+}$and Mg^{2+} were the main ions of the water samples.

The pH, K^+ and Cl^- represented the most impact at the site VP2 (Figure 4-32), to the contrary, the major ions and EC affected less, especially the Ca^{2+} ions were much weaker here. The first canonical axis had a positive relationship with Mg^{2+}, HCO_3^-, NO_3^- and SO_4^{2-} ions, while it was negative with Cl^-, pH and K^+ ions. Most factors were negative with the second canonical axis with the exception of SO_4^{2-} ions.

Bryocamptus typhlops was relatively abundant at VP2 (Table 4-12), and here it presented positive correlation with the first canonical axis, thus, it also demonstrated a positive relationship with Mg^{2+}, HCO_3^-, NO_3^- and SO_4^{2-} ions. Two species, *B.*

pyrenaicus and *P. albicans*, performed positive correlation with the second canonical axis, which indicated that they had a negative relationship with most other factors. The most common species at VP2, *M. dumonti* and *S. infernus* indicated lower effects in the analysis (Figure 4-32).

4.5.3.3 The canonical correspondence analysis on the hydrochemical data from drip site VP3

The first four axes of CCA on the hydrochemical data at VP3 represented 70.4 % of the total variance for the species data (Table 4-19). The first two axes explained 58.2 % of the total variance of species data and 82.6 % of the species variance to the environmental variables. The canonical axes had a strong relationship with the environmental parameter, and the first two exes were with r = 0.867 and r = 0.894.

Table 4-19: A summary of the canonical correspondence analysis (CCA) for the relationship between epikarst invertebrates and hydrochemical parameters at drip site VP3 in the Velika Pasica Cave (central Slovenia).

Axes	1	2	3	4	Total inertia
Eigenvalues:	0.37	0.299	0.104	0.031	1.15
Species-environment correlations:	0.867	0.894	0.831	0.687	
Cumulative percentage variance					
of species data:	32.2	58.2	67.2	70	
of species-environment relation:	45.7	82.6	95.4	99.3	
Sum of all eigenvalues					1.15
Sum of all canonical eigenvalues					0.81

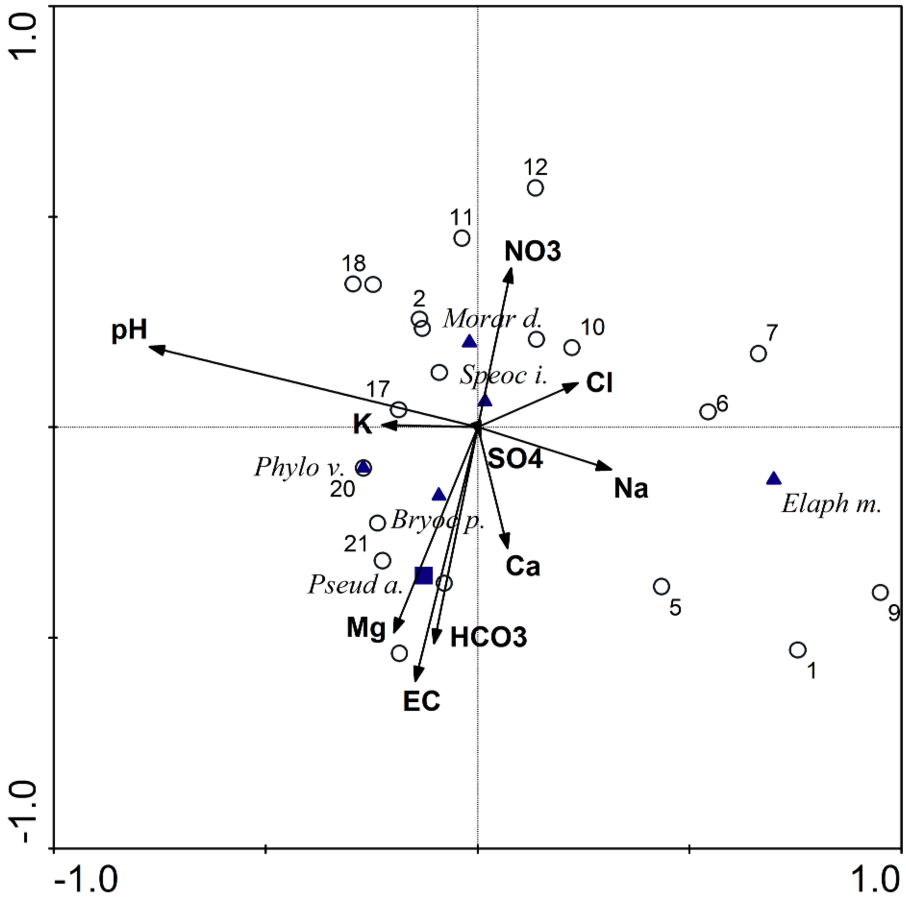

Figure 4-33: Canonical correspondence analysis (CCA) triplot of 21 samples from the drip site VP3 in the Velika Pasica Cave (Slovenia) shows the relationship between the epikarst invertebrate and the ten hydrochemical parameters. The arrow displays the hydrochemical parameters; Triangle for Copepoda; square for Ostracoda; open circles for samples (with the sample numbers next to the circles), each sample includes its fauna composition and its hydrochemical characteristics. EC: the electrical conductivity of the water samples; Cl^-, NO_3^-, SO_4^{2-}, HCO_3^-, Na^+, K^+, $Ca^{2+}$and Mg^{2+} were the main ions of the water samples.

The hydrochemical parameters and the epikarst species were presented on the CCA triplot (Figure 4-33). According to the length of the hydrochemical parameter in the triplot, the pH indicated the most significant impact on the epikarst invertebrate assemblage at site VP3, and EC, Mg^{2+}, HCO_3^- and NO_3^- ions also presented strong impacts. The other factors indicated with less influence, especially the SO_4^{2-}. The pH was strongly negatively correlated with the first canonical axis, while the other main impacts had a negative correlation with the second canonical axis, except NO_3^- ions which was positive related with the second canonical axis.

The most abundant species, *B. pyrenaicus* had a negative relationship with the second canonical axis and *M. dumonti* was positive with the second canonical axis. The site specific species: *E. millennii* was in a strong, positive relationship with the first canonical axis.

4.5.3.4 The Spearman's rank correlation coefficients between the hydrochemical factors and the epikarst invertebrate community

Spearman's rank correlation coefficients between nine hydrochemical factors and nine epikarst invertebrate are presented in Table 4-20. Some species were omitted from the table, due to their rare appearance and the sample selection regime for analyses. These correlation coefficients also supported the results from the CCA. The most abundant species at site VP1 were *P. albicans*, *S. infernus* and *M. dumonti*. *P. albicans* was negatively correlated with Cl^- ions and *S. infernus* was also negatively correlated with K^+ ions. At site VP2, the most common species were *B. typhlops* and *M. dumonti*, although *B. typhlops* was more significantly affected by ions, especially Mg^{2+} and HCO_3^- ions. The most abundant species were *M. dumonti* and *B. pyrenaicus* at VP3, and *B. pyrenaicus* was significantly and positively correlated with Mg^{2+} ions. The specific faunal composition at VP4 from the CCA cannot represent the results here, but the correlation coefficients indicated that the species, *M. varica*, was highly and significantly negative in correlation to NO_3^- and SO_4^{2-} ions (Table 4-20).

Table 4-20: Spearman's rank correlation coefficient between nine hydrochemical factors and nine epikarst invertebrates. EC: the electrical conductivity of the water samples; Cl^-, NO_3^-, SO_4^{2-}, HCO_3^-, Na^+, K^+, $Ca^{2+}$and Mg^{2+} were the main ions in the water samples. *. Correlation is significant at the 0.05 level (2-tailed). **. Correlation is significant at the 0.01 level (2-tailed).

		Phylo v.	Bryoc t.	Bryoc p.	Elaph m.	Morar d.	Speoc i.	Morar v.	Nipha s.	Pseud a.
	EC			-0.22	0.34	-0.36	-0.24		0.06	0.09
	Cl^-			0.34	-0.30	0.24	-0.19		0.29	-0.52*
	NO_3^-			0.22	0.30	-0.28	-0.36		-0.39	-0.14
	SO_4^{2-}			-0.28	0.14	-0.13	0.13		-0.16	0.11
VP1	Na^+			-0.26	0.02	-0.13	-0.10		0.13	0.32
	HCO_3^-			-0.22	0.26	-0.36	-0.28		0.06	0.05
	K^+			0.10	0.06	0.00	-0.45*		0.07	-0.31
	Ca^{2+}			-0.14	0.26	-0.29	-0.17		0.09	-0.01
	Mg^{2+}			-0.22	0.22	-0.33	-0.31		0.06	0.06
	EC		0.41	0.32		0.36	0.45*			0.06
	Cl^-		-0.22	-0.20		0.03	-0.09			-0.30
	NO_3^-		-0.16	-0.32		-0.23	-0.48*			-0.38
	SO_4^{2-}		0.26	0.32		-0.07	0.05			0.26
VP2	Na^+		0.49*	0.20		0.31	0.29			0.02
	HCO_3^-		0.45*	0.03		0.02	0.35			-0.24
	K^+		0.38	-0.23		0.19	0.24			-0.38
	Ca^{2+}		-0.01	-0.09		-0.04	-0.10			0.10
	Mg^{2+}		0.74**	0.17		0.32	0.40			-0.14
	EC	0.05		0.42	-0.24	-0.08	0.17			0.18
	Cl^-	-0.15		0.01	0.43*	0.16	0.06			0.28
	NO_3^-	-0.12		-0.07	0.30	0.16	-0.09			0.03
VP3	SO_4^{2-}	-0.14		0.08	0.30	0.06	-0.17			0.17
	Na^+	0.02		0.29	-0.26	-0.22	0.05			0.11
	HCO_3^-	-0.02		0.32	0.10	0.08	-0.06			0.16
	K^+	0.21		0.27	-0.39	-0.11	0.04			-0.15

	Ca^{2+}	-0.26		-0.01	-0.12	-0.01	-0.21			0.18
	Mg^{2+}	0.05		0.43*	-0.24	-0.11	0.16			0.13
	EC						0.15	-0.27		
	Cl^-						-0.30	-0.31		
	NO_3^-						-0.30	-0.64**		
	SO_4^{2-}						0.22	-0.57**		
VP4	Na^+						-0.22	-0.30		
	HCO_3^-						-0.07	-0.10		
	K^+						-0.22	-0.20		
	Ca^{2+}						0.37	0.00		
	Mg^{2+}						-0.33	-0.42		

4.5.4 Non-metric multidimensional scaling (NMDS) analysis

Non-metric multidimensional scaling indicated the similarity or dissimilarity of the yearly composition of aquatic micro-crustacean at different sites from 2006-2012 (Figure 4-34).

The samples are located distinctly in the two-dimensional plot and they are gathered into four, well defined groups, which are formed only on the basis of the individual drip sites. Marked in Figure 4-34, the samples from VP1, VP2 and VP3 are grouped closely, while points of VP4 distribute dispersedly. The VP3 group stays in the middle relatively close with the VP1 and VP2 groups (Figure 4-34). While the VP1 group and VP2 group distribute far from each other although they are close in reality. Due to the unique community at site VP4 (Table 4-12 and Appendix I), the samples at VP4 in the years 2006, 2007 and 2008 were quite distinctive in comparison with the samples from the following years. The variation is indicated in Figure 4-33 with arrows. As presented in the NMDS diagram, the samples from the years 2009, 2010, 2011 and 2012 were those most distant from other samples, while the samples in 2006 were closer to the VP3 group and the samples in 2007 and 2008 were close to the VP1 group. The differences between the sample groups were mainly due to the most dominant species (Table 4-12 and Appendix I): VP1: *S. infernus* and *P. albicans*; VP2: *M. dumonti*; VP3: *B. pyrenaicus*, *M. dumonti* and *S. infernus*; VP4: *M. varica*.

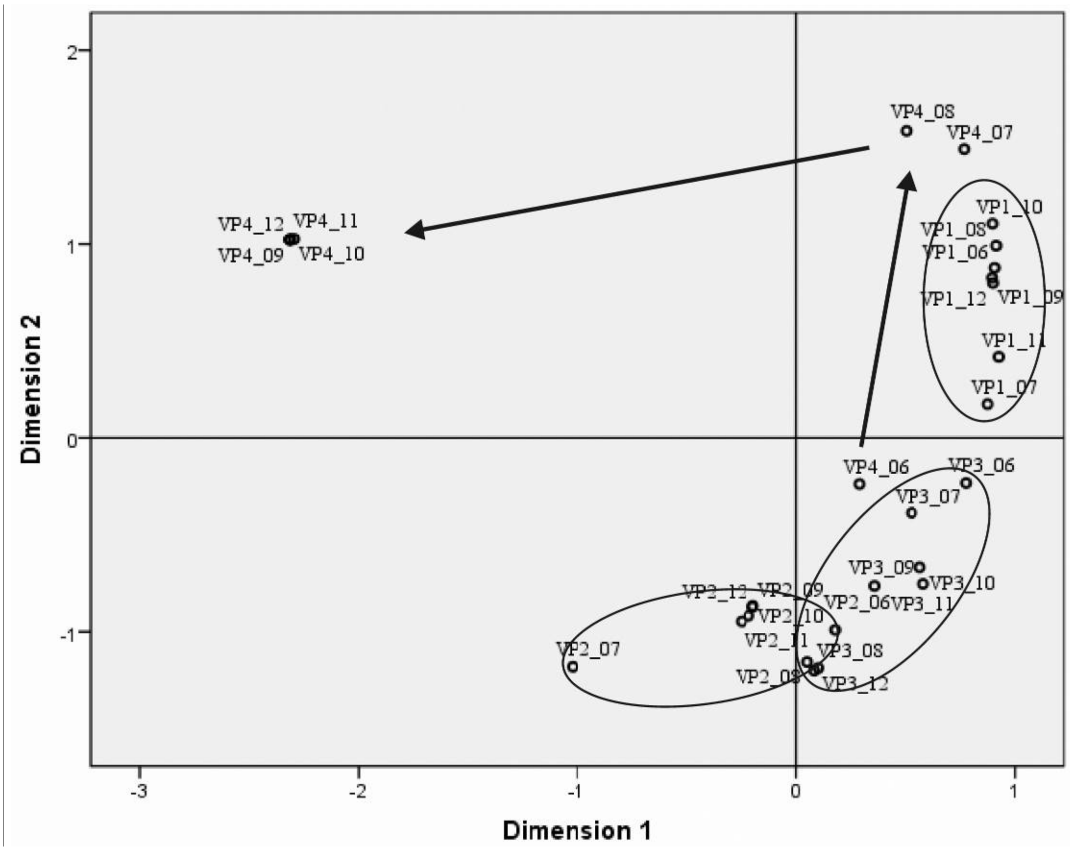

Figure 4-34: Non-metric multidimensional scaling (NMDS) diagram representing the annual data on the populations of different species at different drip sites in the Velika Pasica Cave (Slovenia) from 2006 to 2012. Stress value, 0.173. Legend: VP1_06: the faunal composition in 2006 at drip site VP1. Circles tags out the sampling points in different years of different site; arrows indicate the yearly variation of site VP4.

Chapter 5 Discussion

5.1 Hydrological profile of cave drip water reflects differences in epikarst structure

5.1.1 The hydrological profile of the four drips

The Velika Pasica Cave has a site specific position within the field of cave hydrology research. It is located at an elevation of 662 m a.s.l., on a minor karstic plateau, positioned 100 m below the peak of a small hill, thus, its catchment area is limited (< 0.5. km^2). Additionally, the maximum thickness of the ceiling above the cave is approximately 10 - 12 m or even less (Brancelj, 2002). The result is a relatively low water storage capacity for the catchment area. The discovery of an unexpectedly rich aquatic fauna, which persist permanently in a thin perched aquifer below the soil and above the cave (Brancelj, 2000, 2002, 2009) set several pertinent ecological questions. Across that time span it should continually retain moisture, otherwise faunal extinction would have occurred. Of particular scientific interest is the factor that each drip has its own specific faunal assemblage, indicating very limited horizontal communication between water catchment areas. It was anticipated that the hydrological conditions (especially discharge and size of voids) determined the local faunal composition.

For description of water transport through epikarst/vadose zone, four types of discharge have been proposed: “rapid response without time lag” (dilution effect); “fast response with associated time lag” (dilution and storage access); “intermittent response” (increased rainfall raises the aquifer water pressure and flow is diverted to higher capacity vadose routes) and “no response” (discharge is maintained by substantial storage, with only minor changes in head driving flow) (Smart and Friedrich, 1987; Baker et al., 2000; Tooth and Fairchild, 2003).

According to the drips response speed and their discharge intensity in response to the precipitation and the discharge patterns (Figure 4-3), the drips in the Velika

Pasica Cave can be divided into the above defined four types: “rapid response with high intensity discharge” (VP1); “fast response with moderate discharge” (VP3); “rapid response with congest discharge” (VP4) and “slow response with congest discharge” (VP2) as well. After a storm, with sufficient precipitation, VP1 and VP3 have rapid and significant response with no or short delay (on a scale of few hours); while VP4 has longer response time. The least sensitive to rain events is VP2 which usually did not have any response to the slight/moderate rain.

Factors affecting the response time of the drips to the precipitation are vegetation covering the catchment area of individual drips, the thickness of the cave ceiling, the structure of cover above the ceiling (e.g. soil compaction, the structure and permeability of the soil and rock composition) and amount of residual water in the soil and fractured rocks in combination with the rainfall intensity (Zhou et al., 2005). The vegetation cover enlarged the soil porosity and developed rock joints, which accelerate the speed and amount of rain to percolate through cave ceiling (Zhou et al., 2005). Drip waters in the cave have been characterized according to the varying contribution of source-water types, e.g. the proportion of water transported via direct delivery of the recharge along preferential flow routes versus piston flow, where ‘old’ stored water (residual water) is expelled from pores and fissures by incoming ‘new’ water (Baker et al., 2000; Tooth and Fairchild, 2003; William, 2008).

5.1.2 Hydrological response of the drips to rain event

The case study on fine-scale response of drips to rain events revealed that during the first rain event in May, the highest discharge from drips VP1 and VP3 coincided with a heavy storm event (8.4 mm/h) as their first peaks arrived on May 6th, when 40.8 mm of rain had already fallen (Figure 4-3). At that time the storage capacity of the catchment area was already at its maximum and additional precipitation triggered fast and intensive discharge processes followed by more peaks after additional moderate and short rain events. The steep attenuation curves indicate the low retention capacity of the catchment area.

The discharge pattern in drips VP2 and VP4 was different from the other two drips, with a slow rise in discharge commencing at the end of the first rain event. This indicated that hydraulic conductivity of the voids in their catchment area was low and most water infiltrated was stored in the soil layer or epikarst layer. The highest discharge from both drips arrived close to the end of the rain event (drip VP2 at hour 378 and drip VP4 at hour 359, respectively). In total, 101.6 mm of rain had already fallen, which indicates that both drips have a long-lasting accumulation process within the catchment area and small discharge capacity (7 and 46 ml/min, respectively), reflecting small voids.

5.1.3 Inference on the possible epikarst structure from the water flow at different drips

Over a long-time scale (months) the four drips in the Velika Pasica Cave followed the surface rainfall (Table 4-1), as their discharge varied significantly over the months. In the dry periods, the drips kept low drip rates, while a significant increase in response to the storm was apparent. In the wet period, as the amount and intensity of the rainfall increased, the discharge from all the sites still had rapid and apparent responses. Maximal discharges of individual drips observed in 2010 never lasted more than four hours. This indicates that the recharge water (precipitation) never exceeds discharge capacity of the permanent drips, resulting in a temporary extended perched aquifer. Excess water is thus released through short-lived temporary drips positioned along main channels and voids which help to discharge percolating water from the catchment area.

Relative to the different sites, although they were so closely positioned to each other, the range of discharge and the response time still showed significant differences, which supported the similar results from other research (Baker et al., 1997; Genty and Deflandre, 1998; Baker and Brunsdon, 2003; Tooth and Fairchild, 2003). The water storage capacity of the epikarst for each drip of the Velika Pasica Cave is rather small and consequently the variation in the drip discharge is determined significantly by the seasonal weather conditions with high coefficients of variation (CV) (Table 4-1). Although it has high CV and very low discharge after prolonged periods with no precipitation, the catchment area of each drips never dries out completely as confirmed by the permanent presence of aquatic fauna in the drips (Brancelj, 2000, 2002, 2009).

Maximum discharge and its variation coefficient are hydrological characteristics of individual drips which provide information on connectivity and the storage capacity of the system. Smart and Friedrich (1987) classified the hydrological characteristics of drips in one cave system (G.B. Cave, Mendip Hills, England) according to their maximum discharge and discharge variability, which was similar to those in the Velika Pasica Cave (Figure 4-2). In the Velika Pasica Cave, site VP1 is characterised by the vadose and subcutaneous flow, resulting in 217 hours (i. e. 20 % of the whole observed period) of discharge over the average values, and at most times was well synchronised with the storms (Figure 4-3). According to Baker et al. (1997) subcutaneous flows have high coefficients of variation owing to their intermittent action, and are commonly found in the top 30 cm of the aquifer, which is the most fissured and weathered sector. Such a situation matches the characteristics of the drip VP1 from the Velika Pasica Cave which has a very uniform maximum discharge and highly variable CV. Nearby drip VP2 differs from VP1 and in most months it functions as seasonal flow, and only during some more intensive rain events it shifted into vadose and seepage flow (Figure 4-2). Similarly, most of time drip VP3 also runs as seasonal flow, but it had a wider range of regime discharge, where some fitted to the vadose flow, and few to subcutaneous flow. Also VP4 usually runs as seasonal flow, but after some rain events it shifted into the seepage flow type, which has relatively low discharge and coefficient of variation. This implies that the epikarst zone in the VP4 catchment is well fractioned on a small scale resulting in a low and stable discharge. The seepage flow is characterised by low coefficient of variation, which indicates that it has an efficient buffer system in order to reduce oscillation in discharge from the system. However, it exhibits seasonal variations in discharge related to storage replenishment during precipitation followed by recession during the periods of soil moisture deficiency (Baker et al., 1997). Drips VP2 and VP4 showed a clear, long-lasting progress in recharge and discharge of the drip waters (Figure 4-3). Along the passageway of seepage water flow, pores and fissures take up more space, creating a larger storage capacity which supports the percolation stream with a low but long-lasting discharge.

The extreme events of individual drips could provide additional information on the cave cover structure. The most extreme events (i.e. the highest discharge) provided information on maximal size (actually conductivity) of voids, while "tail" relates to storage capacity / conductivity and "slope" for hydraulic conductivity / porosity.

All the drips are spatially very close to each other (distance in tenths of metres), therefore, they have the same precipitation regime, similar geological features, surface vegetation and also landscape. Thus, local differences in conduit rate between pores (in soil) and fissures (in epikarst) in this medium is one of the main factors that has determined the speed of drip discharge in response to rainfall.

According to Akinson et al., (1977), White (2002), Cronaton and Perrochet (2002), Liedl et al. (2003), the drip sites in the Velika Pasica Cave have typical dual-medium recharge systems, which are characteristic for the widespread fracture-net storage system and the well-developed fracture-net rapid discharge system (conduits). The fast attenuation is due to the conduits rapid flow, while the seepages from the small fracture storage reservoirs are active during slow attenuation (Figures 4-3 and 4-4). The conduit's rapid flow is dominant in drip VP1, the amount of discharge rises and attenuates rapidly, which is indicated by large discharge over short duration which takes up the lowest time, 20.6 % of total observed time in May and June. Drip VP2 has a long process of accumulation, until the small fractures are filled with water and only then it starts to release water. This is the reason why there was no response at beginning of the rain events, while it later rose relatively steeply and after the maximum, released gently (Figures 4-3 and 4-4). However, drip VP2 is very close to the surface and the soil layer is quite thin (0-20 cm), thus it has a limited storage capacity. From Figure 4-3, according to discharge curve, drip VP2 has no response before the water passed through the soil and fissure layer. This indicates the absence of conduits for quick flow and the recharge is quite slow and small. This is known as the piston type of infiltration (Wang et al., 1980; Baker et al., 2000; Tooth and Fairchild, 2003) (Figure 5-1).

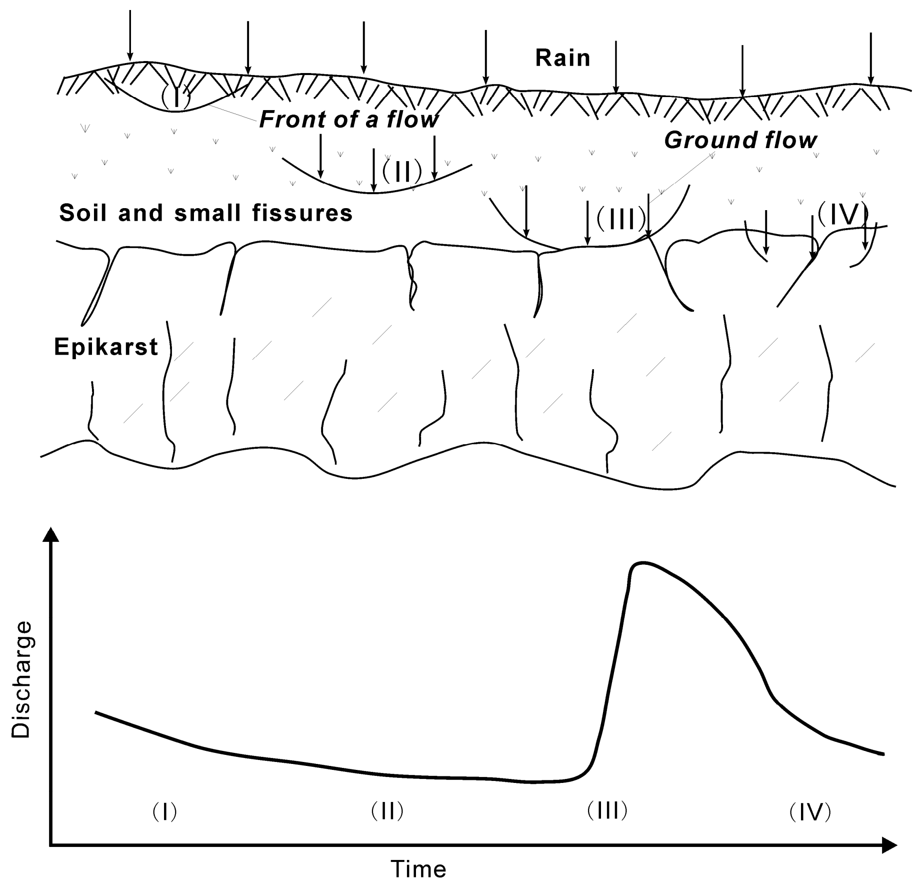

Figure 5-1: A schematic diagram of the process of recharge and discharge of VP2 from the Velika Pasica Cave (Slovenia) in May, 2010. I: the rain commenced; II: the rain water percolated through the soil layer; III: water arrived at epikarst; IV: water dripped out.

Drip VP3 had a rapid response but the discharge rate was lower when compared to that of drip VP1. The volume and cross-section of the conduits in the catchment area of drip VP3 might be lower in comparison to those in VP1. It has strong response to rain fall, but the attenuation process shows the high storage capacity of drip VP3's catchment area, which resulted in that there was not any obvious jump break from the seepage flow between the peaks. Drip VP4 also responds rapidly, however, the conduits of drip VP4 appear smaller, and seepage flow represents most of its discharge with a gently inclined recharge and slow attenuation flow (Figure 4-4).

Although there were several more drips within the cave, their discharge was very slow and /or in some cases some of them completely cease quickly, indicating that they were mainly fed by small fissure water, and the hydraulic connection net is not well-developed or the storage capacity of their catchment area is small. They are similar to the "no response" drips, observed by Tooth and Fairchild (2003).

However, in the Velika Pasica Cave after intensive rain (> 10 mm/h), temporary jets of water can be observed with short life-time (< 24 hours) (Brancelj, pers. observ.) and were not included in the present the study. Their presence indicated intensive subcutaneous flow with little water storage and they were positioned close to VP1 and VP3. They might act as "spill-over channels", connected with both main drips and are activated only during excess events, when the water level within the perched aquifer is temporary raised.

Thus, within the same cave, different epikarst structure has determined the variety of recharge systems and routes, shown as the visible difference in cave drip dynamic discharge and indirectly some information can be obtained on dimensions of voids and fractures within the rock block above the cave.

5.2 The assessment of the storage capability of the epikarst zone

5.2.1 Comparison of different recession analyses methods

In order to describe the storage and structure of epikarst zone, four cave drips were applied for recession analyses. According to previous studies, the most important impacts on the recession rate are the geological characteristics and climatic conditions (Tallaksen, 1989, 1995), which are also proved by the drip responses. The climatic conditions especially affected drip site VP2, and the dry weather was one of the important factors which affected the appearance of the recession segments (Nathan and McMahon, 1990). The rainfall pattern was another obvious factor that controlled the discharge of VP2 (Tallaksen, 1995; Liu and Brancelj, 2011).

According to the Equations 3-2 and 3-4, the recession constant *k* is a crucial parameter. However, determining the constant *k* accurately and objectively is not an easy task. Plotting each recession segment on a semi-logarithmic axis, presented the recession processes intuitively. However, the *k* varied significantly from different events, on account of variations on storage, evaporation loss, recharge rates, etc. (Nathan and McMathon, 1990). Thus, the average recession coefficient was obtained from each individual event, which represented the average storage properties of the epikarst reservoir.

In order to reduce the uncertainty, two most common master recession curves were also applied: the matching strip and the correlation method, which were defined as an envelope of various individual recession curves. Following the understanding of Nathan and McMahon (1990) on the master recession curves for an average characterization of base flow response, they represent the lowest flow integrated from the individual events. However, both strongly rely on visual determination from the graph plots, which results in an imprecise analysis. The results from the matching strip method showed that the line was not straightforward. Moreover, when the flow rate was low, the points stepped out the line (Figure 4-7), this result was also found by Kottegoda et al. (2000). Determining the best fit line on correlation plots was difficult. In order to determine which of the techniques yielded results more representatively of recession behaviour, Quinines et al. (1984) introduced the average Q90 flow duration. Nathan and McMathon (1990) drew the correlations between the results of two methods and the base flow index and the Q_{90}/Q_{50} ratio (the 90 % flow duration value and the 50 % flow duration value), which indicated the matching strip method performed more usefully for the prediction of low-flow characteristics.

As the results shown in Table 4-2, in combination with the hydrological properties of four drips, VP1 had a large and rapid discharge, as Amit et al. (2002) declared it had larger a (Equation 3-2) for the fast flow, namely the recession constant k should be smaller. In contrast, VP2 should have larger k. It is constant with the average values from the individual analysis and the matching strip analysis. Though these analyses had some difference, they showed the same trend between different drips. According to the definition and the charting processes for the matching strip curve, the representation is closer to the slow flow in the epikarst. The results of the correlation analysis were close to the matching strip analysis for VP2 and VP4, which represented the slow flow drips. But significant difference was apparent at VP1 and VP3, where the data contained some fast flow components.

5.2.2 The division of the flow sections

While applied to graph making, according to the Boussinesq exponent equation, the recessions should be a straight line on the semi-logarithmic graph, and its slope is the recession constant. However, the recession curves are not always straight lines, thus the different straight-line segments represented the different components. Accordingly, Amit et al. (2002) fitted the recession curve of spring water by two exponential terms, corresponding to the fast flow and base flow. As presented in Figure 4-10, the recession curve of VP1 could be divided into three components: fast flow, intermediate flow and slow flow.

At the beginning of the recession, the various aqueous voids commenced to discharge, both from the conduit system and the fissure system. The larger channels collect water from the smaller ones, and then concentrate the water volume to discharge. However, the fast flow in the conduits lasts a short period, and after that, when the water in bigger conduits diminishes, the smaller channels (the secondary voids) control the discharge ratio. Thus, the recession processes could be divided into several segments, controlled by the epikarst structure. Each period is accompanied with certain water movement patterns with an average *k*. However, as the discharge deceased successively, it is hard to divide different flows with a determined line. Instead, an average value *k* for a certain period could be determined. Hence, trial and error cannot be avoided in order to find the best fit of the line.

Thus it could be concluded that the structure of the epikarst controls the discharge processes. In VP1, the conduits dominate, while the fissures are the main media for VP2 and VP4, and VP3 is in an intermediate state. Although, occassionally the fast flow also occurs at VP2 and VP4. Differring from flow in the conduits, the fast flow in fissures occurs after the fullfilled piston effect (Genty and Deflandre, 1998; Tooth and Fairchild, 2003). However, the slow flow, wherever it is, mainly discharges from the fissures. The conduits in the epikarst accelerate the slow flow discharge, which consequently shortten the water flow in the fissures as indicated in Table 4-3 by the average recession coefficient *k* of the slow flow, this increased between the drips (0.9900 (VP1) $<$ 0.9913 (VP3) $<$ 0.9939 (VP2) $<$ 0.9952 (VP4).

In summary, regardless of the location, the recession coeffcients for the fast flow in the epikarst at the Velika Pasica Cave varied from 0.8201 to 0.9601, the intermediate flows were from 0.9518 to 0.9882, and the slow flow rates were from 0.9831 to 0.9984. Thus, these ranges provided a reference for the water discharge pattern from the epikarst.

5.2.3 The storage volume of the drip water

According to the method of the drip water storage calculation (Equations 3-8, 3-9, 3-10 and 3-11), which was based on the recession constant *k* for different types of discharge, the volume of stored water could be calculated. For each component of the recession segment, the discharge volumes and the volume of water retained in the reservoir is a function of its specific recession coefficient, the integration of this function corresponds to the storage of each segment. Each segment of discharge with specific *k* could be considered as the storage from different storing voids in the epikarst, i.e. the discharge volumes relies on the profiles of local epikarst structure. In order to accurately assess the epikarst storage, it is of critical importance to consider the selection of an appropriate recession event (or the approach to eliminate the irregular points, e.g. the points affected by extra rain events), the selection of an appropriate demarcation point between each segment and the accuracy of the function fitting in each segment.

5.3 The hydrochemical response of cave drip waters to seasonal climatic variability

5.3.1 The impact factors on the cave drip water hydrochemical variation

Liu et al. (2004, 2007) and Kogovšek (2010) directly measured the continuous electrical conductivity, according to the strong correlation between the EC and dissolved ions, and the EC was applied to estimate calcium, magnesium and bicarbonate concentrations. Furthermore, it was even used to determine continuous variations in carbon dioxide and calcite/dolomite saturation levels. That means EC could directly represent the variation of the main ions in drip water, e.g. Ca^{2+}, Mg^{2+} and HCO_3^-, which could be used for further calculation e.g. SI calcite or SI dolomite even the PCO2.

Several factors can affect the hydrochemical profile of the cave drip water, and they may act independently or in synergy (Verheyden et al. 2000; Baldini et al. 2006). Temperature acts as an important factor for mineral weathering, but concurrently, it also indicates that the "vegetation effect" (the impact of local surface flora) could be an important reason for chemical change. Ca^{2+} and Mg^{2+} ions are mainly from the dissolution of parent rock and their concentrations are closely connected with pCO_2. Thus, seasonal climatic change influences the vegetation growth and (micro) biological activity in the soil, which controls the production of soil CO_2 and the intensification of karst processes (Liu et al., 2004, 2007).

In comparing the drips, the variation patterns of Ca^{2+} and Mg^{2+} ions in the Velika Pasica Cave were different. Frequently, the concentration of Ca^{2+} was higher than Mg^{2+} at the sites of VP1 and VP3, while at the other two sites, it was the opposite. At VP4, the concentration of Mg^{2+} was several times higher than Ca^{2+} ions, and also much higher than in other drips, which came from the .

The parent rock of research area is mainly dolomite (Pleničar, 1970), however, the mineral composition locally may not be pure dolomite. The corrosion processes of dolomite rock behave similarly to limestone. The dissolution of dolomite could be written as Equation 5-1:

$$2CO_{2(g)} + 2H_2O + CaMg(CO_3)_2 \leftrightarrow Ca^{2+} + Mg^{2+} + 4HCO_3^- \quad (5\text{-}1)$$

Groundwater in a mono-mineralic dolomite aquifer should ideally contain an equal amount of Ca^{2+} and Mg^{2+} while the bicarbonate concentration should be four times the Ca^{2+} and Mg^{2+} concentrations (Appelo and Postma, 2005). From the results of the drip water hydrochemical analyses, the aquifer rocks may contain both calcite and dolomite with different percentages.

Namely, the processes of calcite dissolution also occur as in the Equation 5-2:

$$CO_{2(g)} + H_2O + CaCO_3 \leftrightarrow Ca^{2+} + 2HCO_3^- \quad (5\text{-}2)$$

Additionally, different hydrological interactions also lead to characteristic changes in water chemistry, especially at both low and high discharge rates, which are connected to the different resident time of the infiltrated rain water that is stored at different locations (see sections 4.1 and 5.1). The fast response drips have a short residence time or consist of mixed water (fresh and stored water) and the water may be sub-saturated for $CaCO_3$, while the slow flow drips represents a longer resident time, and the water is more likely to have precipitated $CaCO_3$ along its flow path. This prior calcite precipitation (Fairchild et al., 2000; Baker and Fairchild, 2012) leads to enhanced Mg/Ca ratio in the drip water, as Mg^{2+} is excluded relatively to Ca^{2+} during calcite precipitation. This value will undoubtedly vary from site to site, depending on drip water flow rate, residence time, pCO_2 differential between drip water and cave air, and availability of low pCO_2 in void spaces in the vadose zone above the cave (Sherwin and Baldini, 2011).

Essentially, the driver for calcite precipitation is the CO_2 difference between soil/upper epikarst and the cave system (Fairchild and McMillan, 2007). Prior calcite precipitation is enhanced by two processes: the falls of CO_2 partial pressure in the cave air, and low water flows. Patterns both of winter depletion in cave air pCO_2 (Bourges et al., 2001) and summer depletion (Hoyos et al., 1998) can occur. The controlling factors include potentially increased winter ventilation (Spötl et al., 2005) sometimes related to thermal convective instability (Bourges et al., 2006), pCO_2 of the water bearing fissures from the epikarst, and temperature and rainfall controls on soil pCO_2 (Fairchild et al., 2006). Seasonally low flows leading to enhanced degassing into air will tend to be during summer in Mediterranean climates. This may work either together with or in the opposite sense to the pCO_2 effect. Much more cave monitoring is needed in order to more fully understand these phenomena (Fairchild and McMillan, 2007).

The unusual high concentration of Mg^{2+} (Figure 4-13) and SO_4^{2-} ions (Figure 4-14) appeared in site VP4. According to the interview of the farmers near-by, their origin was probably from the construction waste material (plaster), which was deposited just above the cave, near the drip VP4. .

5.3.2 The hydrochemical response of cave drip waters to different rain patterns

5.3.2.1 Different response of EC to different rain types

In the Velika Pasica Cave, the hydrological profiles of different drips suggested that VP1 showed the greatest sensitivity to respond to surface weather change, which also correlated with the fast flow, while VP2 indicated seepage flow through the epikarst. In some dry periods, only VP1 showed a response to the rain events, but the VP2 only had limited response after the diffusion events. Thus, both drips were selected in order to analyse and compare the water chemistry. The EC of VP1 expressed characteristic responses to two different rainfall patterns. During the concentrated rainfall period, the discharge had the peak value after the intensive rainfall, meanwhile the EC had a quick fall (Figure 4-18) in response to the dilution effect (Baldini et al., 2006; McDonald and Drysdale, 2007). After the peak flow, the water flow declined. The water in the epikarst with a high CO_2 content, leaching from the soil layer, reacted efficiently with the bedrock. This resulted in the steep rise in EC as a consequence of dissolution of the major ions. However, the hot, dry weather resulted in the extensive evaporation of the shallow epikarst water which aggravated the flow decline. Without a further fresh water supply input, the CO_2 of the water in the epikarst was depleted quickly, which was represented by the declining EC. The EC of the drip water had a gentle decrease until the drip ceased. The phenomenon is explained as the process of slow flow dissolution. During this dry condition, without sufficient water supplement, the CO_2 affect was one of the controlling impacts on the hydrochemistry of the karst water, similarly discussed by Zhang et al. (2011) from an epikarst spring in Chongqing, China. This situation lasted until the rain event as observed in VP1-OCT2, when the temperature dropped and the rain pattern altered.

The events after VP1-OCT2 (Figure 4-18) were characterised as diffuse rainfall, starting gently and lasting much longer. With this rain patterns, the discharge never ceased. When the rainfall commenced, the drip water was mainly supplied by the conduit flow, which had fast response to the rainfall (Liu and Brancelj, 2011). When the fast flow ceased, the fracture-net became the major source for the drip water. The infiltrated water had slow access to an extended rock surface and reacted efficiently there, resulting in the sharp EC increase. The flow continued to slow down, but it remained at a detectable level. As a result, the EC stayed at a stable value, as the CO_2 can be supplied sufficiently and continuously, and it had enough time to reach the dissolution equilibrium. Since the fractures were already filled with water, when the second storm occurred, the rain water affected the drip water more quickly and directly. This happened similarly in VP1-DEC (Figure 4-18).

However, the dilution effect was less functional in VP2, and the piston effect was principal here (Tooth and Fairchild, 2003; Frenández-Cortès et al., 2008). The highest EC was relevant to the main discharge, which represented the upper 'new' water pushing the 'old' water slowly downward to discharge.

In summary, the comparison of the hydrochemical profiles of different drips represented the dual-medium vadose structure of epikarst (Atkinson, 1977; Liedl et al., 2003). It is not hard to find that at least two key processes were controlling hydrochemical variations: (i) the retention time of epikarst water and (ii) the gas-water-rock interactions (CO_2). The former mainly corresponds to the speed of water flow, while the later predominantly relied on the dissolve ability.

Over the measurement period, the EC decreased gradually from August to December, and the range in the EC variation became less (Table 4-8). The pCO_2 showed a similar depression which indicated the important role of the CO_2 partial pressure in relationship to EC. The CO_2 partial pressure was mainly controlled by the influence of seasonal climatic change on the vegetation growth and soil micro-biological activity, which controlled the intensity of karst processes (Yang et al., 2012).

5.3.2.2 The Mg/Ca ratio

Ca^{2+} and Mg^{2+} ions have a similar variation to the Mg/Ca ratio, but do not correlate exactly to other caves (Baldini et al., 2006; Fairchild et al., 2006). Several factors can affect the cation concentrations in the cave drip water, and these may act independently or in synergy (Verheyden et al., 2000). Different types of rain patterns and the structure of the epikarst were the significant factors for the variation in the Mg/Ca ratio (Figure 4-19), which resulted in different patterns of epikarst water flow (Liu and Brancelj, 2011).

At VP1, during the concentrated rainfall period, when the fast flow arrived, it did not have sufficient time to react with the surrounding rock in the epikarst zone. Later, when the slow flow began to prevail, the water could flow much longer within the matrix and react more efficiently. Prior Calcite Precipitation (PCP) along the flow path resulted in the decrease of Ca^{2+} ions, and the increase of Mg/Ca ratio at the end of each rain event (Huang et al., 2001; Tooth and Fairchild, 2003). During the diffuse rainfall period, with a frequent rain water supplement, the drip water kept a detectable water flow, which was replaced continuously, thus the PCP could rarely be applied, as indicated by the low but stable Mg/Ca ratio. However, from the variation in VP2, the slow water responded as a piston, which resulted in a higher Mg/Ca ratio. Thus, the Mg/Ca ratio in the drip water is affected significantly by the retention time in the epikarst/vadose zone.

5.3.3 Hydrochemical response of cave drip water to snowmelt water

High heterogeneous, complex structure and void topology in the epikarst reflects the large number of parameters for variability and uncertainty in analysing the complicated hydraulic, mechanical, thermal, and chemical processes (Fairchild and Baker, 2012). A study of a small discharge point from the epikarst could provide the details of local variation. Test-site Sinji Vrh, a shallow artificial tunnel, located at in the western part of Slovenia was used to study the water flow and solute transport in the unsaturated zone (Trček, 2005). In this study, the Velika Pasica Cave, a small cave, located in the thick dolomitized epikarst zone, acted as a natural discharge point for epikarst flow water hydrochemical and hydrological research.

In order to further simplify the impact factors on the epikarst processes, the study period was chosen at the end of a long, cold and wet winter. During this time, there were two sources for water replenishment to the drip water: snowmelt water and precipitation. The day time heat melted the surface snow cover, and the rainfall accelerated the melting. Thereafter, both converged and percolated down together, thus the two floods in the drip water discharge represented the Superimposition of these two signals. Additionally, when the rainfall ceased, the drip water discharge mainly represented the snow melt combined with the epikarst storage.

In order to achieve a better understanding of various karst processes, variations in the concentration of ions should be studied with other hydrochemical parameters (McDonald et al., 2007). During the specific study period, the low temperature and high humidity, accompanying the continental wet winter, weakened evaporation at the site. Meanwhile, due to this environmental condition, the respiration of the bio-activities from plant roots and soil microbes was weakened, as indicated by the CO_2 partial pressure in the drip water (pCO_2) with low value (mean = -3.00) and low variation (CV = 1 %) (Table 4-9), although the CO_2 was the main driving force for the dissolution and precipitation of carbonate (Atkin et al., 2000; Liu et al., 2007), and the pCO_2 is generally higher in summer (Atkin et al., 2000). Liu et al. (2007) represented the yearly cyclical variation of those parameters which were higher in summer and lower in winter. Additionally, the entrance was the only detected outlet for the Velika Pasica Cave, thus the CO_2 exchanging from ventilation was insignificant here, which differs from situations in other caves (Fairchild et al., 2000;

Tooth and Fairchild, 2003; Spötl et al., 2005).

The water percolated into the cave acted as a primary driving force for most variations recorded during the winter in the cave, in particular, for the cave water hydrochemical composition (Figure 4-20). Electrical conductivity was an indicator of the amount of ions in solution. According to the analyses, Ca^{2+}, Mg^{2+} and HCO_3^- ions were the dominant ions in drip water. The variation in EC was highly negatively related to the discharge as well as the dominant ions (Figure 4-21, Table 4-10). Electrical conductivity normally decreased after rainfall, and showed inverse variation with the discharge. The strong correlation between the EC and discharge indicated that the intensity of the floods mainly controlled the hydrochemical variation by mixing fresh water with old water (i.e. the water stored in epikarst), which differed from the summer-time situation (Liu et al., 2007), as other factors also have significant impact during that season. Due to the dual-medium systems within the epikarst (Akinson et al., 1977; Liedl et al., 2003), which are characteristic for the widespread fracture-net storage system and the well-developed fracture-net rapid discharge system (conduits), the intensive recharge could be discharged rapidly as considerably diluted drip water (Fairchild et al., 2000; Baldini et al., 2006; Fairchild and Baker, 2012). The two different intensive flood events described here clearly indicated that the degree of dilution or mixing relied on the amount of recharge and the higher discharge correlates with the lower ion concentration (Figure 4-22). When the fast flow ceased, the stored water (old water) was dominate in the discharge, which corresponded with the increase of EC and the dominant ions concentration.

Fairchild et al. (2000) and Baker et al. (2000) discussed water / soil and water / rock contact times, variable degrees of dilution and the PCP in the vadose zone also controlled the calcium dissolution processes, as well as the replenishment from multiple reservoirs (McDonald et al., 2007). However, in this case study, Ca^{2+} and Mg^{2+} ions have a similar variation to the Mg/Ca ratio (Figures 4-21 and 4-22), indicated by the high correlation coefficients (Table 4-10), which does not exactly correlate with other caves (Baldini et al., 2006; Fairchild et al., 2006). Within recent years, the ratio of Mg/Ca in cave drip waters has acted as a good indicator of the climatic condition (Huang et al., 2001). The ratio in the Velika Pasica Cave was quite stable at 0.75, almost as a constant (with CV = 3%), which indicates that the parent rock was not pure dolomite and both ions were not precipitated after they dissolved, such as the PCP. In the discussion above, the low pCO_2 resulted in the low carbonate dissolution and the wet weather continued to replenish the stored water with the fresh water. Thus, the resident time of stored water might not be long enough in order to accumulate a high Ca^{2+} ions concentration for PCP at the drip VP1 in a simple recharge system.

Apart of Ca^{2+} and Mg^{2+} ions, other dissolved ions also play an important role in the studies on mixing processes of drip water in the unsaturated zone above the cave (Huang et al. 2001; Tooth and Fairchild 2003; Fairchild et al. 2006). However, with the exception of SO_4^{2-} ions in VP4, most of the minor ions had relatively lower concentrations (Table 4-9) and lower correlation with the discharge (Table 4-10), which means they were not significantly affected by the percolation events. The origin of the rather high concentration of SO_4^{2-} ions might be from the dissolution of gypsum ($CaSO_4$) in the parent rock or anthropogenic impacts, such as the construction waste material from nearby houses.

The temperature of the drip water represented high correlation and consistency with the discharge (Table 4-10), which also indicated the short resident time of the water. On the other hand, the temperature of the drip water could act as a good tracer for the epikarst flow (Anderson, 2005).

5.4 The thermal system of the Velika Pasica Cave

5.4.1 The thermal characteristics in the cave

Cave temperature is generally directly connected with the external climate (Badino, 2004), especially within shallow caves. In the Velika Pasica Cave, the average thickness of the ceiling above the cave is 10 - 12 m (Brancelj, 2002). This resulted in a quick and intensive reaction of cave meteorology to the external conditions.

Actually, there was a time difference in the variation trend between the external and internal cave conditions. These lags were a result of heat conduction which determined the thermal condition within the cave system (Covington et al., 2011). As shown in Figure 4-24, when the surface temperature dropped lower than the temperature of the inner cave, the internal temperature still kept rising for a while. On the contrary, when the surface temperature increased higher than the temperature of the inner cave, the internal temperature had certain time to decrease to its lowest point. It could be explained as: the mass of the epikarst has an ability to store some heat (Figure 5-2). When the surface was warmer than both the epikarst and the interior of the cave, heat was transferred down through the epikarst into the cave (Figure 5-2, I). When the surface cooled down, even when the external surface was colder than the interior, and the epikarst was still warmer than the cave, it maintained heat transferred into the cave (Figure 5-2, II). The direction of heat conduction could not change, until the matrix cooled down and became colder than the cave interior (Figure5-2, III). When the surface became warmer again, the matrix could retain absorbed heat from both the surface and the deeper ground until it was warmer than the cave (Figure 5-2, VI). This shows that the direction of heat conduction was, therefore, driven by the temperature difference between the surface, epikarst and the cave system.

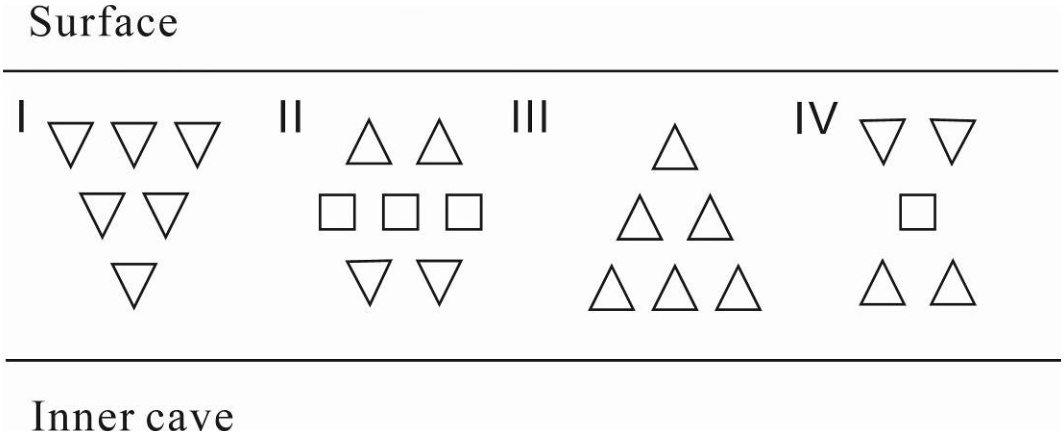

Figure 5-2: A schematic diagram of the process of the annual heat conduction though the epikarst in the cave. The top row of triangles indicate the direction of the heat transference, the square represent the stored heat. I: the period when surface is warmer than inner cave, is generally in summer time; II: the period when surface is cooling down, but epikarst is still warm, indicates autumn time; III: the period when the inner cave is warmer than surface, is the winter time; IV: the period when surface is warming up and the coldest time of epikarst, represents the spring time.

The different temperature variation between two sections of the cave was mainly due to the convective airflows. The convective airflow also was a significant impact on the cave temperature changes (Wefer, 1994). In the Velika Pasica Cave, the entrance passage slopes downward into the cave. During winter, cold air can flow in along the floor of the cave while lighter and warmer air escapes out of the cave along the ceiling toward the entrance. In summer, the surface hot air inflow is difficult, thus the air temperature in the cave during summer was mainly controlled by conduction. In contrast, the inner section represented a relatively close system and had less impact from outside. Therefore, it also was mainly controlled by the heat conduction, which presented as slighter and smoother oscillations in temperature variation compared with the outer section during the summer time. For that reason the inner chamber was insulated as the passage between them was constricted and prevented convective flows sufficiently.

5.4.2 The response of the water temperature to rain event

The cave temperature principally followed the general trend in surface climate. At the same time the rain events were also an important parameter which briefly impacted on the temperature balance inside the cave. The fast flow, which ran quickly, did not exchange heat adequately within the soil and the epikarstic zone. It was reflected in the apparent temperature peaks during the rain events. Difference in the temperature of the drip water depends on difference between surface and cave temperature and discharge, namely the higher volumetric discharge, the larger differences. When the rain ceased, and the drip flow slowed down, the drip water, air, and rock surrounding the cave chambers gained equilibrium. Cronaton et al. (2002) and Liedl et al. (2003) described this feature as a result of the dual media system. Although the air temperature was more stable than the percolating water, when larger rain events occurred, there was sufficient flow of water into the drips to transfer some of the external heat, which can have an influence on the air temperature in the cave (Figure 4-23). Thus, heat also could be the tracer for the hydrodynamic of ground flow.

5.5 Epikarst environment impacts on the aquatic ecosystem in cave drips

Epikarst is interesting not only for karst hydrologists but also for biologists. Approximately forty years ago the first aquatic fauna inhabiting the epikarst were discovered in France (Rouch, 1968). More intensive and systematic study of epikarst fauna started in the past decade, and most of this research focused on the diversity of copepods, both in North America (Pipan 2004; Pipan and Culver, 2005) and Europe (especially in Slovenia) (Brancelj, 2000, 2002; Brancelj and Pipan, 2004; Pipan and Brancelj, 2001, 2003, 2004a, 2004b; Pipan, 2003, 2005; Pipan et al., 2006). Recently, it was found that copepods were also located in many places world-wide (Brazil, USA, Thailand) (Brancelj et al., 2010). Global distribution of these crustaceans has resulted from the largest and most diversified copepod populations identified in the karst environment (Pipan and Brancelj, 2004a). Studies were conducted particularly in the cave systems of North America, Europe and Australia (Culver and Sket, 2000; Brancelj, 2002; Pesce et al., 2004; Pipan, 2005; Camacho et al., 2006; Meleg et al., 2011).

Brancelj (2002) discussed the aquatic crustaceans from the pool in the Velika Pasica Cave. In this case study, the supplementary discussion on the cave drip water was presented here. Table 4-12 indicated the abundance of various species at the four drips.

Although the cave region was quite small, and the cave only had a126 m long horizontal gallery, the community composition was quite distinctive between each site, represented by either the majority or minority species.

Where do they come from and why do they distribute unevenly? Pipan and Culver (2007) stated the local species distribution in the epikarst habitats was considered as colonization by surface-dwelling ancestors, which is still rarely known, and Reid (2001) thought that they probably invaded from above, especially from the soil, as well as superficial aquatic habitats such as wet leaves. In any case, epikarst habitats were possibly colonized at a single site (Pipan and Culver, 2007). However, the structure of the epikarst was extraordinarily complex and heterogeneous (Pipan and Brancelj, 2004b). Therefore, some specific species only appeared on a local scale at a single site, such as *P. nolli alpina* at VP1, *E. tamani* at VP3, *M. varica* at VP4. In particular, *M. varica* at VP4, was not observed there until the summer of 2009 (Appendix I), and has most probably colonized the cave recently.

But why could some other species inhabit different sites at the same time? Pipan and Culver (2007) interpreted this with the lateral movement of water in the epikarst. Smart and Friedrich (1987) found their fluorescent dyes travelled a lateral distance of 80 m in 6 days, Kogovšek and Šebela (2004) proved this lateral water movement in the Postojnska Jama Cave (Slovenia) through a dye trace experiment and Aley (2004) also report it in Tumbling Creek Cave, Missouri, USA. Thus, in the epikarst, there is a potential lateral hydraulic connection. Therefore, these species could travel laterally with the permanent or temporary water connections.

Currently, another question comes naturally, why could only some species travel with the water flow, while some others do not? Pipan and Culver (2007) suggested the movement of copepods in water flow as comparable to mineral particles. According to the Hjulstrom curves (Gordon et al., 1999), the mobilization of the copepods was dramatically affected by their size and the water flow velocity. Intermediate-sized particles between 0.3 to 0.6 mm are the easiest to mobilize at the velocity slightly greater than 0.1 m/s. Body size of the adult copepods ranges from 0.2 to 2 mm, and not all crustaceans could mobilize easily. In addition, contrary to the mineralised particles, copepods can swim in the water, which means some of them select their optimum habitat niche (Brancelj, pers. comm.).

In the Velika Pasica Cave, some species only occasionally appeared in several drips, such as *P. viguieri* and *N. stygius*, or at a single site, such as *E. tarmani* and *P. nolli alpina* (Table 4-12). But it is probably not the result of the hydraulic connection between different drips, for example, the *N. stygius* at VP1 and VP4, which are hard to connect with each other (Figure 3-2). It is probably that these species may be occasional in the epikarst (Pipan and Culver, 2007). Thus, lateral connection had limited use in interpreting the various species distribution.

Following species colonization, a crucial factor is their adaptation and survival in the new habitat. Their adaptation and survival also relates to the population size, gene pool, species richness and intra- and interspecific interactions. Brancelj (2002) discussed the relationship between the composition and abundance of copepods and five environmental parameters: volume of water body, type of watering, the amount of organic matter, persistence of water body in parallel with the amount of clay. Pipan et al. (2006) found the NO_3^- ions and the ceiling thickness were the most important environmental parameters for the fauna in caves after investigating five caves in Slovenia. Meleg et al. (2011) reached similar conclusion for epikarst communities in Romania using pH, temperature, conductivity and precipitation as predictor variables. Moldovan et al. (2012) even combined stable isotopes, drip rate with species composition and abundance in Peştera Ciur Izbuc, Romania, however they found the increase of the number of individuals was generally not correlated with the higher drip rates at the same station.

In order to find the connections between individual species from the drip water and environmental parameters in the Velika Pasica Cave, two groups of parameters were considered: a) the hydrological parameters, i.e. the days between two consecutive samplings (days), the amount of drip water discharge (Q), the maximum discharge during the sampling period (Max), the mean discharge (Mean), the coefficient of the discharge variation (CV) and the mean drip water temperature (Temp); (b) the hydrochemical parameters, i.e. pH, electrical conductivity (EC), and the main ions (Ca^{2+}, Mg^{2+},K^{+}, Na^{+}, Cl^{-}, NO_3^{-}, SO_4^{2-}, and HCO_3^{-}). Species diversity is difficult to assess in that it is hard to collect and identify all the species present (Chao et al., 2005), in particular the rare representatives of aquatic assemblages in the vadose zone (Meleg et al., 2011). Species richness is the simplest and most frequently used parameter for assessing community diversity (Chao, 2005). Most analyses here were based on species richness and relative abundances.

The hydrological characters of the drips in the Velika Pasica Cave are different. The drip VP1 was characterized as "rapid response without time lag", which discharged rapidly with large quantity of water as soon as the recharge events (rain or snowmelt) started. The maximum and the amount of the discharge acted as the most important parameters, as analysed by CCA (Figure 4-28). The Spearman's rank correlation coefficient supported this result. However, of the species sampled in VP1, only *P. albicans* had a high correlation with the amount of discharge, the mean discharge, and the maximum discharge (Table 4-16). In site VP2, responding to the feature of "no response with congest discharge", the hydrological parameters were even more crucial, as the species, as: *M. dumonti* and *S. infernus*, were highly correlated with Q, Max and Mean. However, another common species, *B. typhlops*, was affected strongly by the Temp. As a site-specific species at VP2 (but rare at other sites), it also was indicated in the CCA (Figure 4-29). The hydrological characters of VP3 were close to VP1, "fast response with lag", which also had considerable discharge. However, only *E. millennii* preformed higher correlation coefficient with the Q (Table 4-16). As far as the specific fauna composition at the single drip scale was not achievable by CCA, I can observe that this drip site enters the "rapid response with congest discharge" typology, with similar amount of discharge of VP2. The specific species, *M. varica* was less sensitive to the amount of discharge, more related to variation of the discharge (Table 4-16).

The hydrochemical characteristics of four drips affected the species assemblages significantly. The major species at site VP1, *P. albicans* was negatively correlated with Cl^- ions and *S. infernus* was also negatively correlated with K^+ ions. At the site VP2, one of the most common species, *B. typhlops* was more significantly affected by Mg^{2+} and HCO_3^- ions. At VP3, *B. pyrenaicus* was positively correlated with Mg^{2+} ions more significantly. The specific fauna, *M. varica*, was highly and significantly negative in correlation to NO_3^- and SO_4^{2-} ions at VP4.

After these individual analyses of the species with different hydrological and hydrochemical parameters by CCA, it was not hard to find that there are significant differences between the environmental parameters and species composition in the different drips. Some species were found in large volumes of water with a faster discharge rate, such as *P. albicans* at VP1, while others preferred low water flow, such as *M. dumonti* and *S. infernus* at VP2, as aspects discussed also by Moldovan et al. (2012). Apart from the water volumetric flows, water temperature was also a crucial variable for some species, such as *B. typhlops* at VP2 and it was considered by Pipan et al. (2006) and Meleg et al. (2011) in the caves in U.S.A. and Romania. The hydrochemical profiles of percolation water were also significant factors influencing faunal composition. The most obvious results were that *M. varica* was affected by NO_3^- and SO_4^{2-} ions at VP4, and *B. typhlops* was affected significantly by Mg^{2+} and HCO_3^- ions at VP2. While NO_3^- ions with high concentration at VP4 may result from the pollution (dung hill) from the surface, which may also be applied in order to interpret *M. varica*'s colonization during the middle of the research period. The species *B. typhlops* at VP2 kept higher correlation both with the hydrological and hydrochemical parameters, which indicated that the fauna composition and distribution in the epikarst was the result of the combined effects from various environmental factors. All the other species, which had lower correlation with these environmental parameters, may be affected by other factors which I have not considered as yet although a reason for the habitat occupation requires explanation.

Chapter 6 Conclusions and Recommendations

6.1 The summary of the drip water hydrology

The Velika Pasica Cave is a shallow karstic cave in dolomitized limestone. The hydrology is controlled by the continental climate in combination with the thin epikarst cover, overlaid by thin soil, resulting in the predominantly seasonal recharge of the cave drip waters.

This study produced a significant connection between hydrological and ecological research related to a unique epikarstic aquatic faunal assemblage discovered in the cave 14 years ago. Observations in this cave found that some of drips have a relatively low water storage capacity, but the vadose zone of each drips' catchment area never completely dry-out as confirmed by the permanent presence of aquatic fauna in the drips. Each drip has its own specific faunal composition, and it is possibly related with the localised hydrological conditions, e.g. the discharge patterns and intensity, especially size of voids. More details have been discussed in the ecohydrology section.

The discharge of some cave drip waters when studied on a fine scale (one-hour intervals) revealed close connection between the intensity of precipitation and discharge pattern / quantity which is influenced by vegetation cover, soil characteristics and geomorphologic structures in the geology above the cave. From the hydrodynamic response of the four drips to two different rain events, the structure of the invisible epikarst was partly revealed, which has determined habitats for the groundwater fauna.

In next section, the hydrochemical characters of the cave drip waters were studied combined with their hydrodynamic features. As the results, already indicated by preliminary measurements in the Velika Pasica Cave and previous studies on cave drip water chemistry, the retention time of precipitated water within soil and voids effects the water quality. Differences in water quality, quantity and dynamic are important ecological parameters for aquatic organisms, both microbes and multicellular organisms, also contributes to speleogenesis. Understanding hydrodynamic processes in the epikarst can contribute to research on some other interdisciplinary topics, for example, groundwater ecology and biodiversity.

6.2 The storage of each drip

The recession curve contains valuable information on storage properties and aquifer characteristics, such as porous, fractured, cracked lithologies. In order to understand and interpret more details on the storage properties and storing media in epikarst, the cave drips were monitored for the first time for the recession analysis. This analysis does not only explain some previous conclusions but also provides a quantitative reference for water flows in epikarst zone.

After comparing the individual recession segment analyses, the matching strip analyses and the correlation analyses, for the slow flow in epikarst, it was concluded that the matching strip method could represent it more appropriately. It is hard to give a determined line in order to divide the recession segment into different components; instead an average value k for a certain period could be applied.

Accordingly, VP1 commonly was divided into the fast flow, the intermediate flow and the slow flow, while the intermediate flow dominated in VP3, and VP2 and VP4 mainly run as the slow flow. The different flows also could infer the storing media of epikarst, meanwhile according to the Boussinesq's equation, the volume of water (the epikarst storage) retained in the reservoir could be understood as a function of its specific recession coefficient, meanwhile the different flows also could be applied to infer the storing media of epikarst, for that the discharge volumes relies on the ratio of voids in local epikarst.

6.3 The hydrochemical characters of the cave drip water

6.3.1 The possible impact factors on the cave hydrochemistry

According to the geology and the status of the hydrochemistry of the drips, I found that: A) the main aquifer is of carbonate formation, the main influential mineral could be dolomite ($CaMg(CO_3)_2$) and calcite ($CaCO_3$); B) the precipitation is the only source for the cave dripping water ; C) the cave is in the shallow underground which is the groundwater recharge region .

Thus, the evolution of the ground water should follow this pathway: when the precipitation recharges the ground water, it takes amounts of CO_2 from the surface and the soil layer where are high concentrations. While the CO_2 makes the water weakly acidic, it has certain dissolvability to the carbonate. At the beginning of the flow path, the concentration of HCO_3^-, Ca^{2+}, and Mg^{2+-} ions are increased, together with the TDS. But when the CO_2 expires, which is consumed along the flow path, the dissolution of the calcite can no longer continue, consequently, the concentration of HCO_3^- ions in the groundwater will be stabilized while the dolomite will continue to be dissolved.

6.3.2 The response of drip water hydrochemistry to rain patterns

The transformation from rain water to cave drip water occurs over a relatively short distance and within a short time span (several hours) with significant changes in ion content (three major ions: Ca^{2+}, Mg^{2+} and HCO_3^-) reflected in differences in EC. Because of the high correlation between these main ions and EC, the high resolution monitoring of hydrochemical variation could be conducted. From the discussion above, the different rain patterns occurred as concentrated rainfall and diffuse rainfall, were one of the principal impacts on the hydrochemical composition of the cave drip water, which corresponded to the seasonal variation from August to December at VP1. Induced by the different rain intensity and patterns, the time profile of the EC at VP1 had two characteristics: A) it had an obvious response to the dilution effect whenever intensive rainfall occurred; B) after the fast flow of the concentrated rain events, it had a process of slow flow dissolution, with decreased EC; while during the diffuse rain events, it can arrive at the dissolution equilibrium, rising to a stable EC. In comparison with VP2, due to the seepage flow, the high EC synchronized with the high discharge as piston driven. Meanwhile, Mg/Ca ratio in cave drip water showed a distinct pattern over time, affected by the prior calcite precipitation (PCP) effect and the retention time, which resulted from different rain patterns. As reflections of the complexity of the epikarst system, the impact factors on hydrochemical variation of the drip water were various, e.g. the temperature, the depth of surface soil layer and the structure of epikarst. The discussion here focused on the rain patterns but further discussion on other impacts, such as the temperature and the relative humidity, will conducted.

6.3.3 The response of drip water hydrochemistry to a snow melt event

In order to interpret accurately the geochemical processes during the snow melt period in the epikarst, high-frequency sampling and chemical monitoring on cave drip water was conducted at the Velika Pasica Cave (central Slovenia). As the common findings, the major qualitative transformation between rain and dripping water in relationship to chemical and physical properties occurred in a thin epikarst layer, which extends only a few meters in depth. The study period occurred at the end of a long, cold, wet winter. The main replenishment for the cave drip water was rain fall and snowmelt water. Under this special condition, some conclusions could be presented as: A) after a long cold and wet period, the water percolated into the cave performed as a primary driving force for water hydrochemical variations in the cave, and the fresh water mixed with the old water in epikarst and diluted it; B) the effect of CO_2 corrosion and PCP was weakened during this condition; C) the main ion composition (Mg^{2+} and Ca^{2+}) presented high correlation with Mg/Ca ratio and the drip water discharge, indicated the weakened PCP; D) the variation of low concentration ions had lower correlation with the discharge, as they did not strongly respond with the recharge event. On the contrary, the drip water temperature acted as a good tracer in short term (within a few hours).

The research revealed more detailed and accurate results from the high-frequency monitoring over a specific period, which confirmed and deepened the previous work on cave drip water. However, long-term monitoring should be continued for interpretation of the seasonal hydrochemical variation and climate change.

6.4 The thermal characters of the cave system

Caves in shallow carbonate terrains have air temperatures that mimic the mean annual temperature of the surrounding surface. Rock and soil cover acts as a thermal insulator and prevent significant temperature variations inside most shallow caves. Such thermal insulation also creates stable temperature variations in the Velika Pasica Cave. Temperature was principally controlled by conduction of heat by the overlying rock. Another important element in cave's climate was air convection, which was significant near entrance during the cold period of the year. The third element, which effected temperature conditions in the cave, was precipitation as drip water also acts as a thermal source for the cave. At the same time it could act as the tracer for hydrodynamic process of an underground flow in the epikarst.

6.5 The cave ecosystem characters

The epikarst fauna is particularly vulnerable due to the specific environmental characteristics of the epikarst. With the exception of detecting and identifying new species in the percolation water, interpreting their composition and distribution and indicating their relationship with environmental factors are also interesting and crucial ecological variables for the epikarst faunal research.

Various aquatic species (predominantly stygobionts) were found in the Velika Pasica Cave. The specific composition and distribution of species at different dripping sites was the result of the combined effects from various environmental factors. After the aquatic species had colonized, the quantity and quality of the water in epikarst is crucial in order for them to adapt and survive in the new habitat. According to the CCA of the species with different hydrological and hydrochemical parameters, it was found that there are significant differences from the environmental parameter impacts on the species composition at different drips, for example the maximum discharge and the amount of discharge affected significantly at VP1; water temperature and pH at VP2 and VP3 and the abnormal hydrochemical characters with high concentration of SO_4^{2-} and NO_3^- at VP4. While the distribution of these species was not only affected by these environmental parameters, other factors, such as the thickness of the cave ceiling also should be considered in future research.

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APPENDICES

Appendix I: The number of different species caught in different seasons in the Velika Pasica Cave (Slovenia) from 2006 to 2012. Legend to labels: VP1_06 = collected in 2006 at site VP1. With the exception of the Nipha_s. (*) and Pseud_a. (#), the remainder are Copepoda. Phylo_v: *Phylognathopus viguieri*; Bryoc_t: *Bryocamptus typhlops*; Bryoc_p: *Bryocamptus pyrenaicus*; Elaph_m: *Elaphoidella millennii*; Elaph_t: *Elaphoidella tarmani*; Morar_d: *Morariopsis dumonti*; Paras_n: *Parastenocaris nolli alpina*; Speoc_i: *Speocycops infernus*; Morar_p: *Moraria poppei*; Morar_v: *Moraria varica*; Nipha_s: *Niphargus stygius*; Pseud_a: *Pseudocandona albicans*.

	Phylo_v	Bryoc_t	Bryoc_p	Elaph_m	Elaph_t	Morar_d	Paras_n	Speoc_i	Morar_p	Morar_v	*Nipha_s	#Pseud_a
VP1_06	0	0	0	1	0	7	1	21	0	0	0	30
VP1_07	0	1	0	0	0	6	2	7	0	0	0	11
VP1_08	0	0	0	0	0	7	0	22	0	0	0	38
VP1_09	0	0	0	0	0	5	0	18	0	0	0	19
VP1_10	0	0	0	1	0	6	1	14	0	0	0	41
VP1_11	1	0	3	0	0	8	0	21	0	0	1	15
VP1_12	0	0	0	1	0	9	0	27	0	0	2	32
VP2_06	0	4	0	0	0	3	0	0	0	0	0	1
VP2_07	0	9	0	0	0	3	0	0	0	0	0	0
VP2_08	0	15	0	0	0	33	0	1	6	0	0	0
VP2_09	0	0	0	0	0	25	0	1	0	0	0	0
VP2_10	0	2	1	0	0	119	0	2	0	0	0	1
VP2_11	1	0	0	0	0	102	0	0	0	0	0	0
VP2_12	0	22	2	0	0	347	0	11	1	0	0	0
VP3_06	0	1	6	6	0	10	0	11	0	0	0	0
VP3_07	0	0	0	4	0	12	0	5	0	0	0	0
VP3_08	0	0	28	1	0	36	0	4	2	0	0	1
VP3_09	0	0	8	4	0	12	0	4	0	0	0	1
VP3_10	0	0	9	11	0	8	0	5	0	0	0	0
VP3_11	0	0	15	1	0	32	0	8	0	0	0	0
VP3_12	1	0	68	0	0	40	0	11	0	0	0	2
VP4_06	0	0	0	0	0	2	0	1	0	0	0	0

VP4_07	0	1	0	1	0	0	0	1	0	0	0	0
VP4_08	0	0	0	0	0	0	0	3	0	0	1	0
VP4_09	0	0	0	0	0	0	0	0	0	12	0	0
VP4_10	0	0	0	0	0	0	0	1	0	42	0	0
VP4_11	0	0	0	0	0	0	0	0	0	135	0	0
VP4_12	0	0	0	0	0	0	0	0	0	51	0	0