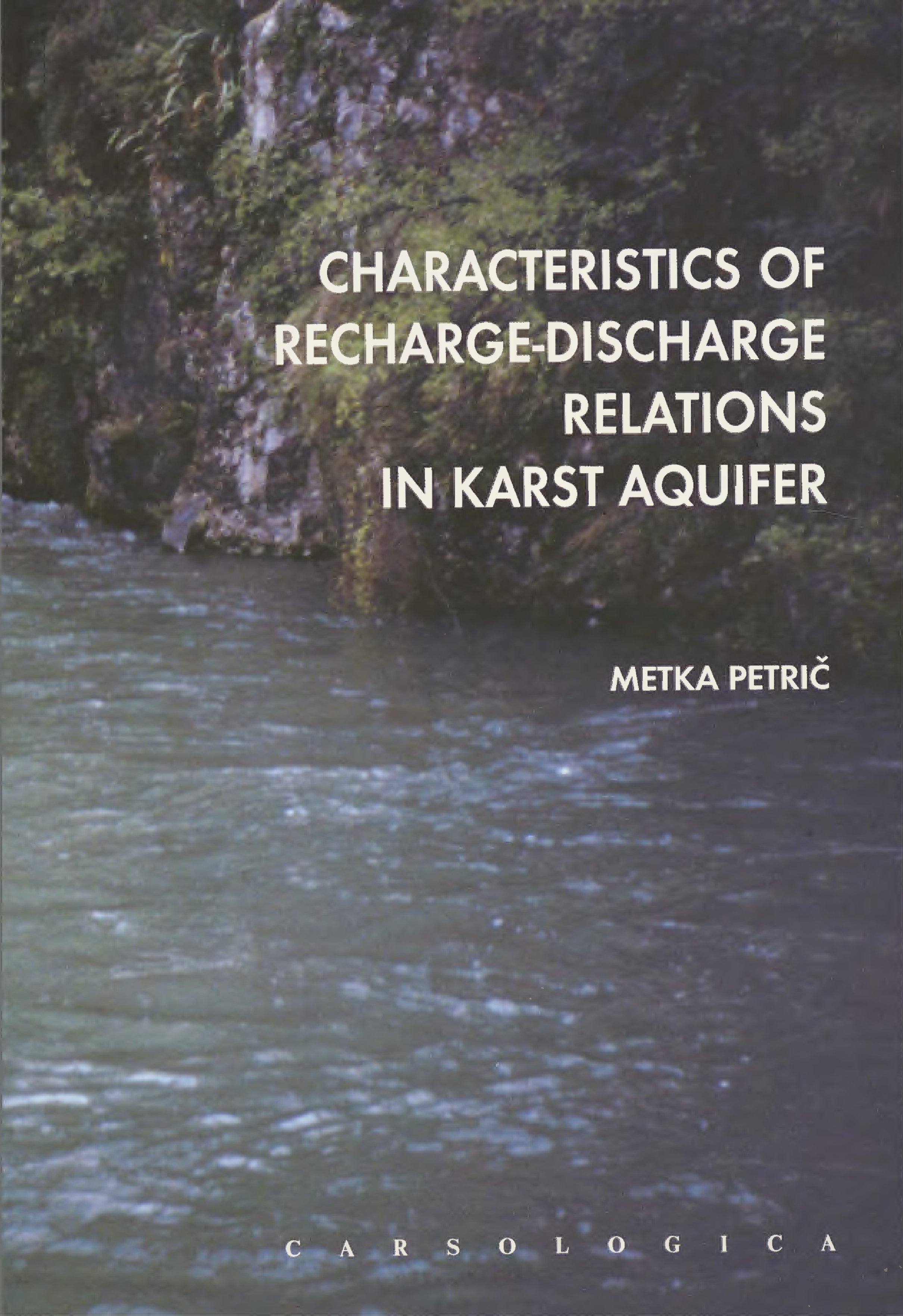
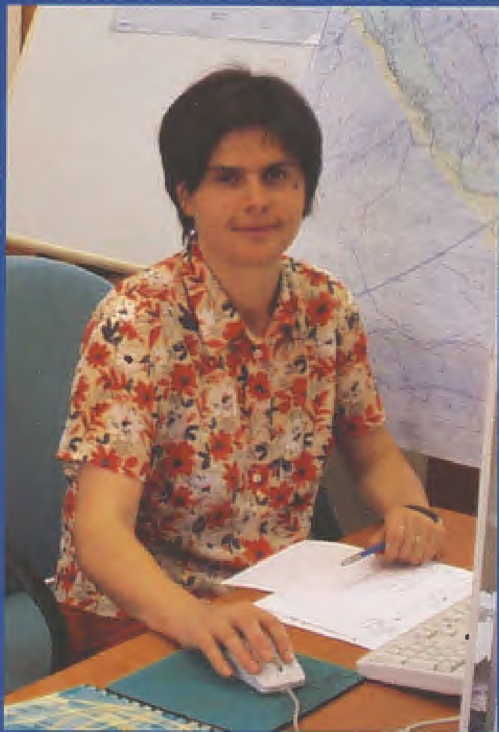


CHARACTERISTICS OF RECHARGE-DISCHARGE RELATIONS IN KARST AQUIFER

METKA PETRIČ

C A R S O L O G I C A



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In the field of karst hydrology she is studying the properties of groundwater flow and the relations between recharge and discharge of karst aquifers. An important part of her work are researches related to the water supply problems and the protection of karst waters against pollution. She is also involved in several international research projects.

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CHARACTERISTICS OF RECHARGE-DISCHARGE RELATIONS IN KARST AQUIFER

METKA PETRIČ

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CONTENTS

INTRODUCTION

Karst aquifers hide immense quantities of underground water and thus represent water resources of considerable importance. In order to preserve this natural treasure or to exploit it in a correct, sustainable manner, we have to plan its utilisation adequately and avert or at least limit eventual negative impacts. Yet, in implementing this, our efforts may prove effective only if we take into consideration all specific properties and peculiarities of karst aquifer systems. Due to their heterogeneous structure and complex functioning, identifying these characteristics is by no means an easy task. In a search for solutions, numerous research methods have been developed. Their reliability and applicability to selected areas depend on many factors, but each one of them signifies an additional step on our way towards better understanding of the forces and natural laws that govern the flow and storage of underground karst water.

Some of them were incorporated also in my research on the karst aquifer in the recharge area of Vipava springs in south-west Slovenia and this represents the main subject of the present book. This area, with its vitally important water resource, had already been subjected to investigations undertaken by numerous experts from various fields of knowledge for more than a hundred years. With presented study of characteristics of recharge-discharge relations I endeavoured to add some findings about hydrology of this area, as well as to contribute a tiny stone in the vast mosaic of our current knowledge of karst hydrological systems.

I completed the major part of my research already as a junior researcher within the framework of the Ministry of Science and Technology's programme under the mentorship of Dr Miran Veselič, to whom I would once again like to express many thanks for his help and valuable expert counsels. Many thanks also to Mr Boris Zupančič of the Environmental Agency of Slovenia, who enabled me to obtain the extensive base of meteorological data free of any charge. After concluding my doctoral studies I continued with my investigative scientific work at the selected polygon in the Vipava's recharge area within the framework of the research programme of the Karst Research Institute ZRC SAZU. I supplemented this work by participating in the European project STALAGMITE - Sustainable Management of Groundwater in Karstic Environments -, which is a part of the INCO-Copernicus programme. It enabled me to put to the test also some other investigative methods during collective work at the selected polygon with researchers from other countries. These international connections were further developed in the

course of the project »Partnerships in Science«, which was supported by the Ministry of Education, Science and Sport and the British Council.

The present book thus represents results of my research work, while at the same time it reflects also various experiences collected during collaboration with other researchers. First and foremost, I owe much gratitude to co-workers at the Karst Research Institute ZRC SAZU, who were not only offering the basis for the fruitful co-operation on various projects but were moreover providing a pleasant and supportive working atmosphere that promoted creativity. I would like to express my thanks also to the colleagues at my first professional appointment in the former Research Unit of the Idrija Mercury Mine, because their attitude to research work proved to be a valuable example that I attempted to adhere to also in the years that were to come. Especially to Dr Jože Čar, because it is also owing to him that my professional course has taken a direction to karst hydrology. Thanks to Dr Trevor R. Shaw for the revision of the English text.

CONCEPTUAL MODEL OF KARST AQUIFER

A karst aquifer system represents a formation with karst-fissured porosity and good permeability, which is surrounded with boundaries. These boundaries receive water and other incoming components and it is also through them that the transport of the output components of the system is carried out. The structure of the system incorporates the flow paths, along which water streams from the point where it enters the system until the place of the outflow from the system. All along these paths, however, various changes are taking place, which transform the incoming quantities into the output ones (Chow *et al.* 1988). In karst aquifer systems this structure proves to be fairly heterogeneous and the relations among individual parameters very complex. In our studying of their characteristics we are for this reason compelled to resort to certain simplifications. For the general, simplified demonstration of the system's functioning we use the so-called conceptual model (Fig. 1). It is composed of independent components - subsystems - , which are interrelated and act as a whole, yet we may study them also separately. We thus distinguish between the subsystems of surface flow and of underground flow. The subsystem of surface flow includes two input components. One of them is sinking streams, which represent the inflow of water from a non-karstic neighbouring environment and which, in contact with a karst area, sink underground as a point input into the karst system. The second occurs in the form of precipitation, which across all karst region infiltrates underground in a dispersed manner. The water that cannot percolate through the soil may flow on the surface as the surface runoff. Evapotranspiration is a collective term for all processes by which water in the liquid or solid phase at or near the land's surface becomes atmospheric water vapour (Dingman 1994).

The groundwater flow subsystem comprises unsaturated (vadose) and saturated (phreatic) zones. The soil represents the upper part of the unsaturated zone, within which the precipitation water may, dependent on the thickness and hydrological properties of the soil, get temporarily stored or just percolate down into the epikarst zone. Numerous investigations in the literature have demonstrated that epikarst plays a significant role as a control factor, which regulates the time-related distribution of the recharge. At higher waters the infiltrated precipitations are partly transferred fast into the karst channel network, while the other part may get stored in the base of the epikarst zone and subsequently, when the water level subsides, slowly flows out in the less permeable aquifer zones. The entire process of the infiltration of precipitation and the flow of water which reaches the saturated zone is called recharge, and previously described are fast and slow component. Its aftermath is the rise of the water table and the consequential increase of the outflow of karst springs. The actual flow of water in the saturated zone, however is going on through the well permeable system of conduits and also through the fissured matrix; dependent on hydrological conditions there may occur an interchange of water between them. The water flows through channels until reaching karst springs, where it once again enters the subsystem of the surface flow. In addition to the concentrated outflow through karst springs we may in some cases witness also the non-concentrated, diffused outflow of water from the fissured matrix onto the surface.

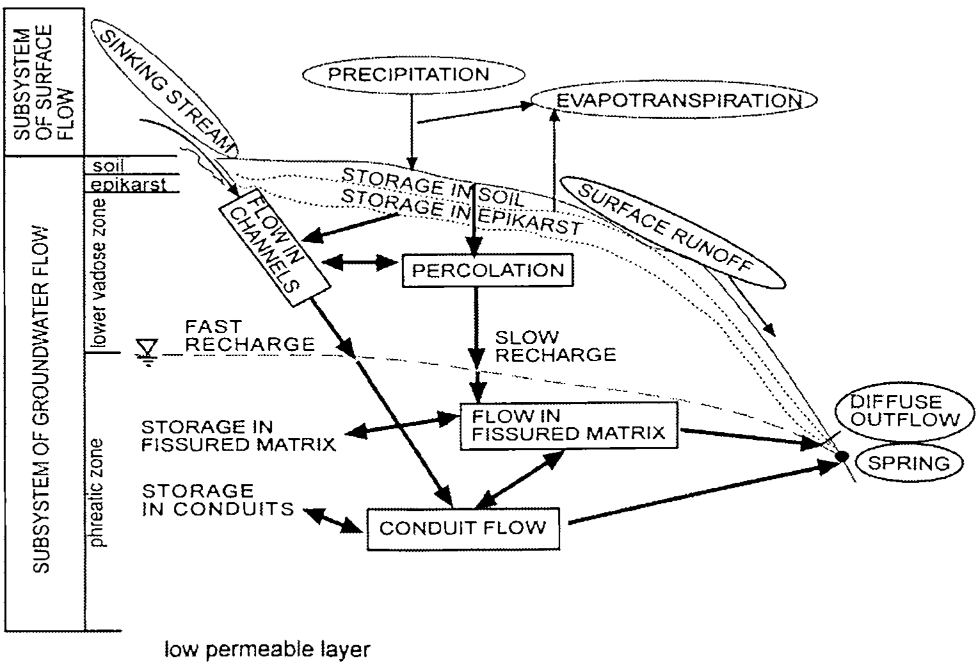


Figure 1: Conceptual model of the water flow in a karst aquifer system

SELECTION OF THE RESEARCH METHOD

For the purposes of studying the flow and storage of karst waters, numerous research methods have already been developed and tested. Their common finding is that karst aquifers represent very complex systems and that the conception and development of adequate principles and methods, which would enable us to simulate hydrodynamic conditions in these systems, therefore prove to be replete with apparently insurmountable difficulties. The choice of the most suitable and relevant approach for resolving such problems is conditioned by many factors, such as the presupposed characteristics of karst system, the anticipated results, availability of data, etc. The most well-known and accessible part of the karst water flow is the surface flow subsystem, which introduces precipitation as the source of recharge, and springs as places of discharge. Their accessibility allows constant meteorological and hydrological measurement; from the standpoint of investigating hydrodynamic characteristics, also hydrochemical analyses are becoming of increasing importance. The logical consequence of all this is the development of numerous research methods that are based on the comparison of the input and output parameters of karst aquifer system. This is especially so owing to the fact that the activities that take place underground for the most part cannot be observed in a direct manner and usually we are also not in possession of sufficiently extensive and reliable data bases describing the geometry and hydrodynamic parameters of the aquifer.

The lack of such data restricts the utility of deterministic models, wherein otherwise individual processes are defined within the system by relevant physical laws. Black-box methods, on the contrary, deal with the karst system as the central point of dynamical processes, determined by the input and output signals (Fig. 2). By applying a functional or system approach to our study we may, on the basis of the analyses of the relation between the input and output, assume characteristics of the processes that are taking place within the system (Mangin 1994). Only input and output signals have physical meaning, whereas for all connections between them, empirical or mathematical functions are being used which reflect physical processes within the system (Chiew *et al.* 1993). This role may be enacted by the so-called transfer functions. Their main characteristic is the transformation of the input function into the system's response, which is described by the output function. Although the transfer functions unite influences of various complex processes, they provide the essential information about the functioning of the karst systems (Dreiss 1982). We may determine them on the basis of the measured meteorological and hydrological time-series and subsequently we may use them for testing the system's response to various hydrological scenarios (Long & Derickson 1999). This method is founded upon the principle of linear systems. With regard to the physical and geometrical heterogeneity of karst aqifiers, its usefulness in this environment is somehow restricted, and yet it has yielded to numerous authors in the course of diverse types of research highly interesting and also acceptable results (Knisel 1972, Ashton 1966, Estrela & Sahuquillo 1997, Wicks & Hoke 1999, Labat *et al.* 2000, Wicks & Bohm 2000).

Such methods represented the foundation upon which also the research of characteristics of the recharge-discharge relations of the karst aquifer in the recharge area of Vipava springs was organized. In this area numerous investigations have been undertaken in recent years and, while they succeeded in explaining the basic laws of the functioning of the karst system, at the same time they also opened a multitude of new questions about its hydrodynamic properties. The data measured were for the most part related to meteorological conditions and the characteristics of karst springs, whereas much less information was collected about the aquifer's inner structure and about its hydrodynamic parameters. For this reason, it was primarily the criteria of the availability of the data which turned out to be crucial factor in deciding in favour of the use of the black-box method.

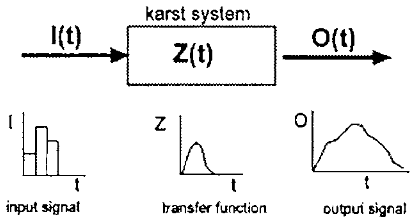


Figure 2: Input-output system

AIMS AND OUTLINE OF THE RESEARCH

At the beginning of my research I raised three basic questions:

- Is it viable to apply to the karst system the black-box model, by means of which one could describe the system's reaction on the recharge with sufficient accuracy?
- Is it possible to infer the hydrodynamic characteristics of the karst system on the basis of the comparison between various input and output functions?
- What are the characteristics of the recharge function and what is its role in karst systems?

In order to obtain the answers I accepted the basic principles of the black-box method; with regard to my specific aims and the available data, however, I have made some slight modifications. I proceeded from the premise that the hydrological complexity of karst aquifers is primarily the consequence of changeable conditions of the recharge and the heterogeneous properties of the underground flow. In the set conceptual model special attention was paid to processes determining these conditions and properties. The correlations between elements of individual subsystems were defined with equations that describe physical processes taking place between them, or by means of empirical dependences and effective parameters. With regard to the presupposed form of the input function three different input-output models were set up. By varying the properties of the input signal it was attempted to come as close as possible to the real conditions.

In the first model the input function is represented directly by the measured quantity of precipitation. In the second I replaced them with an effective infiltration, which includes the influences of various processes which take place in the air, in vegetation and in the soil, on the actual infiltration of water into the rock. I took into account the effects of the interception of precipitation in the vegetation cover, the effects of snowfall and snow melting, of evapotranspiration and the storage of water in the soil, as well as of secondary infiltration of sinking streams that collect the surface water in the surrounding flysch area. In the third model I simulated the functioning of the hydrological mechanism in the epikarstic zone, which makes possible the division of the recharge into fast and slow components. The discharge function is represented by the measured discharges of the Vipava springs.

I assumed that the accurate evaluation of the recharge provides us with sufficiently trustworthy data, which may be employed as an input function during further study of hydrodynamic characteristics of the karst system. In this manner we are able to minimise the problems that may arise due to the oscillation of the transfer function, since they for the most part occur as a consequence of input data errors and as a consequence of the non-linearity due to processes that are affecting precipitation during the recharge period.

In testing the proposed hypothesis I used a somewhat modified black-box method. This method is usually based on the comparison between the recharge and discharge functions related to individual precipitation events; in the research undertaken, however, I compared the data from the entire two-year period and thus took into consideration during my analysis also the circumstances at different hydrological conditions. Applying the mathematical-statistical comparison of the input and output signal, I determined for each model its corresponding transfer functions, which reflected processes taking place within the examined system. By taking into account these functions and the measured input parameters, the discharge values of Vipava springs were also simulated with this model.

As the criterion for the adequacy of models I took the accuracy of the simulation, which is related to the transfer function's ability to reproduce discharges on the basis of which it has been determined. With regard to the correspondence between the measured and calculated discharges, I thus assessed the adequacy of the selected models; whereas considering their structure and properties as well as the form and characteristics of the transfer function, I inferred the role of the recharge function and its components in the flow and storage of water in the karst aquifer systems. By means of the applied method it was, however, not possible entirely to exclude errors in determining the input and output parameters of the system, and the application of the linearity principles does not completely correspond to real conditions. Despite all this, I estimated that, supposing the simulation ensures sufficient accuracy, the testing of its utility proved to be reasonable, since it allows a fairly interesting and innovative approach to the study of hydrodynamic characteristics of karst aquifers.

SURVEY OF RESEARCHES UP TO THE PRESENT

The analysis of the rainfall-runoff systems is already widely used in hydrology, and many have applied it also to their investigation of the karst underground water (Ashton 1966, Brown 1973, Knežević 1976, Graupe *et al.* 1976). In their surveys of the karst hydrological methods, it is mentioned by Mijatović (1990), Krešić (1993) and Mangin (1994).

In his comparisons of the transfer function for individual storm events Knisel (1972) used various deconvolution techniques. Highly approvable results were obtained also by Poitrinal & De Marsily (1973) and Poitrinal (1974), who ascertained the stable, physically changeable transfer functions for the behaviour of Fontaine de Vaucluse spring in France over a long period of time. The transfer functions were determined on the basis of the data collected during several years and at 5-days intervals and for this reason they allow the determining of the general trend, yet they do not present also the individual reactions of springs on the precipitation events.

By comparing different statistical techniques Labat and his co-researchers (2000) reviewed the possibilities of the use of linear and stationary rainfall-runoff model for the assessment of the hydraulic behaviour of karst systems. On the basis of the obtained results he concluded that they possess certain advantages, yet their ability of simulating conditions at high or low waters was somehow lessened.

Shirley Dreiss consecrated a lot of her investigative efforts in similar research. In order to determine the karst systems she applied linear functions. With regard to deconvolution she introduced the individual storm events as the system's input signal, whereas the direct or the fast flow at the spring served as the output signal. The average error rate of the discharge evaluation amounted to 3%, but due to the use of the empirical coefficient in the soil moisture balance, the established correlations could not be deployed for the simulation of discharges (Dreiss 1982, 1989a and 1989b). She also tested the possibility of the application of the method in identifying the recharge area of karst springs (Dreiss 1983).

In order to determine the transfer function, Estrela and Sahuquillo (1997) made use of the correlation among the slopes of the recession curve sections in semi-logarithmic measure for the annual recession and not for individual precipitation events.

Of significant interest also proved to be the parallel use of the transfer function for modelling of the groundwater flow and transport through the karst aquifer (Wicks & Hoke 1999). On the basis of processing selected individual storm events, three transfer functions were determined: one related the recharge to the spring's discharge, the second related the point-source input of the solution to the concentrations of solutions in the spring and the third connected the diffuse input of matter with concentrations of solutions in the spring. The method proved to be suitable for forecasting the underground water flow and the transport of solution through large karst basins.

A somewhat different approach was deployed in the investigations of the Big Spring in Missouri, where the transfer function was determined on the basis of the unit hydrogram (Wicks & Bohm 2000). The method was evaluated as simple and fast, yet unsuitable for the discharge simulation.

Long and Derickson (1999) deployed the analysis of the linear systems and the deconvolution method in order to study the response of the water table to the recharge.

Drogue and Guilbot (1977) adopted the mathematical model, which connects the precipitation and the discharge (CREG model) on an experimental polygon; subsequently however, they used it in simulation of monthly and daily discharges in the larger karst aquifer. They defined the production function and the transfer function. The former describes the recharge of the aquifer, whereas the latter the transfer through the karst system. Applying the mathematical functions they ascertained for both functions also their individual recharge and flow components.

The transport of matter in karst or in fissured aquifers (Diaconu *et al.* 1984, Duffy & Harrison 1987, Duffy & Gelhar 1986) is also frequently based upon the principle of linear systems. Nathalie Doerfliger (1996) used the deconvolution of the tracer breakthrough curve with the corresponding input function. By comparing the transfer functions of approximately 100 tracing tests, she analysed their variability in dependence on the changes in the extent of the recharge area and hydrological conditions or geologic and hydrogeologic properties.

I dealt with the analysis of the relationships between precipitation and discharge already in one of my previous researches. I combined it with my work at the experimental site Tičnica near Idrija in north-west Slovenia, the accurate dimensions of which, as well as its location and properties of springs were already sufficiently well known (Petrič 1996a, 1996b and 1998). Due to precise knowledge of this test site, I was able thoroughly to monitor the additional influences on the relation between precipitation and runoff and consequently it became manifest that the most significant role is played primarily by preceding precipitations.

BASIC CHARACTERISTICS OF THE STUDY AREA

THE CHOICE OF THE STUDY AREA

The recharge area of the Vipava karst springs is a part of the wider region of the High Karst in south-west Slovenia. As a vitally important drinking water reservoir it was already in the past the subject of numerous investigations, from which an extensive database has been collected. These were, however, predominantly just individual and unrelated researches, aimed just at a specific target. A significant step towards a more united, interdisciplinary research including the collaboration of different experts from various fields was undertaken only after joining the international project "7th SWT - Spreading of Pollutants in Karst; Tracers and Models in Various Aquifers". 17 organisations from Germany, Austria, France and Slovenia took part in these collective research activities. As a junior researcher at the Karst Research Institute ZRC SAZU I was one of the participants. Within the framework of the geographical, geological, geomorphological, speleological, hydrogeological and hydrological researches in the period between 1992 and 1996, measurements of the wide spectrum of hydrogeological parameters were taking place and some new measurement stations were set up, which operated only during the course of the project. Particularly by means of geological mapping, meteorological and hydrological measurements, chemical and isotope analysis and by tracing tests, all of which were performed in an uninterrupted time period, an extensive database was collected, which was subsequently adequately processed, while all the results were published in the final collective publication (Kranjc 1997). However, there still remained a significant range of open possibilities for further processing and re-deployment of the collected data. I ventured on one of these open paths leading to continuation of the research and the outcomes of my investigations are presented in this book.

GENERAL CHARACTERISTICS

GEOGRAPHICAL LOCATION

High Karst represents a typical morphological form of south-west Slovenia and comprises a string of regional units (Fig. 3). Thus the areas of Banjšice, Trnovski gozd, Črnovrška planota, Nanos and Hrušica extend one after the other from north-west towards south-east. The entire karst massif with its total area of approx. 700 km² is encompassed along its borders by the valleys of Soča, Idrijca, Vipava and Pivka rivers.

Its south-east part with Nanos and Hrušica represents the central part of the karst recharge area of the Vipava springs (Fig. 4). The Nanos karstic mountain ridge with its altitude of over 1300 m, its length of 12 km and width of 7 km, rises with its high and steep walls from the flysch margins of Vipava valley and Pivka basin. On its north-west

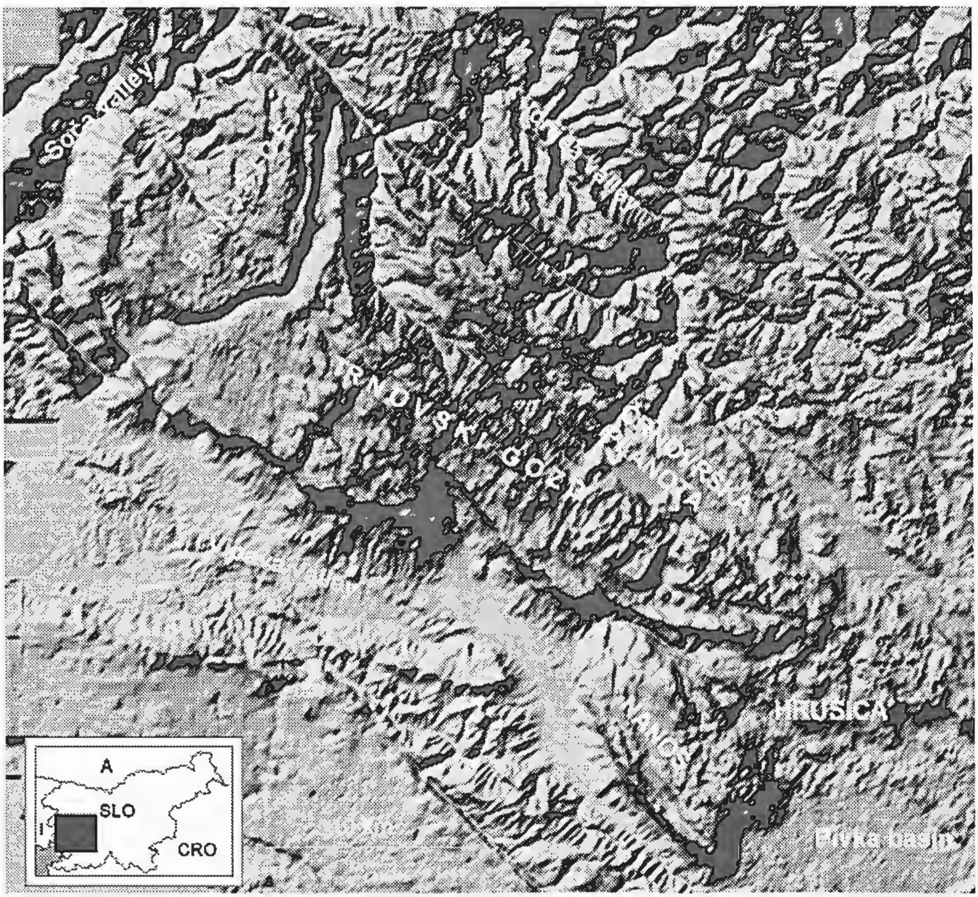


Figure 3: High Karst in south-west Slovenia

side it is enclosed by the Bela valley, while further towards north-east it passes onto the lower altitudes of Hrušica. One may notice the typical karst relief with rounded peaks and intermediate depression forms. According to the prevailing relief types we may divide Nanos mountain into two parts. The higher eastern shelf with its altitudes from 900 up to 1300 m distinctly differs from the approx. 300 to 400 m lower, western part of Nanos (Habič 1968 and 1997). Hrušica can be similarly perceived as consisting of two separate parts. The western part is the central Hrušica, which towards the east passes in Zagora.

By means of tracing tests it has been proved that karst waters from the western margins of Javorniki flow also in the direction of Vipava springs (Kogovšek *et al.* 1999, Kogovšek 1999). Javorniki is an 11 km wide and 30 km long mountain range that extends in a north-west - south-east direction. Its highest parts are located in its central ridge with altitudes up to 1300 m; the major part of it is, however, somewhat lower.

The described karstic massifs rise above the lowland flysch region of Vipava valley and Pivka basin. Vipava valley with its altitudes below 200 m, along which Vipava river is flowing westward to join the river Soča, represents the undulating surface between Kras on the southern side and the High Karst on the northern side. Between Javorniki

Figure 4: Topographic map of the Vipava springs recharge area

The Nanos and Trnovski gozd plateaux are raising from the flysch margins of Vipava valley (Photo S. Šebela)

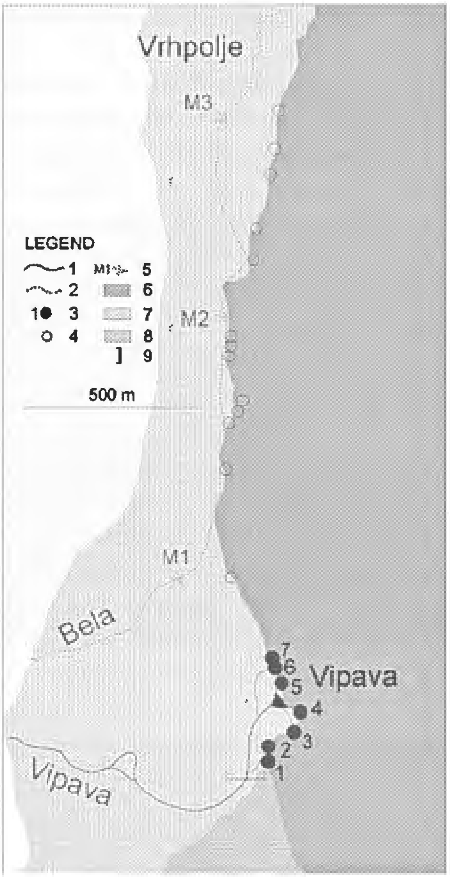
Flow from springs Vipava 4 and 5 at high waters (Photo M. Petrič) and Nanos lies the slightly elevated Pivka basin with Nanoščica and Pivka rivers, which at Postojna sink into Postojnska jama cave.

Vipava river rises at one of the most important karst springs at the foot of the High Karst. Water flows to the surface through several permanent and temporary springs, which all flow into the Vipava river. This and the Idrijca are the largest tributary streams of the Soča, which in turn flows into the Adriatic Sea. The area considered thus belongs to the Adriatic water system, whereas its eastern boundaries correspond to the Adriatic - Black sea watershed. The exact positioning of this watershed on the basis of the extant data is, due to its karst nature, practically impossible to define.

HYDROLOGICAL CONDITIONS

In the centre of Vipava town at an altitude of 98 m above the sea, seven permanent springs of Vipava river are to be found within a span of some 300 m (Fig. 5). Ranged from the south towards the north one comes across the succession of the following springs: Pri kapelici, Pod lipco, Za Perkavcovim mlinom, Vipavska jama, Za gradom and two springs called Pod farovžem, which are usually marked with successive numbers from 1 to 7. Pod lipco or Vipava 2 spring is exploited for the Vipava valley's water supply; the water outtake does generally not exceed 100 l/s.

Figure 5: Satellite map of the Vipava's permanent springs area



Between Vipava and Vrhpolje, located towards the north and at altitudes of up to 125 m, another six intermittent springs are to be found (Fig. 6).

The springs demonstrate typical karst hydrological regime with high short-term flow rates and prolonged periods of medium and low waters. The extreme peaks of the discharges appear simultaneously with the excessive precipitation. In the period between 1961 and 1990, according to the Hydrometeorological Survey of Slovenia, the lowest measured discharge amounted to 727 l/s, the highest was

Figure 6: Permanent and intermittent Vipava springs (1. The Vipava River, 2. Temporary surface stream, 3. Permanent Vipava springs 1-7, 4. Intermittent spring, 5. Point of discharge measurement, 6. Karst aquifer, 7. Alluvial deposits, 8. Flysch, 9. Gauging station)

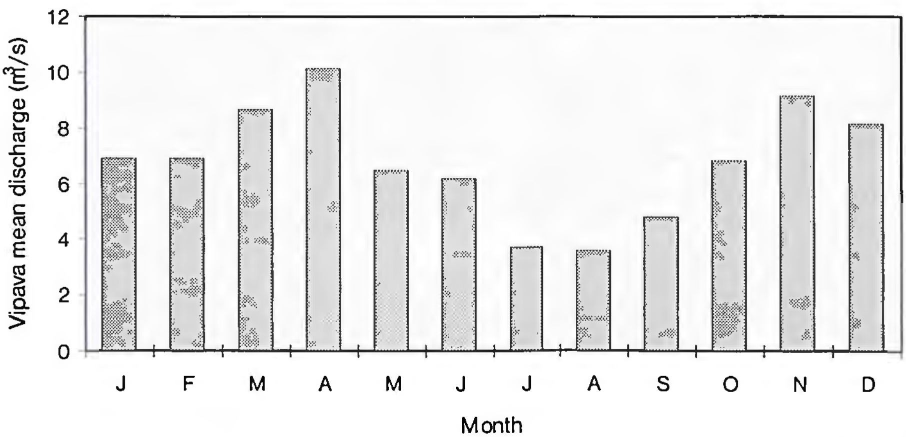


Figure 7: Average monthly discharges of permanent Vipava springs in the time period between 1961 and 1990

70 m^3/s, whereas the medium discharge in this time interval was 6.78 m^3/s. The ratio between low, medium and high waters is thus approximately 1:10:100.

Vipava's highest discharges are in April and November. November peaks are mostly the result of the extensive autumnal rains, whereas high flow rates in April occur also as a consequence of snow melting. The lowest water levels were measured during July and August (Fig. 7).

Flow from springs Vipava 4 and 5 at low waters (Photo M. Petrič)

In addition to the already described permanent and intermittent Vipava's springs one may find also several smaller springs at the southern part of the Nanos's base (Gospodarič 1987, Kranjc & Šebela 1992). They are captured for the water supply of smaller settlements or individual houses. It has been estimated that their overall discharge at low waters does not exceed 10 l/s. The patches of the slope rubble scattered across the Nanos's slopes may also act as local aquifers.

In the karstic part of the Vipava springs recharge area there are no surface waters, whereas at its margins numerous sinking streams are to be found. In the north-west part of Pivka basin, after their short flow over the flysch surface the rivulets Lokva, Belščica, Ribnik, Mrzlenk, as well as streams in Stranske and Šmihelske ponikve sink into the Nanos karst aquifer. The rivulet Bela at the north-west edge of Nanos, similarly loses part of its water along its stream and supplies the permanent Vipava springs. The intermittent Vipava springs, on the other hand, flow in the Bela's water channel as well. The main water flow in Pivka basin represents the river Pivka which is, according to the tracing testing results, connected to Vipava springs by means of subterranean water channels.

Spring Vipava 7 at high waters (Photo M. Petrič)

GEOLOGICAL STRUCTURE

Scientists were already studying and investigating the High Karst's characteristics in the 19th century, yet through the course of history the explanations of its geological structure were subjected to constant changes. The current understanding, in its stratigraphic-lithological sense, relies primarily on the research undertaken by Buser and Pleničar. Their foundational work was the Basic Geological Map at the scale 1:100,000. The western part of the area considered is charted on the Gorica sheet (Buser 1968 and 1973), while its eastern part by sheet Postojna (Buser *et al.* 1967, Pleničar 1970). Placer (1981 and 1994/95) explained in detail the origin and development of structural units and presented his model of the tectonic structure for south-west Slovenia. Studies dealing with geological conditions on the surface and below were completed also for the Predjama region (Šebela 1991, Šebela & Čar 1991). Čar (1997) and Janež (1997) summarised geological and hydrogeological characteristics; additionally they also made detailed maps of the immediate background of Vipava springs (Janež & Čar 1997). From above mentioned studies I am excerpting the basic characteristics of the geological structure.

The thrust structure intersected with numerous neotectonic faults is a typical feature of south-west Slovenia. The flysch occurs in thrust and under-thrust structural units in Vipava valley, in the Pivka basin and in Vodice village. The central part of the area considered, together with Nanos and Hrušica, as well as the north-east part of Vipava valley, belong to the Hrušica nappe. This is in turn thrust onto the Snežnik thrust sheet, which within the area considered comprises also the surrounding area of Postojna, Pivška kotlina, Javorniki and the narrow belt of Eocene flysch rock which after passing the Nanos's southern edge extends into the Vipava valley. At the contacts on the western margins of Pivka basin Bukovška, Debelovrška and Suhovrška interjacent slices were also formed, which in comparison to other thrust units prove to be of insignificant extent.

The most important faults we come across in this area are Idrija, Zala and Predjama faults, which have Dinaric direction. Idrija and Zala fault zones are located on its northeast edge; they run across Planinsko polje, whereas the recharge area we are concerned with is between Nanos and Hrušica intersected by the Predjama fault. Under this name we denominate the eastern continuation of the Avče fault, which may be traced back all the way from the Soča valley up to the edges of the Pivka basin. In addition to these strongly pronounced faults the area is intersected also by numerous smaller faults extending in various directions.

The area considered is predominantly composed of carbonate rocks. The oldest among them are Norian-Rhaetian dolomites located at the southern edges of Hrušica. At Nanos's eastern part and on Hrušica, the Liassic, Doggerian and Malmian lithostratigrapfic units were developed as representatives of limestone and partly also dolomite with all their transition forms. Cretaceous rocks, however, prevail in the composition of the karst recharge area of Vipava springs. The Lower Cretaceous at the edges of Pivka basin as well as on Nanos and Hrušica is developed as limestone with inclusions of bituminous dolomite, which is followed by Upper Cretaceous organogenic limestones. Carbonate Cretaceous development is concluded with the erosion discordance, above which are positioned Eocene flysch rocks. These build up the entire area of Vipava valley and the Pivka basin, and they break out onto the surface also in the Bela valley and in the surrounding area of Vodice. They are developed as marlstones or quartz sandstones with inclusions of calcarenite and calcirudite. The steep slopes of Nanos that rise above Vipava valley are covered with Quaternary breccia and non-agglutinate slope rubble. Alluvial sediments are deposited along streams.

HYDROGEOLOGICAL CHARACTERISTICS

On the basis of the already identified geological structure we were enabled to determine also basic hydrogeological units (Fig. 8). The central part of Vipava springs recharge area represents a very well permeable karst aquifer of Nanos and Hrušica, which is composed of Cretaceous and Jurassic limestones. The considerable karstification is indicated by surface karst features and numerous karst caves, especially shafts. Nanos and Hrušica are in the geological sense divided by the Predjama fault, which nevertheless does not represent any hydrological barrier. The direct proofs of this were provided by tracing tests, which confirmed the underground connection between Lokva and Belščica sinking streams and Vipava springs (Habe 1970, Behrens *et al.* 1997). The thickness of the carbonate packet is considerable and it is within this kind of rock that the deep karst has been developed. The depth of the groundwater is also substantial, so that not even one among numerous shafts reaches the constant water table of karst waters. Detailed data about the position of the impermeable flysch base is not available; by interpreting the geological structure (Placer 1981), however, it has been assessed that flysch rock lies much deeper in the Nanos area (in its north-west part even at the altitude of -1300 m) than on Hrušica (roughly at sea level) (Janež 1997).

Similar properties of the karst aquifer are displayed also on the western edges of Javorniki, which at least partially also drain their waters towards Vipava springs.

Somewhat less permeable is the smaller belt of Jurassic and Upper Triassic dolomites with fissured porosity, located on the edges of Hrušica.

Quaternary periglacial breccia and Holocene slope rubble at the foot of Nanos represent well permeable aquifers with intergranular porosity. Within them numerous smaller springs may be found, which are important for local water supply.

The role of the impermeable barrier, however, is played by the Eocene flysch, which occurs in Vipava valley, Bela valley and Pivka basin. Furthermore it has been ascer-

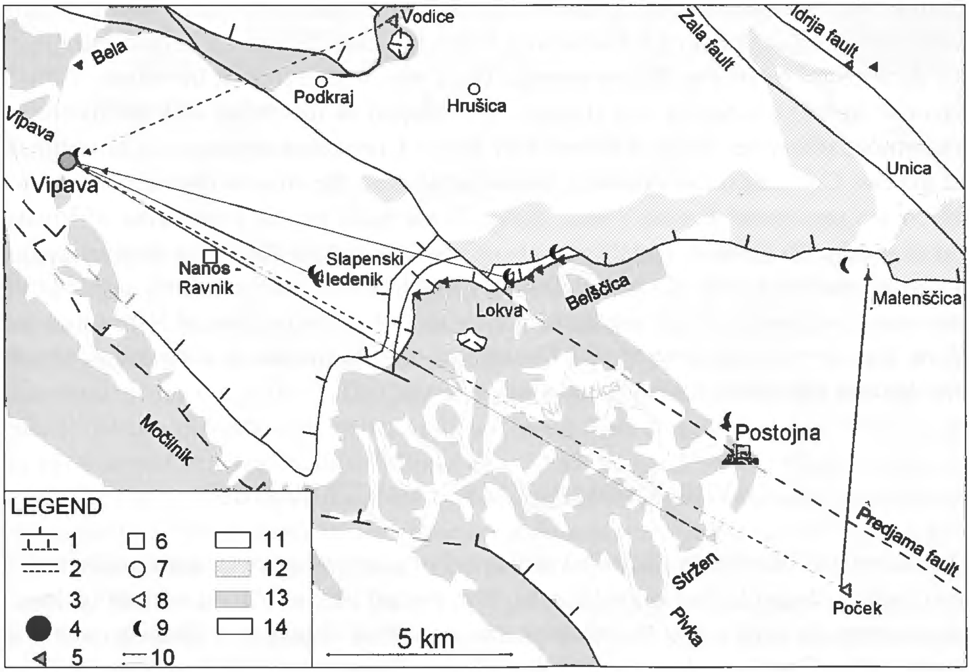


Figure 8: Hydrogeological map (1. Visible and covered thrust plane, 2. Visible and covered fault, 3. Surface stream, 4. Spring, 5. Ponor, 6. Meteorological station, 7. Precipitation station, 8. Point of tracer injection, 9. Karst cave, 10. Main and secondary direction of proved underground water connection, 11. Karst aquifer, 12. Fissured aquifer, 13. Very low permeable rocks, 14. Porous aquifer)

tained for the area of Pivka basin that karst has been developed also under the flysch layers, since some waters from Pivka valley and the western margins of Javorniki flow under flysch towards Vipava springs. This underground connection was confirmed by tracing tests (Habič 1989, Kogovšek *et al.* 1999, Kogovšek 1999).

The location of Vipava springs is restricted to the territory where the impermeable flysch border area is removed at its deepest. Near Vipava in the area of Nanos's base the flysch was eroded under the present valley floor. The sunken part of the valley was partly filled up by Quaternary alluvium, which in turn dammed the outflow of karst waters from Nanos and thus occasioned the delta-like arrangement of Vipava springs. The springs Pod farovžem and Za gradom are connected to otherwise rare bigger fissures, additionally widened by corrosion. In case of the southernmost springs Pri kapelici, Pod lipco and Za Perkavcovim mlinom the water flows out along bedding planes of steeply positioned limestone layers (Janež *et al.* 1997). During low waters the water table in permanent springs reaches approximately 98 m. Following more intensive precipitation it may rise for about half a meter, whereas some fissures may get activated up to 5 m higher. Intermittent springs between Vrhpolje and Vipava, located at altitudes of up to 125 m, may also start operating during high waters (Habič 1983).

SPELEOLOGICAL CHARACTERISTICS

On Nanos and Hrušica over 200 caves have already been discovered. The major part of them are shafts the deepest among which, Strmadna, located on the plateau's central part, reaches a depth of 222 m. There may be several other shafts that are deeper than 100 m, and yet not one among them reaches the underground water table. Šušteršič (1996) stated that between Predjama and Vipava springs 104 caves were already discovered. He described some of them as broken sections of "horizontal" caves.

Near Vipava, at Nanos's lower edges where the springs are located, only shorter karst channels are currently known to us. Of much greater significance is Vipavska jama cave, the entrance of which passes through the artificial passage which in case of high waters acts as a true effluent. The passage intersects two larger natural caverns; in one of them cavers discovered and examined a maze of epiphreatic galleries about 1.3 km long developed along fissures (Mihevc 1997, Remškar 2001).

Even larger and of greater significance are the caves at the area of sinking streams at the north-west edge of Pivka basin. The biggest among them is Predjama cave, which comprises three levels. In the lowest one at altitude of 462 m, the Lokva stream sinks underground. Until very recently it was believed that the cave's length amounts to approx. 8 km (Šebela 1996). In the next few years, however, divers swam through several siphons and discovered new passages. They disclosed also the connection with the 1300 m long Jama v Grapi cave, where the Belščica brook sinks. The overall length of cave discovered thus far has increased to slightly more than 13 km (Vrhovec 1999). Other ponor caves in this area are considerably smaller.

RECHARGE OF THE AQUIFER

The recharge of the aquifer describes the flow of the infiltrated water, which reaches the permanent underground water table and produces as its consequence an increase of the stored water (Lerner *et al.* 1990). As the source of the recharge one may consider precipitation, rivers, channels and lakes or phenomena which are results of human action (e.g. irrigation). We differentiate between direct recharge, which comprises the vertical percolation of precipitation water through the unsaturated zone (also known as primary or autogenic recharge) and indirect recharge that includes also some other, indirect ways in which the precipitation water may find its way into the aquifer (called also secondary or allogenic recharge).

Due to factors such as the spatial and temporal distribution of precipitation as well as different properties of the soil, land use and the topography of the hydrological basin, the recharge function changes in time and space. For this reason the determination of its values encounters numerous difficulties. Direct measurement in the regional sense is practically impossible, and that is why in practice, we apply various assessment methods.

The simplest among these is a method where the recharge is indicated by values of the measured precipitation. Thus numerous hydrological studies introduce into their system as their input signal simply values for precipitation. The main reason for such decision usually lies in the lack of any adequate data. In karst systems, however, the frequent rationale for this constitutes also the premise that due to their heterogeneous structure and complex functioning the uncertainty is so immense that an additional error because of the simplification of the recharge assessment does not exert any significant impact on the final result. In some situations such assumptions may be confirmed, yet in numerous other cases the processes which affect the precipitation before and during the infiltration, do significantly alter the form of the input signal and should therefore be taken into account.

During my research work I dedicated particular attention to these processes as well. Their interconnection is based upon the conceptual model, which is schematically represented in Figure 9 without considering the actual dimensional proportions. The model is composed of two main subsystems. The first one is represented by the estimate of the effective infiltration I_{ef}, whereas the second by the division of the recharge on the slow R_s and fast component R_f.

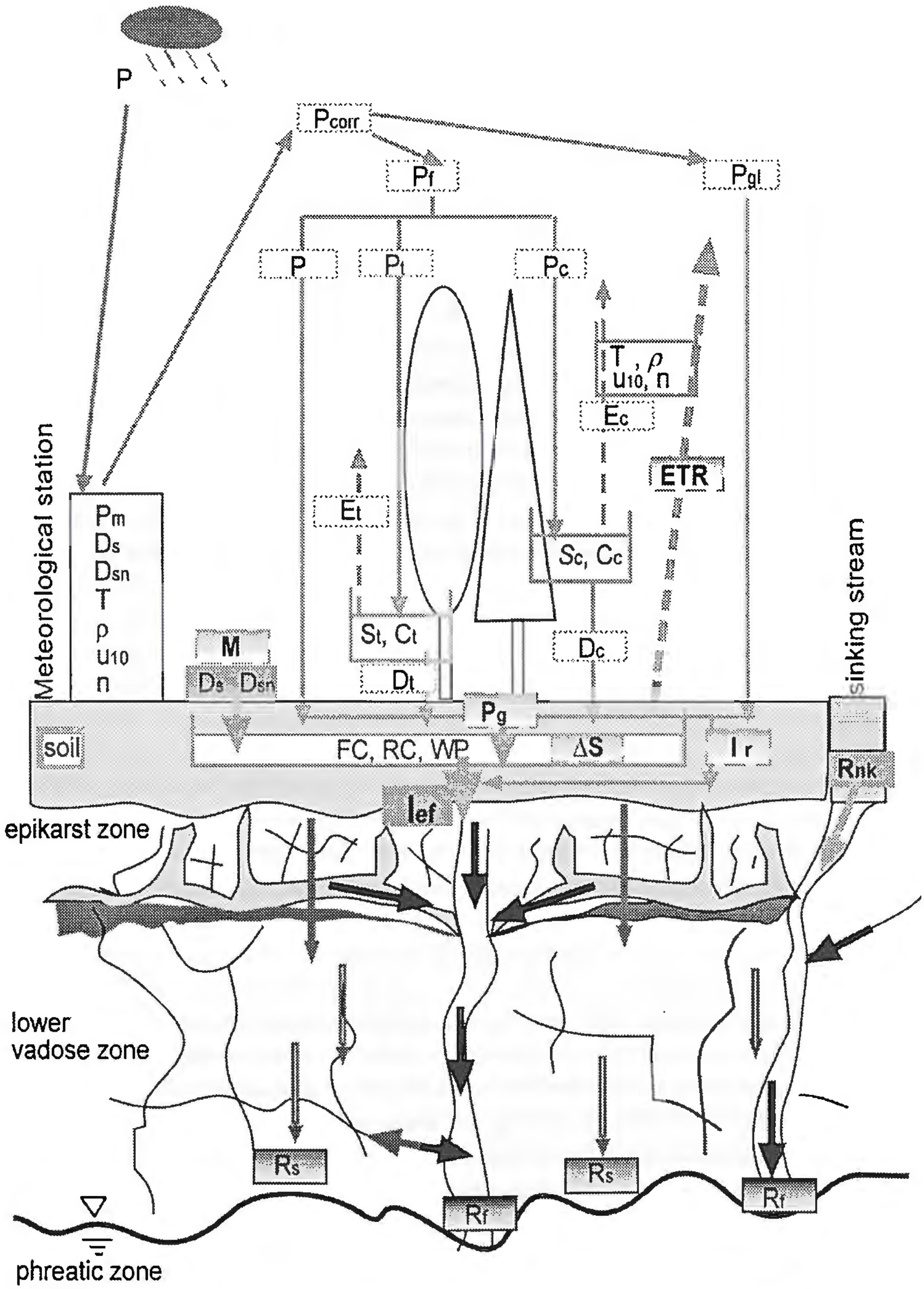


Figure 9: The conceptual model of recharge (Symbols are explained in the text)

Effective infiltration includes influences of various processes that take place in the air, in vegetation and in the soil and thus describes the actual input of water into the rock. This water is capable of promptly continuing its vertical way through the well permeable karst drainage network until it reaches the saturated zone; it may also get temporarily stored in less permeable areas and subsequently it slowly percolates towards the water table. These processes are denominated by the terms fast and slow recharge; in the conceptual model, however, I presupposed, in accordance with the results of various studies, the existence of a certain mechanism within the epikarstic zone that enables such a distinction.

The effective infiltration model is based upon the water balance. Due to lack of adequate data, I presumed during its calibration that within the period of certain hydrological years the overall effective infiltration present in the Vipava springs recharge area is equal to the overall discharge of these springs. In my distinction between fast and slow components I applied the method of hydrological balance, which is based upon the hydrogram analysis. I compared the values of effective infiltration for individual precipitation intervals with the shares of direct and base flow of Vipava springs and thus also determined the temporal variability of the division on fast and slow recharge.

EVALUATION OF THE EFFECTIVE INFILTRATION

The conventional method of effective infiltration evaluation is based upon the difference between precipitation, runoff and evapotranspiration. With regard to ascertained hydrological conditions and the set conceptual model, however, these parameters are defined more accurately. The main equation may be presented in the following form:

$$I_{ef} = P_g + M - ETR - \Delta S \qquad (1)$$

In the set water balance the source of water is precipitation, reduced by the amount of precipitation intercepted by the vegetation cover - P_g. In favourable climatic conditions additional quantities of water are provided by the melting of snow - M. Actual evapotranspiration ETR with its sending the water back into the atmosphere thus denotes also the amount of water consumption. The relation between the receipt and consumption is affected by the hydrological properties of the soil, which in turn determine the amount of water that may get stored in it. Change in water storage is defined with parameter ΔS.

In course of assessing the balance it is necessary firstly to determine the extent of the recharge area which drains water towards the observed springs. On the basis of the results obtained from field measurement and from various well-known meteorological and hydrological methods I determined the aforementioned components of the balance also for this area. Owing to the lack of required data I managed to determine some of the parameters only on the basis of the final calibration of the model with respect to the overall discharge of Vipava springs.

SURVEY OF PREVIOUS RESEARCHES

I may here state some research work, wherein the effective infiltration was determined on the basis of measured precipitation, which took into account also the method of soil water balance.

The simplest among them is the Penman-Grindley model (Penman 1950, Grindley 1967), which was primarily developed for the evaluation of the soil moisture deficit and the actual evaporation, but was simultaneously used also for the effective infiltration evaluation. Various direct and indirect measurements have demonstrated that the method underestimates the real recharge values (Kitching & Bridge 1974, Kitching *et al.* 1977, Smith *et al.* 1970). Such deviation was particularly prominent in summer months and in the autumn. For that reason many different modifications of the classical method have been proposed.

Some of these cases of modification are summarised in a paper on the evaluation of the aquifer recharge developed in chalk, located in the area of northern Lincolnshire in England (Rushton & Ward 1979). Of special significance is its handling of the introduction of rapid recharge as the potential enhancement of the model. The study of the sensitivity of this method to the changing of individual parameters for the same area was also produced (Howard & Lloyd 1979). Results demonstrated that errors in the assessment of the input data may considerably affect the final values and for that reason it is highly reasonable to verify results by testing the sensitivity. The comparison between the analyses of the monthly, ten-days and daily intervals revealed that the most reliable results were obtained in utilisation of daily values.

In the literature we may come across numerous similar more or less complex models, yet their practical implementation usually makes it evident that the final result of the differences between models prove to be less important than the accuracy of the determination of the input parameters (Lerner 1997).

I would particularly like to point out another two studies, wherein the method of the soil moisture balance was applied during the evaluation of the recharge function as the input component of the karst aquifer model. Sauter (1992) determined the recharge in the recharge area of Gallusquelle spring in the south-west Germany with the aid of the double porosity model on the basis of daily precipitation measurements; additionally he took into account also the influences of interception, snowmelt and evapotranspiration. He united the described parameters into the soil moisture balance and ascertained daily recharge values. Despite some deviation, which occurred at the comparison of the amount of the discharged water at the spring, he assessed the obtained results as fully compatible with the values of the actual recharge and thus included them into his model.

Jeannin and Grasso (1995) made similar calculation for the karst basin of Milandrine in Switzerland. In their soil moisture balance they took into account the measured precipitation and the calculated values of the potential evapotranspiration and thus gave their evaluation of the daily recharge value. The obtained values are comparable to the runoff from the basin.

OUTLINING THE KARST RECHARGE AREA

In order to ascertain the quantitative evaluation of the recharge function it is necessary to ascertain the extent of the recharge area. The outlining of boundaries of the karst springs recharge area is based upon an understanding of the geological structure and upon results obtained by tracer tests; the accurate location of the boundaries is, however, due to the specific peculiarities of the karst aquifers (unknown routes of the underground waters, bifurcation, the changes in the size of the recharge area at different hydrological conditions, the hidden underground flow in the covered karst) practically impossible. For that reason I was, in my assessment of the extent of Vipava springs recharge area, persuaded to resort to certain simplifications.

Its central part stretches across the karst area of Nanos and Hrušica, yet on the basis of the available data we are still not able to determine the position of the watershed between Vipava and the springs of Ljubljanica within the Hrušica region (Adriatic - Black sea watershed). By means of tracing tests it has been proved that the sinking streams from the flysch area at the north-west edges of Pivka basin flow towards Vipava springs. In this region we may draw the borderline of the recharge area along the surface watersheds separated from sinking streams, that flow towards Pivka river (Habe 1970, Behrens *et al.* 1997). Hydrological measurements and tracing tests also confirmed the restricted and hydrologically conditioned inflow from the surface stream of Bela into Vipava springs (Baker *et al.* 2001). The tracing tests additionally indicated underground water connections between the Pivka valley and the western edges of Javorniki (Habič 1989, Kogovšek *et al.* 1999, Kogovšek 1999). Although the main flow is directed towards the springs on Planinsko polje, a part of the underground waters flows also towards Vipava.

Because of all the above-mentioned characteristics, I also applied the water balance method to my assessment of the extent of the recharge area. This method is based upon the premise that within a longer time period the overall runoff from the karst system is equal to the amount of water, which has in the same period fallen on the entire recharge area in the form of precipitation; it is reduced for that part of water that is sent back into the atmosphere by evapotranspiration. In my dealing with the Vipava recharge area I used the data covering the 30-year period from 1961 to 1990. I determined values of the average annual precipitation (2075 mm) and that of the evapotranspiration (640 mm), on the basis of the precipitation map and the evapotranspiration map, which were made for the stated time period within the framework of the 7th SWT project, which was intended for the wider area of High Karst (Pristov 1997 and 1998). The difference between these two values (1435 mm) indicates the amount of water that infiltrates into the aquifer during an average year. The comparison of this value with the average discharge of Vipava springs (6.78 m^3/s), however, enabled us to evaluate the size of the recharge area at approximately 149 km^2 (Petrič 2000b).

Due to the fact that the measured discharge of Vipava springs includes the recharge from the karst as well as non-karst part of the recharge area, the calculated surface of 149 km^2 takes into account both types of recharge area. I evaluated the share of the non-karst recharge area of the northwest edges of Pivka basin by means of separating the surface watersheds of sinking streams on flysch, which in contact with carbonate aquifer sink and supply (as has been proved) the Vipava springs. This area covers no more than about 9 km^2.

I further focused my study on the influences caused by connections to the surface stream of Bela, which similarly collects its waters from the flysch terrain. Along its flow over carbonate rocks and at favourable hydrological conditions it partly sinks and supplies Vipava springs. Yet on the other hand in the case of high waters the intermittent Vipava springs, which flow into Bela, get activated and their flow is not included in the measurement of the discharge of the Vipava springs. The comparison between both components demonstrated that within the enclosed periods of hydrological years their influence is practically annulled. For that reason I considered their role within the balance of several years as negligible. Due to the difference in the direction of the connection in various hydrological conditions, I took into account the hydraulic correlation between Bela's surface flow and Vipava springs in the comparison between the recharge and discharge functions. With regard to the available data this influence was included in the evaluation of the discharge function, whereas the analysis itself is represented in further detail later.

Out of the calculated total extent of 149 km^2, I thus estimated the size of the non-karst part of the recharge area, which covers the flysch region of the north-west edges of Pivka basin, at 9 km^2; the remaining 140 km^2, however, I identified as the karst part of the recharge area in the Nanos and Hrušica region (Fig. 10). Yet doing this I had to neglect, due to the lack of required data, the part of the recharge area at the western margins of Javorniki. Although two tracing tests found that the underground waters from this area partly flow towards Vipava, such confirmed relationships cannot be quantitatively expressed and the outlining of the recharge area proves practically unachievable. For that reason I have, with respect to the assumption that the western part of Javorniki displays similar hydrogeological properties as the karst land of Nanos and Hrušica, assumed and accepted that the error introduced by not considering the Javorniki area as the part of the recharge area and by overestimating the extent of the recharge area on Hrušica is ultimately negligible.

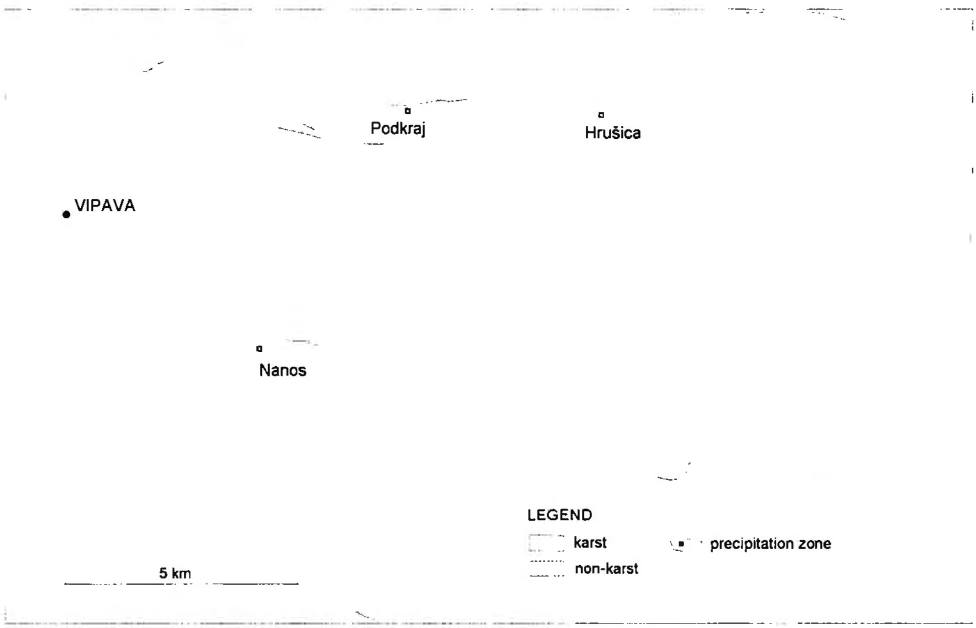


Figure 10: The extent of the study polygon and the division of precipitation zones

THE TIME FRAMEWORK INTERVAL OF THE USED DATA

Owing to the fact that the most intensive measurements of hydrological parameters at the area of the study polygon were undertaken within the framework of the 7th SWT project from 1992 to 1996, I consequently linked my investigations to this time interval. With regard to the arrangement of hydrological years, the majority of data was collected within a period of two hydrological years, that is, from 25 August 1993 until 23 August 1995. For that reason I also calibrated the established models within this time interval. In course of their validation, however, I considered also the data gathered in the eight hydrological years from 1 August 1985 until 24 August 1993.

In my assessment of the general hydrological characteristics I took into account the average values that span many years, that is, from 1961 to 1990, which are based upon the statistical comparison of the measured daily values. The daily data were used also in the analysis of the relationship between recharge and discharge.

PRECIPITATION

Precipitation is the main source of the recharge and represent the basis for the formation of the karst system's input function. The Hydrometeorological Survey had in operation only three precipitation stations within the recharge area through a longer period of time: Nanos (Ravnik), Hrušica and Podkraj, where the precipitation was measured with a rain-gauge of the Hellmann type once a day at 7 a.m. (Zupančič 1995). The figure represents the distribution of the average monthly precipitation for these stations from 1961 to 1990 (Fig. 11). The most abundant precipitation takes place during autumn with a peak in October and even more so in November, whereas it is at its least during winter in February and during summer in July. The typical phenomenon is intensive precipitation, which is temporally and topographically unevenly distributed. The share of snowfall is also of considerable significance; it starts already in November and the snow may still be found in some places as late as May.

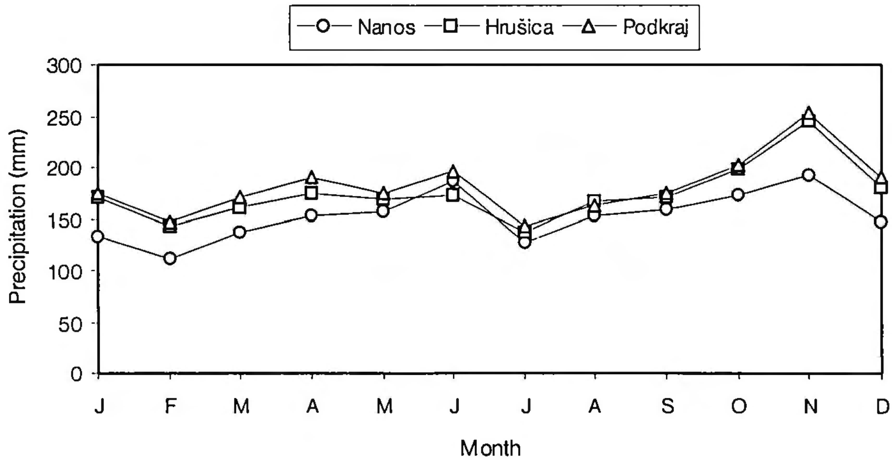


Figure 11: Average monthly precipitation in the period from 1961 to 1990

The application of the precipitation data in hydrological studies faces numerous problems. The first such is associated with the vast differences in the spatial distribution of precipitation. Due to the fact that precipitation is point measured while in the evaluation of the recharge it is also its distribution over the land that is of considerable importance, we have at our disposal various methods for the transformation of the point data. The quality of the obtained results is lower in case of lower frequency of precipitation stations or when they are not positioned in an adequate manner. The second substantial problem, which has not been resolved despite scientists' efforts over many years, represent errors in the measurement processes. Although measurement itself is relatively simple, the errors may markedly reduce the accuracy of the obtained results. The most frequent among them are systematic errors due to the influence of wind, evaporation and wetting loss. At wind velocities that exceed 5 m/s the values measured in rain-gauges of the Hellman type reach only 22 % of the actual amount of snowfall and 87 % of the actual rainfall (Yang *et al.* 1994). According to Neff (1977) the entire amount of the measured precipitation is from 5 % to 15 % lower than the actual value; at individual precipitation events, however, the error due to the effect of the wind may range from 0 to

75 %. Meteorological services usually present uncorrected data, wherein the share of errors cannot be considered negligible. Many corrective methods have been proposed to cancel them out, yet none of them has yielded reliable results and the decision on their suitability is entirely left to the subjective evaluation of users. For these reasons, we are in our hydrological studies frequently facing the dilemma whether it is better to use uncorrected data or to introduce a correction with the aid of methods that cannot yield the best results and may, moreover, introduce into the extant data base a new error with different properties and effects.

Both problems are also typical of the Vipava recharge area, and that is why I primarily verified the sensitivity of the area to these errors. On the basis of the isohietes made by the Hydrometorological Survey within the framework of the 7^{th} SWT project (Pristov 1997) for the wider area of Trnovski gozd, Banjšice and Nanos using the data from the 30-year period from 1961 to 1990, I determined the characteristics of the average precipitation distribution within the recharge area. I compared the map with mean annual amounts of precipitation at three precipitation stations and according to these values divided the entire recharge area into 3 precipitation zones (Fig. 10): the southern part - Nanos (82.9 km^2 or 59.2 % of the karstic part of the recharge area), central part - Hrušica (49.8 km^2 or 35.6 %) and the northern part - Podkraj (7.3 km^2 or 5.2 %). The extent of these belts differs and is determined in such a manner that with regard to the already known properties of the precipitation distribution the sum total of the infiltration of all three belts is the best possible way to describe and demonstrate the conditions reigning across the entire karst region of the polygon. In my further analysis I evaluate the effective infiltration separately for individual precipitation zones and subsequently with respect to their extent I ascertained also their uniform value.

Pristov (1998) evaluated the measurement error for the karst recharge area of Vipava at rainfall stations Nanos, Hrušica and Podkraj. He used the data recorded in the period from 1961 until 1990 and taking into account the effects of wind, wetting loss and the configuration of the terrain, ascertained correction coefficient for the annual amount of precipitation. The measured average precipitations for the period from 1961 until 1990 range between 1834 mm (Nanos) and 2179 mm (Podkraj). The obtained difference of 345 mm points towards the considerable variability of the precipitation distribution on the relatively small area; nevertheless it partly reflects also the errors in the measurement processes. The most underestimated are said to be the measured values at the Nanos station (correction factor k=1.14), while the discrepancy at Podkraj (k=1.04) and Hrušica (k=1.02) was somehow lower. If we take into account this correction, the average annual precipitation in the period from 1961 until 1990 amounted to 2091 mm on Nanos, to 2125 mm on Hrušica and to 2266 mm at Podkraj, and the difference is 50 % lower. Bearing in mind that the differences between the actual and measured values presented in such a manner are relatively large, I decided to use the precipitation correction method despite the well-known deficiencies inherent to the dealing with daily precipitation as the input function in the karst aquifer system.

With respect to the recommendation from the reference literature (Bonacci 1994) and according to my knowledge of the present conditions and availability of the data, I made use of the simplified correction equation, in which the most important influences are considered to be aerodynamic effect and the wetting loss of the inner walls of the raingauge.

$$P_{corr} = k_a \cdot P_m + \Delta P_w \quad (2)$$

where:

P_{corr}	corrected precipitation (mm)
k_a	wind correction coefficient (-)
P_m	measured precipitation (mm)
ΔP_w	correction due to wetting loss (mm)

Firstly I corrected the data collected at Nanos station, as it provided all the required measured meteorological parameters. The influence of the aerodynamical effect was evaluated according to the equation introduced by Allerup and Madsen (1979), wherein the correction factor is determined as a function of the wind's velocity and on the intensity of precipitation.

$$k_a = \exp(-0.001 \cdot \ln i_{pd} - 0.0082 \cdot u_{10} \cdot \ln i_{pd} - 0.042 \cdot u_{10} + 0.01) \quad (3)$$

where:

i_{pd}	daily intensity of rain (mm/h)
u_{10}	wind speed at the height of 10 m above surface (m/s)

According to the literature the correction due to the wetting loss in days with precipitation over 1 mm amounts to 0.3 mm in case of rain, 0.2 mm for mixed precipitation and 0.15 mm for snow (Sevruk 1982). Where the precipitation is lower than 1 mm, we have to reduce the factors by a half. Taking into account these values and availing myself of equations 2 and 3 above, I opted for the corrected daily precipitation at the Nanos station in the period of two hydrological years, i.e. from 1993 to 1995.

I verified the correction in two ways (Petrič 2000b). Firstly, I ascertained by comparison between the measured and corrected precipitation the corrective factor for the period of two hydrological years. Thus the obtained coefficient 1.14 exactly matches the one achieved by Pristov in his analysis of the thirty-year period (Pristov 1998). In addition to this I also made use of Sevruk's method for calculating the monthly precipitation correction (Sevruk 1986). The comparison between the monthly totals of the corrected daily precipitation for the period of 24 months displayed very slight deviations, for the difference reached 5% only in two cases. On the basis of the accomplished comparison one cannot draw any final conclusions on the quality of the obtained correction results; nevertheless they may serve as a verification by means of which we may avoid the possibility of greater errors which might be occasioned by the choice of an unsuitable method.

Special problems are associated with the correction of the measured precipitation at the Hrušica and Podkraj stations. The wind velocity at these locations was not measured and the application of the above method for ascertaining the k_a corrective factor proved impossible. As an approximate evaluation I thus adopted the value k_a for Nanos and reduced it according to the correction coefficients which were set up by Pristov (1998) in his investigation of the 30-year period. I thus minimised the increase of the precipitation amount due to the use of the correction factor ($P_{corrected} - P_{measured}$) for each individual day with the factor, which according to Pristov's results represents the ratio between the coefficient of the precipitation increase due to the correction for Nanos, Hrušica and Podkraj stations. In this manner the overall quantity of precipitation at the Hrušica station increased by 2 %, whereas the rise at Podkraj amounted to 4 %.

These corrective measures are related exclusively to rain events. Errors that may occur in the case of snowfall are bigger and prove even more elusive in their evaluation. I tried to evade the complexities related to the snow precipitation correction by selecting the method of effective infiltration evaluation, by means of which I dealt with each day with the recorded height of snow cover separately. In favourable climatic conditions I adopted as an input component in my calculating the soil moisture balance the amount of the melt snow, whereas the potential precipitation was assumed to reflect the increase of the snow cover's thickness. For the studied period of two hydrological years, the average number of days with different precipitation types and with snow cover is demonstrated in Figure 12.

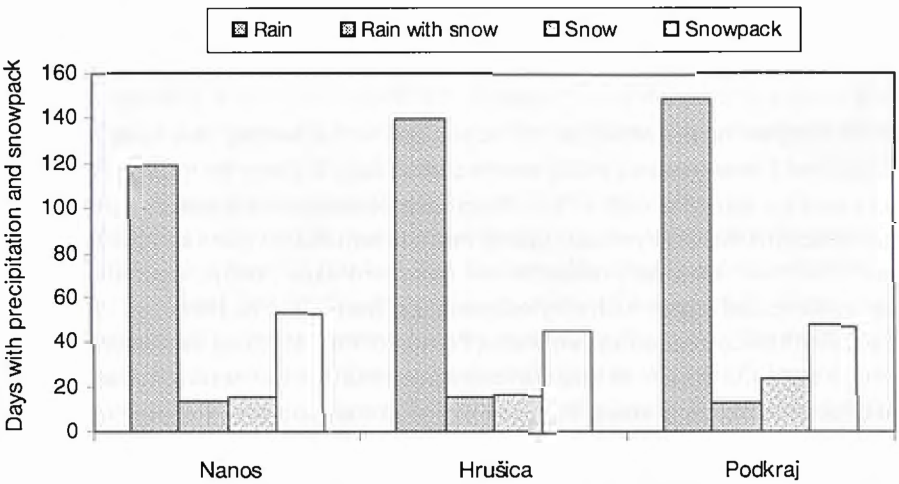


Figure 12: Number of days with different precipitation types and having snow cover in the period from 1993 until 1995

INTERCEPTION

In the equation of the evaluation of effective infiltration it is not the entire measured or corrected precipitations that are taken into account as the input component, but only that part of the precipitation which actually reaches the ground and is not intercepted by vegetation. Numerous studies described in the literature (Calder 1977, Gash & Stewart

1977, Gash & Morton 1978, Rutter *et al.* 1971, Stewart 1977) have demonstrated the significant effect that precipitation interception exerts on the recharge of the aquifer. The interception is defined as the process by which precipitation falls on vegetative surfaces, whereas the loss due to this interception is the share of water which returns back into the atmosphere by evaporation. It depends on vegetation type and stage of development, and the intensity, duration, frequency and form of precipitation. Because these factors fluctuate quite considerably, the proportion of interception is also subjected to change (Dingman 1994).

I took the process of interception into account in the water balance of the study polygon, because approximately 4/5 of the Vipava springs recharge area is covered by forest and for that reason the amount of water intercepted by the vegetation cover is by no means negligible. In this area (Fig. 13) one may detect 6 different land use types (Puncer *et al.* 1982). The central part of the karstic recharge area, and at the same time also its largest share (around 57 %), is covered by mixed fir and beech tree forest; it is followed by 15.9 % of meadows, shrubs cover some 15 %, deciduous forest 6.2 % and coniferous forest 4.2 %, whereas the remaining part of this territory represent smaller and interconnected settlement areas with urban and agricultural surfaces (slightly over 1 %).

The water loss due to interception is very difficult to measure; that is why hydrological investigations mainly apply various conceptual models (Rutter *et al.* 1971, Rutter

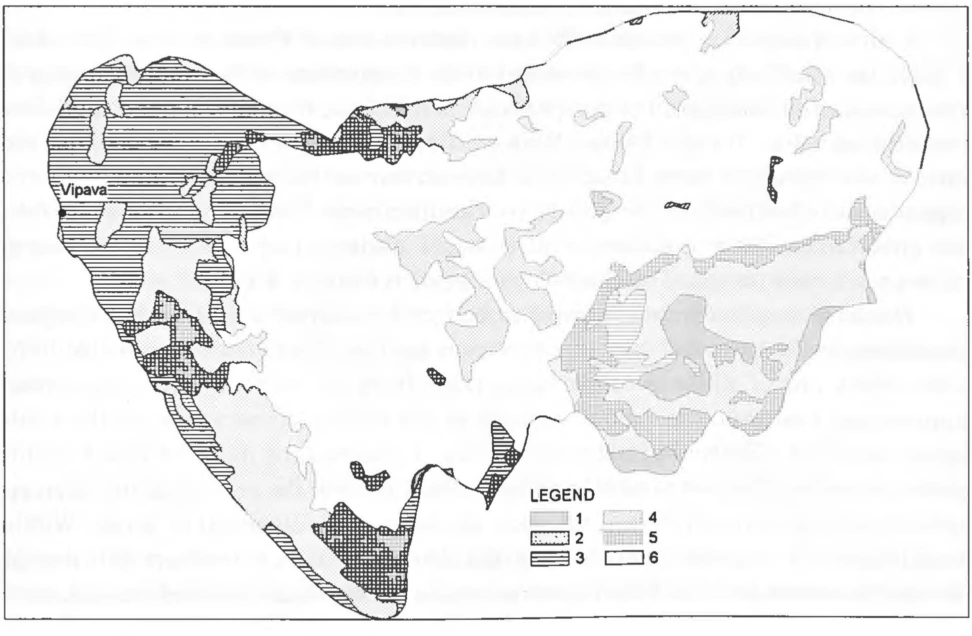


Figure 13: Vegetation map (1. Urban and agricultural surfaces, 2. Meadows, 3. Shrubs, 4. Coniferous forest, 5. Deciduous forest, 6. Deciduous-coniferous forest)

1975, Gash & Stewart 1977, Gash & Morton 1978, Sauter 1992, Dingman 1994). When dealing with the Vipava springs recharge area, I used as a conceptual basis the Rutter model, which computes a running water balance of the forest canopy and the tree trunks (Rutter *et al.* 1971).

The water in the canopy and on trunks is supplied by precipitation and removed by evaporation and by drainage towards the ground (Fig. 9). Precipitation in forested area (P_f) partly passes unhindered through the vegetation (P), and the rest falls on canopy (P_c) or trunks (P_t). When the actual amount of water on the canopy C_c exceeds the storage capacity S_c, evaporation E_c occurs according to the Penman formula (Dingmann 1994). The quantity of water which is drained from the foliage to the ground D_c is equal to the difference between C_c and S_c. Yet in the case when C_c is lower than S_c, the drainage is zero and the actual evaporation in comparison with the potential decreases by a factor represented by a quotient between C_c and S_c. Similar relations for D_t and E_t are present also in ascertaining the share of the runoff along trunks on the basis of the comparison between parameters C_t and S_t.

Another dilemma in hydrological practice occurs also in determining parameters which describe the properties of the canopy and trunks. A range of studies, which compared the results of the conceptual model with field measurements of specific interception parameters, ascertained these properties on the basis of various experimental measurements. In the analyses of the water balance, however, they are frequently just transcribed from the available literature and subsequently simply incorporated into the calibration of the effective infiltration evaluation model.

I applied such an approach to the karst recharge area of Vipava springs. First of all, I tested the sensitivity of the Rutter model to the fluctuations of the canopy capacity in the ascertained conditions. For comparison's sake I chose from the reference literature two extreme values: 0.8 and 7.6 mm. With presumed constant values of the other parameters of the vegetation cover I calculated for both extreme examples the amount of precipitation which actually reaches the floor. The differences between the obtained results are quite large, for the deviation of daily values amounts to 6.8 mm and the overall difference for the period of two hydrological years is equal to 970 mm.

Due to these differences and owing to the fact that, on the basis of our knowledge of conditions in the karst recharge area of Vipava springs, it is virtually impossible to resolve which one of all the possible values taken from the reference literature is most appropriate, I adopted the canopy capacity as the calibration parameter in the established model of effective infiltration evaluation. I assumed the different values for the green (when the foliage is present) and for the bare parts of the year, since the interception capacity is markedly dependant upon the size and development of leaves. Within such framework the model's sensitivity to the changes of trunk parameters were negligible and the selected values of trunk parameters did not significantly affect the evaluation of the precipitation reaching the ground. When dealing with the vegetation cover of the karst recharge area of Vipava springs I thus adopted values already used by Gash and Morton (1978). As calibration parameters, however, I introduced the share of precipitation that passes unhindered through the vegetation and reaches the ground (free throughfall coefficient) as well as the percentage of precipitation taken up by trunks.

The procedure of the model's calibration is described later, while at this point I am just stating those parameter values that were included in the final calculation. I therefore adopted 2.8 mm as the value for the canopy capacity in the green part of the year, whereas for the part of the year without foliage this value was 2 mm. Owing to the calibration nature of the parameter I did not introduce a separate distinction between deciduous and coniferous forest. For the free throughfall coefficient I took the value of 32 % and for the trunk water capacity 0.014 mm, whereas for the proportion of rain that is diverted to stemflow 1.6 %.

By entering these parameters into the Rutter model I determined the average share of interception for the entire observation period of two hydrological years as 16.5 % and, when divided into the green and bare part of the year, as 17.4 % and 14.8 %, respectively. The daily values however, being dependent on the intensity of precipitation and on the type of season, may fluctuate between 2 % and 68 %. For comparison I may point out some examples in similar literature. Dingman (1994) summarises the results of measurements and evaluations of the intercepted precipitation for 41 different tree combinations at 25 locations in various countries of the world. The share of interception ranges between 5 % and 49 %. Chow and his co-researchers (Chow *et al.* 1988) state that in the green part of the year 10 % to 20 % of the entire precipitation is intercepted. They also emphasise the dependence on the intensity of the precipitation. In case of precipitation lower than 0.25 mm the interception would range from 40 % to 100 %, whereas in case of precipitation being above 1 mm, it would equal 10 % to 40 %. For the area of White Mountains Chow (1964) gave two examples of deciduous trees that intercepted 20 % and 15 % in the green season and 17 % or 12 % in the bare season when the leaves were shed. The comparison of the obtained results with already described values from the literature, as well as the data on the vegetational composition of the karst recharge area of Vipava springs, demonstrates that they can be ranged into the lower end of values presented in the reference literature. This appears entirely acceptable when taking into account the fact that the Vipava's recharge area belongs to the area of intensive precipitation with annual average values at approximately 2000 mm. It has namely been proved that the share of interception declines proportionally with the rise of the precipitation intensity.

SNOWFALL AND SNOW MELTING

Climatic characteristics in the karst recharge area of Vipava springs are of such a kind that, due to the effect of the water retention in the form of snow cover on the land surface, they play a very significant role in the assessment of the effective infiltration in case of the snow precipitation. Snowfall may occur already in November and snow may remain present at certain spots until May. Due to the accumulation of snow the share of precipitation that is directly infiltrated into the soil decreases. In favourable climatic conditions the snow afterwards begins to melt and with a certain time lag the water starts to infiltrate into the soil.

At the three precipitation stations in the area of the karst recharge area of Vipava springs data on the thickness of the snow were recorded on between 39 and 54 days in the entire measuring period of two hydrological years. The overall thickness of freshly fallen snow amounted to 398 cm on Nanos (177.5 and 220.5 cm), on Hrušica 460.5 cm (211.5 and 249 cm) and in Podkraj 283.5 cm (118.5 and 165 cm). In the year 1993/94 snow fell for the first time on 13 November 1993 and the last of it melted away on 21 April 1994, whereas in 1994/95 the first snow occurred on 9 October 1994 and the last of it disappeared on 2 April 1995.

Already in presentation of this basic characteristic it is quite obvious that the share of the snow precipitation in the recharge area of Vipava springs is by no means negligible. For up to 5 or even 6 months in a year, differences in infiltration may occur due to the storage of the snow precipitation in the form of snowpack or due to the snowmelt. Another thing to be taken into account is the fact that errors in measuring the snowfall quantities and the thickness of the snowpack are relatively large, primarily due to the effects of wind and to an inadequate measurement method. Precipitation stations in the recharge area of Vipava are not equipped with special equipment for measuring the snowfall and for that reason the data at our disposal are merely the approximate daily values of the water equivalent of the presumed level of the fallen snow. What they do record, however, is the type of the precipitation, which enables us to distinguish between those days when it snowed only and the days when the snowfall was combined with rain. The thickness of the snowpack D_s and the thickness of the freshly fallen snow D_{sn} were recorded separately as well.

Owing to the ascertained characteristics and lack of measurement data I dealt with the snow precipitation in my effective infiltration evaluation as an independent part of the recharge, represented by the melting of the snow cover. I assumed that during days with snowfall the amount of precipitation which reaches the ground $P_g = 0$; and this is why the measured values of precipitation P_m during those days were not included in the calculation of the water balance. Instead of them I made use of the data on the thickness of the snowpack, which was also regularly measured at all three stations. I calculated, according to the selected empirical equations, for all days with the recorded thickness of the snowpack and with favourable climatic conditions, the quantity of the water that originated from the melted snow which contributed a certain portion to the overall effective infiltration.

Basic methods for the assessment of the amount of the melted snow are the degree-day method and the method of energy balance. Due to the lack of adequate data one may make use of various empirical formulae. These were defined on the basis of field observations and measurements at specific locations and for that reason should, strictly speaking, be applied only to those restricted areas. In the absence of any better solutions, however, they may be in practice adopted also for environments with slightly different conditions. With regard to the data at my disposal and with respect to the anticipated results I availed myself in my assessment of the snow melting in the karst recharge area of Vipava springs of the equations introduced by the US Army Corps of Engineers (1960), which proved to be the simplest. They are presented in various forms according to the precipitation and vegetational conditions. In days with rainfall we evaluate the quantity of the melted snow in the forest area according to the first of the equations 4 below, whereas on meadows and the areas only partly covered by forest it is done according to the second of the equations:

$$M = (0.3 + 0.012 \cdot R) \cdot T + 1.0 \qquad \textit{and} \qquad M = (0.1 + 0.12 \cdot R + 0.8 \cdot k \cdot v) \cdot T + 2.0 \quad (4)$$

where:

M	daily amount of the snowmelt (mm)
R	daily precipitation (mm)
T	mean daily air temperature (°C).
k	basin parameter (between 0,3 for medium dense forest and 1,0 for open grassland)
v	wind velocity 10 m above ground (m/s)

In days without rainfall, the melting of snow depends exclusively on the air temperature T_m. The first one of equations presented below applies to the forested areas, whereas the second applies to the open areas. M is given in inches, while T_m in °F:

$$M = 0.05 \cdot (T_m - 32) \qquad \textit{and} \qquad M = 0.06 \cdot (T_m - 24) \qquad (5)$$

Taking into account the precipitation conditions and the distribution of the vegetation in the recharge area of Vipava springs, I adopted the most suitable combination of the presented equations and for the period of two hydrological years (1993-1995) calculated the daily values of the snowmelt. I afterwards compared these results with the field measurements. Armbruster and Leibendgut (1997) investigated conditions in the area of Nanos and Hrušica during the snowmelt for only a short time in April 1996. Subsequent to the heavy rainfall on 1st and 2nd of April, the recharge area was completely covered with snow. The intensive melting started after 5 April, when the average temperatures rose to 8 °C. The average daily amount of the melted snow was evaluated at 20 mm/day, on the basis of the measurements using specially prepared plates that were located at different altitudes. Using the above-mentioned equations, I myself calculated the average daily amount of the melted snow for the same time interval at 18.3 mm.

The correspondence of values within this short interval was satisfactory. To obtain more reliable evaluation of the method's adequacy one should of course perform the comparison over a much lengthier time period and in different weather conditions. Due to the lack of any adequate field measurements, however, this proved to be impossible.

EVAPOTRANSPIRATION

Precipitation that reaches the ground and the snowmelt represent the source of water for the soil moisture balance, whereas the evapotranspiration expresses all those processes during which water on the soil's surface or very close to it is passing from its liquid or solid state into the atmospheric vapour. In the calculation of the potential evapotranspiration the Penman equation is fairly frequently being used (Penman 1948):

$$ETP = (\frac{\delta \cdot H}{\gamma} + E_a) / (\frac{\delta}{\gamma} + 1) \quad (6)$$

where:

ETP	potential evapotranspiration (mm/day)
δ/γ	relation between the slope of the curve of the saturated vapour pressure plotted against the temperature and the hygrometric constant (-)
H	available heat (mm/day)
E_a	aerodynamic evaporation (mm/day)

Owing to the fact that this equation was originally developed for calculating the evaporation from water surfaces, the areas overgrown by vegetation should require certain modifications. In one modification (Shaw 1994), the parameters H and E_a are calculated as:

$$H = (1-r) \cdot R_a \cdot (0.18 + 0.55 \cdot \frac{n}{N}) - 0.95 \cdot \sigma \cdot T^4 \cdot (0.1 + 0.9 \cdot \frac{n}{N}) \cdot (0.56 - 0.092 \cdot \sqrt{e_d}) \quad (7)$$

$$E_a = 0.35 \cdot (e_a - e_d) \cdot (1 + \frac{u_2}{100}) \cdot (1 + \frac{h}{20000}) \quad (8)$$

where new parameters are:

r	albedo (-)
R_a	solar radiation (fixed by latitude and season) (mm/day)
n	measured sunshine hours (h)
N	maximum possible sunshine duration (h)
σ	Stefan-Boltzmann constant (5.67×10^{-8} W/m^2K^4)
T	air temperature (° K)
e_d	vapour pressure of air (mm Hg)
e_a	saturated vapour pressure (mm Hg)
u_2	mean wind velocity at 2 m above ground (km/day)
h	altitude (m)

In the Nanos meteorological station the following parameters are regularly measured: the mean air temperature (T), wind velocity 10 m above the ground (u_{10}) and the relative air humidity ($\rho = 100 \times e_d/e_a$). I took parameters δ/γ, N and R_a from tables, whereas e_a is defined by an equation dependent on the air temperature (Dingmann 1994). I determined the albedo on the basis of typical values for different types of vegetation, which are already available in relevant literature (Dingmann 1994). Parameter h represents the mean altitude. Because meteorological parameters at the Hrušica and Podkraj stations were not measured I calculated daily values of potential evapotranspiration at the Nanos station and subsequently adopted them as typical of the entire recharge area of Vipava springs.

SOIL MOISTURE BALANCE

All the methods described enable us to ascertain the quantity of precipitation that reaches the ground, the amount of the melted snow and the potential evapotranspiration, whereas the evaluation of the actual evapotranspiration and the changes in the water storage in the soil depend on the hydrological properties of the soil. All parameters are included in the soil moisture balance, which represents the basis for establishing the model for evaluation of effective infiltration (Fig. 9).

The process of storing water in the soil is connected with the changes in the soil moisture, which in turn depend on the ratio between the input and expenditure of water and on the hydrological properties of the soil. These are: soil moisture, field capacity, root constant and the maximal moisture deficit or the wilting point. The soil moisture S represents the water which is retained within the soil due to capillary forces. It is extremely sensitive to the effects of precipitation and evapotranspiration, and for that reason changes in those two parameters are always accompanied by changes in the soil moisture. If the precipitation is greater than the evapotranspiration, the soil moisture increases until it reaches the field capacity. The field capacity FC stands for that value of saturation at which drainage influenced by gravity occurs and at which effective infiltration also begins. When evapotranspiration exceeds the precipitation, the soil moisture starts to decrease. In normal atmospheric conditions, however, evapotranspiration cannot entirely dry up the soil. For that reason evapotranspiration in most cases continues at maximal or potential value only to the point when the soil moisture decreases to the value of the root constant RC. This value represents the quantity of water which is available within the reach of roots and is expressed by the rainfall equivalent. Within the range between the root constant and the wilting point WP, actual evapotranspiration continues at the lower level. The wilting point is attained at the moment when the soil moisture is so reduced that plants are unable to draw up the water (Howard & Lloyd 1979). The subsequent dilemma in hydrological practice is how to ascertain these characteristics of the soil. Field measurements give rise to a multitude of difficulties and are usually restricted only to small sized test polygons. That is why we frequently adopt the values straight from the literature, which we afterwards correct in the calibration process of the model for the evaluation of effective infiltration.

I procured the basic information on the soil characteristics of the recharge area of

Vipava springs from the pedological map put at my disposal by the Centre of Pedology and the Protection of the Environment as well as from the published data on pedological profiles (Lobnik 1991). In the karst area investigated the prevailing soil type is rendzina; only in insignificant quantities and as an addition to rendzina one may notice also brown carbonate soils and lithosol. Some supplementary data on the hydrological characteristics of these kinds of soils were yielded also by results of research carried out on the small study polygon in the Trnovski gozd area under the 7th SWT project (Vrevc 1994). Taking into account characteristics obtained thus and in accordance with the calibration of the model for the evaluation of effective infiltration I adopted, with regard to the uniformity of the pedological composition and insignificant variability of the soil thickness, a field capacity value of 100 mm, root constant of 95 mm and a wilting point of 85 mm for the entire area.

As already mentioned, by taking into account these parameters it is assumed that the effective infiltration may be carried out only if the moisture exceeds the field capacity. Detailed research of the infiltration processes has demonstrated that the so-called rapid recharge I_r may take place entirely independent of this condition anyway (Rushton & Ward 1979). In such case the precipitation water infiltrates through the cracks in the soil and is not conditioned by prior fulfilment of the soil moisture deficit. One of the methods that takes this process into consideration is based upon the threshold determination (Jeannin & Grasso 1995, Sauter 1992, Veselič *et al.* 1989). I applied it also to my evaluation of the effective infiltration for the recharge area of Vipava springs. For the model calibration I adopted a quantity of 6 mm as the most adequate threshold value. The excess precipitation is used directly for infiltration, whereas the remaining part stands for the input component in the calculation of the soil moisture balance.

SECONDARY INFILTRATION

The evaluation of secondary infiltration proved to be more immediate owing to the possibility of measurements of the discharges of sinking streams supplying the karst aquifer. The most important among the sinking streams in the recharge area of Vipava springs are those located at the north-west edge of Pivka basin: i.e. Lokva and Belščica as well as some temporary streams at Šmihelske ponikve, Stranske ponikve and sinking streams south of Bukovje (Fig. 8). Quite exceptional, however, is the case of the Bela stream, which is supplied by intermittent Vipava springs at high waters, while at low or medium waters it sinks underground along its bed and flows towards the permanent Vipava springs. The surface and groundwater interaction of the Bela stream and Vipava springs is more thoroughly discussed in the following chapter.

The Lokva stream sinks at an altitude of 462 m in the lower part of the Predjama cave, underneath the 123 m high wall of Predjama castle. The minimum measured discharge of Lokva in the period 1994/95 amounted to 19 l/s, the mean one to 215 l/s and the maximum one to 10.8 m^3/s. The Belščica stream sinks into the Jama v grapi cave.

The measured discharges for the period from 1993 until 1995 ranged between 21 l/s and 2.77 m^3/s, whereas the mean discharge was 132 l/s. In addition to both main tributaries there are also some other smaller streams in the area considered, which also sink underground (Habe 1970). The small stream at Stranske ponikve attains the discharge of approximately 10 l/s at high waters, whereas at low waters it may even dry up. Slightly larger is the stream at Šmihelske ponikve with a maximal discharge of 50 l/s. The Ribnik and Mrzlenk streams sink in the blind valley under the village of Bukovje, their discharge being 50 l/s. The largest among them is the Osojščica, which disappears from the surface into the Osojca cave, pouring into it an amount up to 150 litres per second.

Within the framework of the 7[th] SWT project, the Hydrometeorological Survey equipped Belščica at Bukovje and Lokva at Predjama with limnigraphs and staff gauges. The data on mean daily discharges of Belščica which were put at my disposal covered the period of two hydrological years from 1993 until 1995; whereas the measurements on Lokva began only in 1994, and so data for 1993 are not available. For the purposes of the elaboration of the recharge evaluation I consequently determined these data on the basis of the correlation with discharges of Belščica, which are governed by a similar hydrological regime. The correlation coefficient for the data collected from 1 January 1994 to 31 December 1995, when the measurements were carried out on a regular basis at both gauging stations, is equal to 0.88.

For other, smaller sinking streams, only approximate discharge evaluations at dif-

The Lokva stream is flowing on the flysch surface and sinking below the Predjama caste at the contact with karst aquifer (Photo M. Petrič) ferent hydrological conditions were available. By comparing them to the similar hydrological regime of Belščica I evaluated their combined overall capacity at 25 % of the Belščica's discharge.

Comparison between the evaluated total inflow of sinking streams at the edge of the Pivka basin (R_{nk} on Fig. 9) and the total discharge of Vipava springs demonstrates that the share of secondary infiltration for the considered period of two hydrological years amounted to only around 6 % (Fig. 14). In consequence of this I conclude that the error due to the application of approximate evaluations exerts a negligible effect on the overall recharge function.

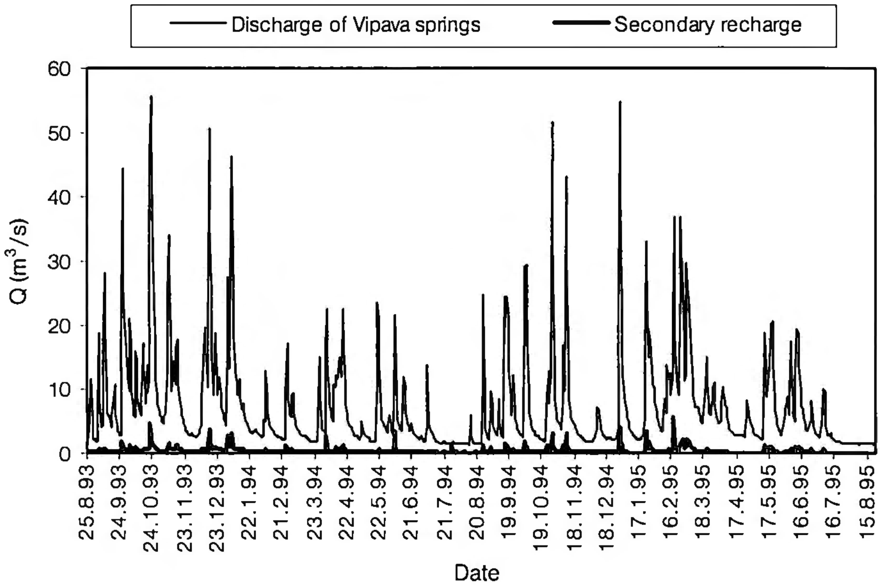


Figure 14: Comparison between discharges of Vipava springs and the tributaries from the non-karstic part of the recharge area in the period from 1993 to 1995

SURFACE AND GROUNDWATER INTERACTION OF THE BELA STREAM AND VIPAVA SPRINGS

The Bela stream collects its water in the area of very low permeable flysch at the northwest edge of Nanos; subsequent to its entering the limestone area it starts to sink underground along its course. It is only at high waters that it flows as an overland stream up to the town of Vipava and afterwards flows into the Vipava river. Some studies from the past already indicated the hydrological connections between the Bela stream and the Vipava springs. Comparing specific electrical conductivity of the individual permanent Vipava springs it has been discovered that the spring Vipava 7 markedly differs from all the others (Harum *et al.* 1997). During two tracing tests with the injection of tracer into the recharge area of Vipava springs, this spring displayed a different tracer breakthrough curve (Behrens *et al.* 1997, Zupan 1997). By observing changes in the Bela's discharge, however, its sinking underground at various spots along its overland flow has been ascertained.

Besides the Bela's inflow to the Vipava springs, field observations detected also the reversed connection, whereby at high waters the intermittent Vipava springs flow into the Bela stream. The activation of these springs is reflected also in comparison of discharges of individual permanent Vipava springs. In addition to their overall discharge the total discharge of springs Vipava 6 and Vipava 7 were also measured in the period from 1 January 1994 to 23 August 1995. For the purpose of comparison and on the basis of these data I separated the springs into two groups. The first one comprises both the previously mentioned springs (Vipava 6 and 7), whereas the second includes all the other permanent Vipava springs. The ratio of mean discharges of both groups is approximately 1 : 1.3, while that of maximal discharges is 1 : 4.5. The comparison of daily values reveals similar deviations as well (Fig. 15). The most typical differences occur in case of springs Vipava 6 and Vipava 7 during high waters when discharges are considerably restricted. The discharge is most likely limited by the permeability of fissures at both springs; simultaneously, however, the temporary springs north of Vipava 7 also get activated.

We have inferred the hydraulic connection between the flow of Bela and Vipava springs already on the basis of the above observations, yet in order to determine this connection in more precise terms, I elaborated a plan for additional research. It included a tracing test with injection of the tracer into the Bela's overland flow and the measurement of its discharge at different points along its course. Gerry Baker from Ireland, MSc student at the University Newcastle Upon Tyne (GB), subsequently joined our research. He undertook the major part of the field measurements and of the sample taking during the tracing tests as well as processing of the measured values. The tracing test was supervised by Janja Kogovšek from the Karst Research Institute ZRC SAZU. The results were published in their entirety (Baker *et al.* 2001). At this point I will try to

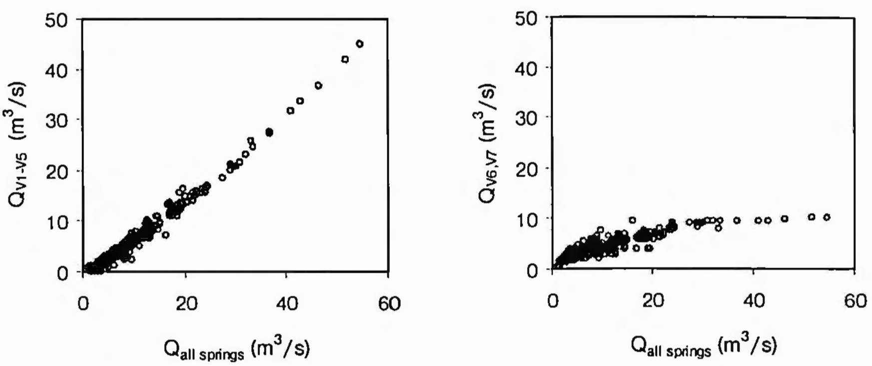


Figure 15: Comparison of discharges of two groups of permanent Vipava springs

Bela surface stream is sinking along its riverbed (Photo M. Petrič)

summarise some of the basic findings about the correlation between the Bela stream and Vipava springs.

On 29 May 2001, the first injection of 170 g of uranine tracer into the Bela stream was carried out about 2.8 km away from the Vipava springs. The discharge of Vipava springs measured at that time was 3.8 m^3/s, yet after two days a short but fairly intensive storm occurred and on 1st of June 2001 the discharge rose to 22 m^3/s. Samples were taken automatically each hour by the automatic sampler ISCO 6700 at the spring Vipava 7, as well as manually once or twice a day at all the other permanent Vipava springs. The fluorescence analysis was performed in the laboratory of the Karst Research Institute ZRC SAZU with the luminescent spectrometer LS 30 (E_{ex}=492 nm, E_{em}=515 nm) in June and July. Primarily, we analysed the crude and afterwards also the filtered samples (filter 0.45 μm). A probe YSI 600 was attached to the automatic sampler, with which we measured the specific electrical conductivity and temperature at five-minute intervals. We measured both parameters also at other springs by means of the WTW conductivity meter LF 196. At the same time we undertook 10 measurements of the overall discharge of the Vipava 6 and 7 by current meter OTT C20, and we additionally carried out two separate measurements at both springs as well.

To monitor the variability of the discharge we selected eight points for discharge measurement. All chosen points were regularly distributed across the area between the village of Sanabor and Vipava town (Fig. 16). Parallel to these activities, the specific

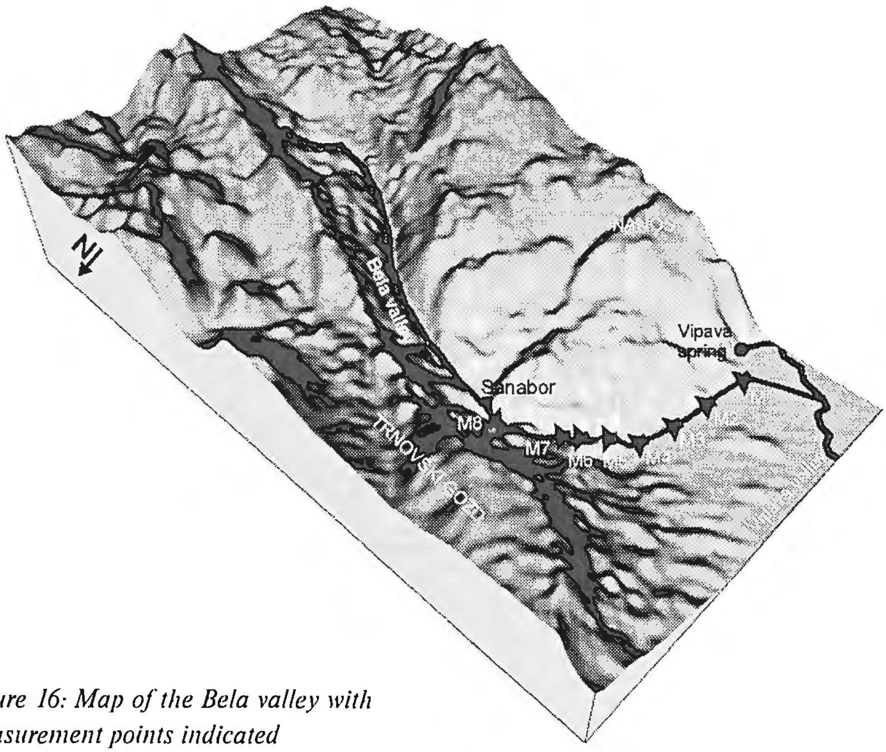


Figure 16: Map of the Bela valley with measurement points indicated

electrical conductivity and temperature were also measured at these points by means of WTW conductivity meter LF 196.

Hydrological conditions during the observation period from 29 May until 30 June are shown in Figure 17. The values of daily precipitation were measured at the Nanos station, which reflected the conditions prevalent in the major part of the karst recharge area of the Vipava springs, and at the Podkraj station which is located at the flysch recharge area of the rivulet Bela. Discharges of Vipava were measured at the spot where the water from all seven permanent springs joins into one stream; this data was provided by the Environmental Agency (at present it unites all former services of the Hydrometeorological Survey). The missing data for the overall discharges of Vipava 6 and 7 were determined on the basis of correlation with the discharges of the Vipava springs. Owing to the fact that the comparison was carried out at low waters, the correlation was sufficiently high (R^2=0.97). Individual measurements of discharges of Vipava 6 and 7 revealed that the share of Vipava 7 amounted to around 50 %, whereas that of Vipava 6 was approximately 5 % of the measured total discharge. This may lead us to conclusion that there might exist some other additional tributaries prior to the confluence. In the evaluation of discharges for individual springs we took this relationship into consideration with regard to the total discharge of Vipava 6 and 7.

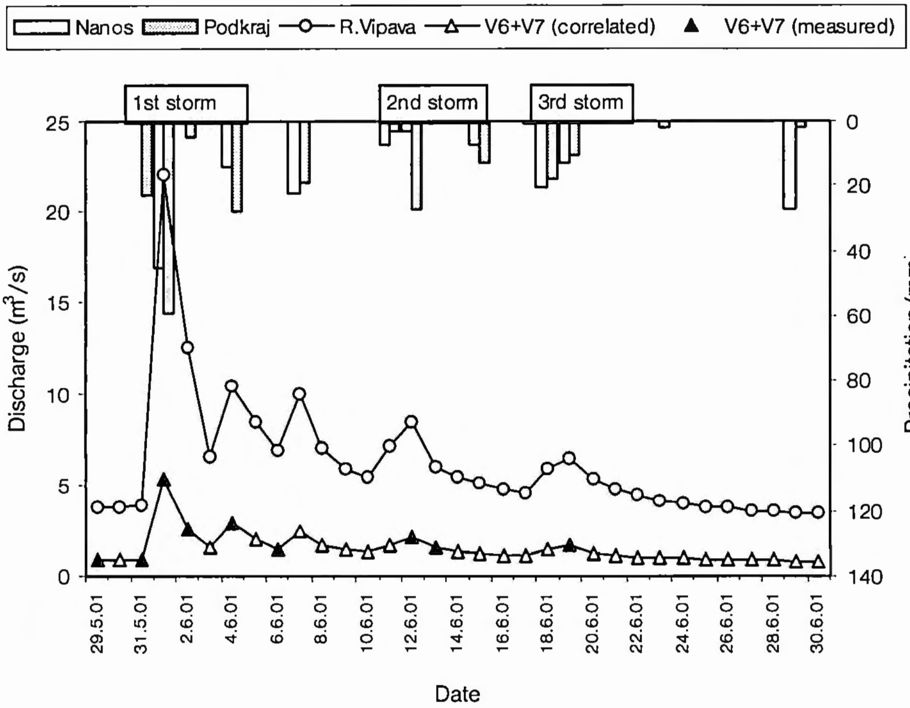


Figure 17: Hydrological conditions in time of the tracing test

The outcomes of the monitoring of the tracer concentration at the observed Vipava springs are shown in Figure 18. The uranine showed up most conspicuously in Vipava 7 and slightly increased concentrations were recorded also in Vipava 6 and 5, whereas other springs displayed rather insignificant responses. Of considerable interest is the comparison with the curve of total discharges of springs Vipava 6 and 7. The tracer started to emerge only when the discharge, after the intensive storm, already began to subside, or in other words, parallel to the renewed increase of the discharge. The peak value was attained 136 hours after the injection, which gave us the dominant apparent velocity of 20 m/h. The subsequent, lower peaks of the discharge curve corresponded to the increased tracer concentrations as well. Also noteworthy was the relative increase of concentrations in springs Vipava 6 and 5 and especially in springs Vipava 3 and 2 when compared to those of Vipava 7 after the precipitation of 11 and 12 June. This precipitation event differed from the first, which caused the marked discharge increase in the beginning of June, in the ratio between the rainfall quantities of Nanos and Podkraj stations. During the first precipitation event, over 40 mm of rain fell at both station, whereas during the second, the rainfall was fairly intensive only at Podkraj station with 20 mm and practically negligible at Nanos. Considering the fact that the recharge area of Vipava is noticeably larger than that of the Bela, the entire volume of rainfall in first event proved higher at the Nanos plateau than in the Bela's recharge area and vice versa in the second event. The third precipitation event of 18 and 19 June displayed similar characteristics as the first one, yet once again the tracer concentration in the spring Vipava 7 was relatively higher. Already these comparisons indicate that the interconnection between Bela and the Vipava springs is importantly influenced by the hydrological conditions within the recharge area.

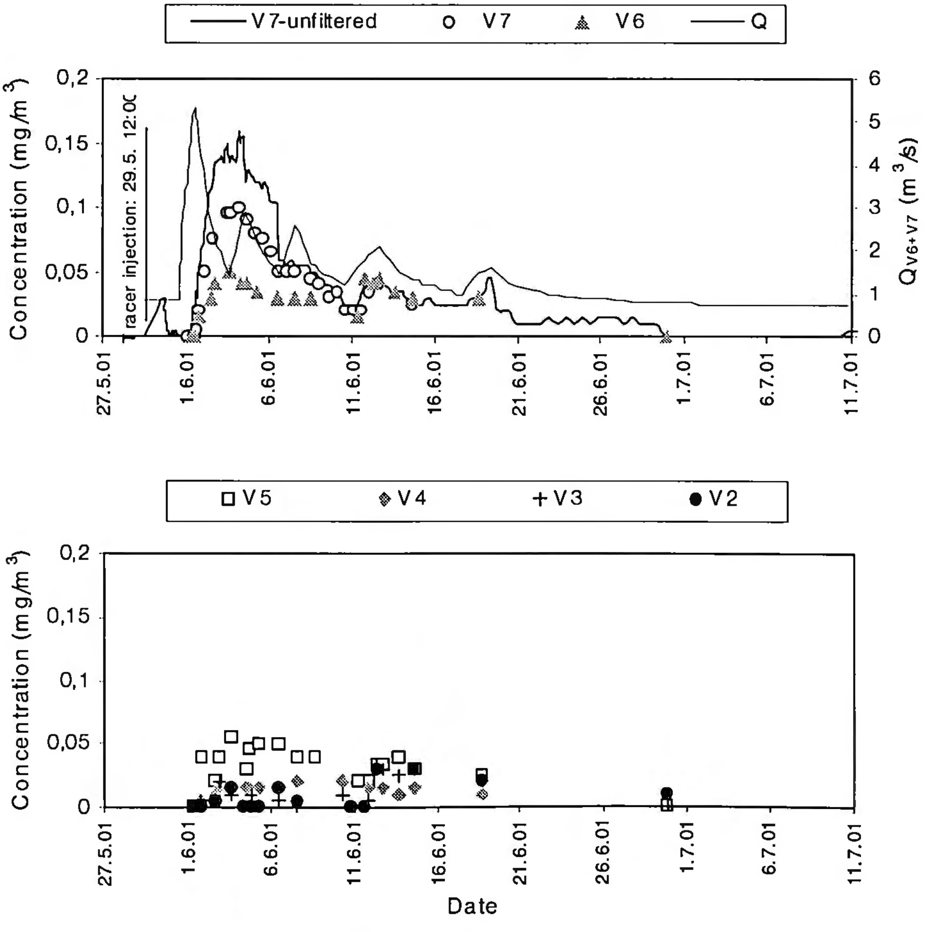


Figure 18: Tracer breakthrough curves in the Vipava springs

Similar findings were yielded also by the measurement of Bela's discharge at different points along its course. Within two weeks we carried out 8 series of measurements (Fig. 19). Bela's discharge at Sanabor (M8) was higher on 11 June (0.98 m^3/s) than on 1 June (0.521 m^3/s), while the opposite applied to Bela's discharge in Vipava, where on 1 June the discharge between points M2 and M1 increased from 0.446 m^3/s to 2.543 m^3/s. The cause of this difference was the activation of intermittent Vipava springs. It is interesting that, despite the higher discharge at M8, on 11 June these springs did not function, which again points toward the predominant influence of the flysch area on the Bela's recharge. In general the curves also reflect the great variability of discharges, because even within the same sections losses or extra quantities may occur on different days. Measurements from 1, 4 and 6 June displayed a similar trend with an exception of the M2-M1 section with its typical influence of the intermittent Vipava springs.

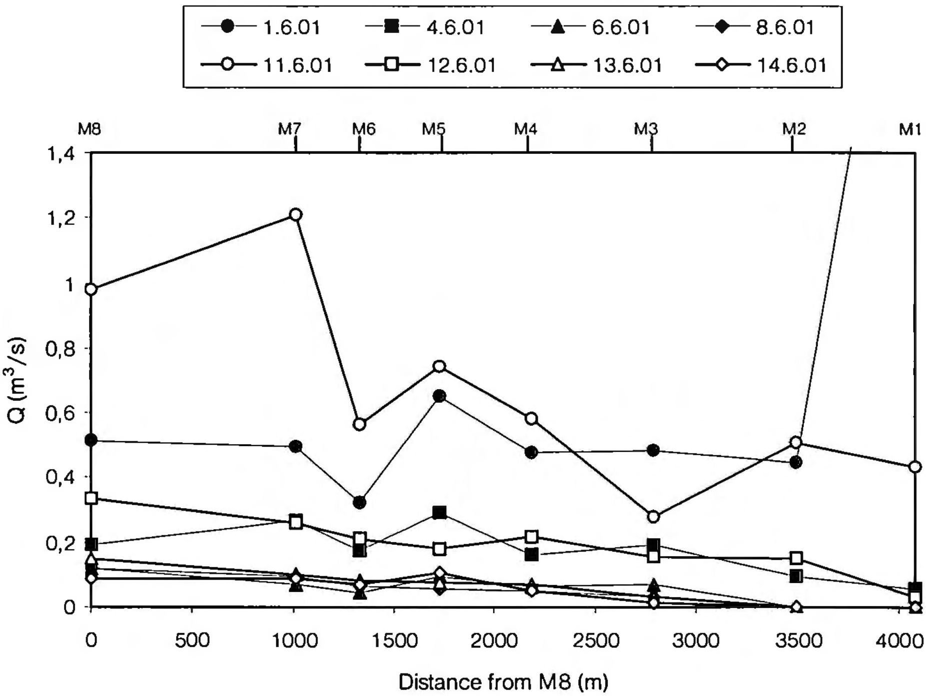


Figure 19: Discharge fluctuations in measurement points of the Bela stream. The measurement points from Sanabor village (M8) to Vipava town (M1) are proceeding from left to the right. Black symbols represent measurements in time of the first precipitation event, whereas the white those in time during the second one.

The measured discharges for each succession of two measurement points on different days were more thoroughly compared using the method described by Bonacci (1987). For each measurement the ordinate displays the measured discharges at the point located upstream, whereas the abscissa represents the difference in the measured discharges at both points. Negative values indicate loss, while positive ones denote increment in the water flow. When entering all the measurements into the graph it was impossible to ascertain typical interdependences among the obtained points. Connections became clearer after the division of the data into two groups, which were separated according to the prevailing area of recharge, that is, the flysch or the karst recharge area (Baker *et al.* 2001). Once again we could surmise the substantial role of such a division, yet because properties of these dependence are obscured by additional influences, our research was not in a position to ascertain them more accurately.

By means of a linear mixing model equation we finally evaluated also the share of water from Bela that found its way into Vipava 7. In addition to discharges we took into account measured values of specific electrical conductivity. Following our hypothesis that the water from Bela as well as karst water from Nanos area are both flowing out of the spring, we set up two following equations:

$$Q_{V7} = Q_N + Q_B$$
$$Q_{V7} \cdot C_{V7} = Q_N \cdot C_N + Q_B \cdot C_B \qquad (9)$$

where:

Q_{V7}	total discharge of the spring Vipava 7
Q_N	part of the discharge of the spring Vipava 7 from the karst aquifer
Q_B	part of the discharge of the spring Vipava 7 from the Bela stream
C_{V7}	specific electrical conductivity of the spring Vipava 7
C_N	specific electrical conductivity of the spring Vipava 2
C_B	specific electrical conductivity of the surface Bela stream

The estimation of the Vipava 7 discharge is described at the beginning of the present chapter, whereas the unknown quantity in the equations is the ratio between Q_N and Q_B. The specific electrical conductivity in Vipava 7 was measured by automatic probe, whereas in the surface flow of Bela, it was done manually. As the most typical karst water from

Spring Vipava 7 at low waters with installed automatic sampler and probe (Photo M. Petrič) the Nanos area we adopted the water from spring Vipava 2, since we had previously assessed that the influence of Bela at this spot proved to be the most insignificant and negligible. With the described method of dividing the flow of Vipava 7 we found out that the share of the inflow from Bela is around 20 %. Also noteworthy were the falls in this share during the storm on 1st of June and the increase of the influence of Bela's inflow at the rainfall event on 11 and 12 June (Fig. 20).

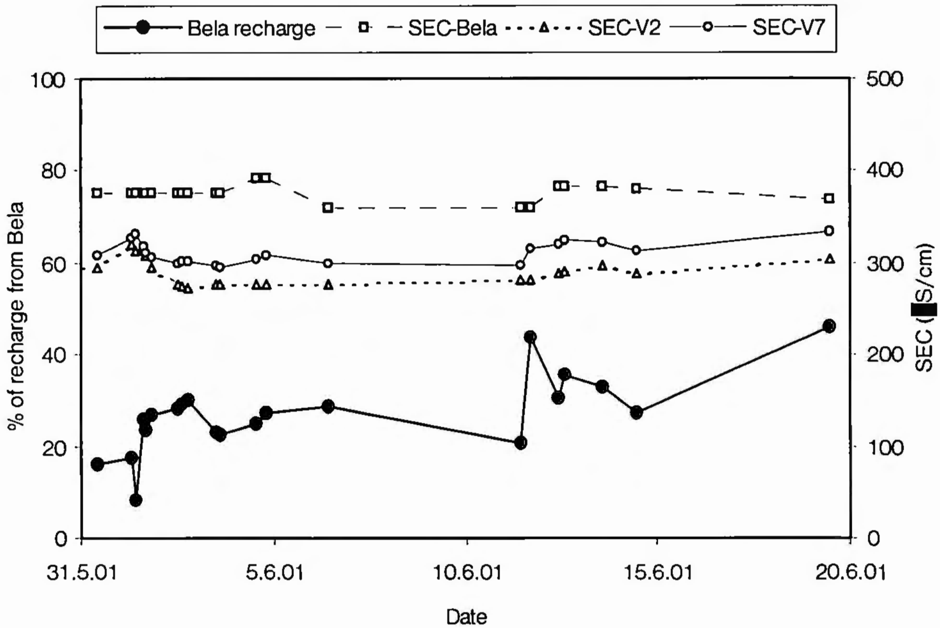


Figure 20: Dividing the flow components in Vipava 7 spring

The tracing test undertaken confirmed the assumption about the inflow of water that sank along the Bela surface stream into the Vipava springs. The flow is mostly directed towards Vipava 7 (around 60 % of the tracer returned); according to hydrological conditions, however, it runs in different shares also toward other permanent Vipava springs. It became evident that the hydrological response was changing in accordance with the share of the recharge from the karst or flysch recharge area. High waters in the direct karst recharge area of Vipava springs restricted the inflow from the Bela's direction, while on the contrary, during the period of low waters the effect of the inflow from the Bela surface stream increased not only in Vipava 7 but also and even more prominently in other permanent Vipava springs. The inflow that was hindered due to the increased hydraulic potential in the karst aquifer was probably also the reason for the delay of the tracer's arrival after the first discharge peaks on 1st of June. The functioning of intermittent Vipava springs, however, was also connected to the high waters conditions.

Our investigations thus corroborated the assumptions about the reciprocal influence between Bela surface stream and Vipava springs. The great significance of hydrological conditions exerted by the nature of this connection was distinctly manifested. The share of the infiltrated water from Bela stream and the discharge of the intermittent Vipava springs are, due to their complex nature, exceedingly difficult to quantify. Yet, because the inflow from Bela represents an addition to the recharge of the karst aquifer in the recharge area of Vipava and because the outflow through the intermittent springs, which flow together into the Bela stream and were thus not included into the measurement of the total discharge of Vipava springs, was not taken into account in the discharge function, I nevertheless included the evaluation of the effect of this connection in my recharge-discharge comparison of the considered karst system within the period of two hydrological years (1993-1995). During that time the Hydrometeorological Survey organised additional measurement of Bela's daily discharges at Sanabor Q_{Bs} and daily values of the Bela's water level in Vipava town H_{Bv}. At the second station the dependence curve $Q_{Bv}=f(H_{Bv})$ was regrettably not ascertained, but a series of individual, parallel measurements of the discharge were, however, undertaken. On the basis of this, I determined the correlation dependence, which I subsequently applied to evaluation of the Bela's discharge in Vipava town. Although the accuracy of results thus obtained is likely to be reduced, I nevertheless used them in my further analyses. Reliable, however, were values for days when the Bela's riverbed in Vipava dried up. The number of such days amounted to no fewer than 391 or approximately 53 % within the period of two hydrological years between 1993 and 1995.

With regard to the availability of data, I elaborated the evaluation of the effect of the interconnection between Bela and Vipava springs on the basis of the comparison between Bela's discharges in Vipava and in Sanabor (Q_{Bv}-Q_{Bs}). Depending on the hydrological conditions, the difference can be positive or negative. Positive values mostly reflect the influence of the functioning of the intermittent Vipava springs, whereas negative ones occur due to the Bela's sinking underground along its surface flow. Since the share of this component within the overall discharge of Vipava proved to be extremely small I decided to take it into account in its entirety during the analysis of the recharge-discharge relation or more specifically, in my determination of the discharge function. In this manner I reduced values for days with the negative difference of the measured discharges of Vipava springs by the value of the difference $|Q_{Bs}-Q_{Bv}|$; following an assumption that this part of discharges was a consequence of the recharge related to the sinking of Bela. Conversely, I added this value for days with the positive difference on the assumption that this is a case of the outflow through intermittent Vipava springs into Bela, which was not included in the measurement of the overall discharge of Vipava springs The described manner of my quantitative evaluation of the reciprocal effects of Bela and intermittent Vipava springs simplified the actual conditions and an error was consequently to certain extent unavoidable. Yet since the difference (Q_{Bs}-Q_{Bv}) represented on average only 2.8 % of the entire discharge of Vipava springs I considered it acceptable.

CALIBRATION OF THE MODEL FOR EVALUATION OF EFFECTIVE INFILTRATION

I finally connected all the described parameters into the model for evaluation of the effective infiltration in the document PREPAD of the Microsoft Excell software tool. The model is based upon the assumption that within a period of an individual hydrological year the overall effective infiltration is equal to the total outflow through the Vipava springs. The overall effective infiltration is a sum total of primary and secondary infiltration. In evaluation of the primary infiltration I took into account, in my application of the method of soil moisture balance, the precipitation which reached the ground, the quantity of snowmelt, evapotranspiration, rapid recharge and the change in the soil storage, whereas in the secondary one I considered just the measured discharges of sinking streams from the flysch edges in the north-west part of Pivka basin. Calibration parameters in the model were correlated to the assessment of interception (canopy capacity, free throughfall coefficient, proportion of rain that is diverted to stemflow), rapid recharge (threshold) and soil storage (field capacity, root constant, wilting point). Input data were represented by: measured daily precipitation and measured thickness of snow cover at stations Nanos, Hrušica and Podkraj, mean daily air temperatures, air humidity, sunshine hours, and wind velocity at the Nanos station and the measured daily discharges of Lokva and Belščica, which were corrected in accordance with the additional effects of other sinking streams from this region. As the output data I applied to the model calibration for the period of two hydrological years (1993-1995) the daily discharges of the Vipava springs, corrected with respect to the interactions between these springs and the Bela surface stream.

By selecting the most appropriate values of calibration parameters, correspondence between the evaluated values of the effective infiltration and the value of discharge

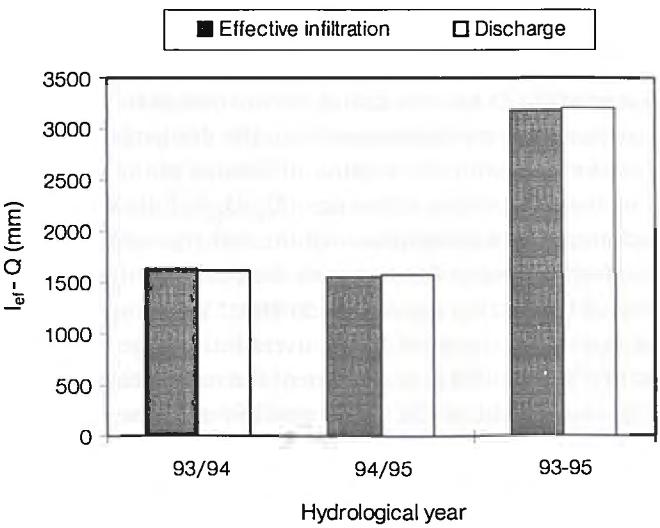


Figure 21: Comparison between effective infiltration and discharge for the period of two hydrological years

through the Vipava springs for both hydrological years and for the entire period of two hydrological years was satisfactory (Fig. 21). In the table the annual quantities of effective infiltration or the discharge during the hydrological years 1993/94 and 1994/95 as well as overall values for the entire period of two hydrological years from 1993 to 1995, which are presented in millimetres, were ascertained as the average value for the entire karst and non-karst environment (Tab. 1).

Table 1: Comparison between effective infiltration and discharge for the period 1993-1995. (The values within brackets express the mean discharge)

	1993/94	1994/95	1993-1995
Effective infiltration	1632 mm (7.924 m^3/s)	1554 mm (7.123 m^3/s)	3186 mm (7.512 m^3/s)
Discharge	1622 mm (7.876 m^3/s)	1574 mm (7.214 m^3/s)	3196 mm (7.555 m^3/s)
Difference	10 mm (0.048 m^3/s)	-20 mm (-0.091 m^3/s)	-10 mm (-0.043 m^3/s)

CALCULATIONS OF DAILY VALUES OF EFFECTIVE INFILTRATION

Finally, I applied the calibrated model to the calculation of daily values of effective infiltration in the recharge area of Vipava springs. Due to the largest extent of the precipitation zone of the Nanos area, I worked out the comparison between individual components for the period of two hydrological years from 1993 to 1995 for this same area (Fig. 22). The measured precipitation, which represented the basic data we had at our disposal in our hydrological analyses, is displayed in the upper part. Taking into account the correction of the precipitation measurement, the part of precipitation intercepted by vegetation and the quantity of the melted snow, I ascertained the input component of the soil moisture balance, which is indicated in the graph as P_g+M. Owing to the correction of the precipitation measurement, the values are increased; correction factor 1.14 for the entire interval is identical to the one, which was adopted by Pristov (1998) for the 30-year period from 1961 to 1990, whereas the daily coefficients range from 1.01 to 1.40. The decline in value is a consequence of the interception, which is conditioned by the type of season. In the forested area the share of interception amounts to 17.4 % in the green part and to 14.8 % in the leafless part of the year. These values match those from the relevant literature, when we assume that due to the relatively high intensity of precipitation in the area considered, the share of interception is proportionately lower. For the daily data the interception ranges between 2 % and 68 %. The snowmelt is indicated primarily in the time delay of the infiltration, which is conditioned by climatic conditions.

The loss in the soil moisture balance is represented by the actual evapotranspira-

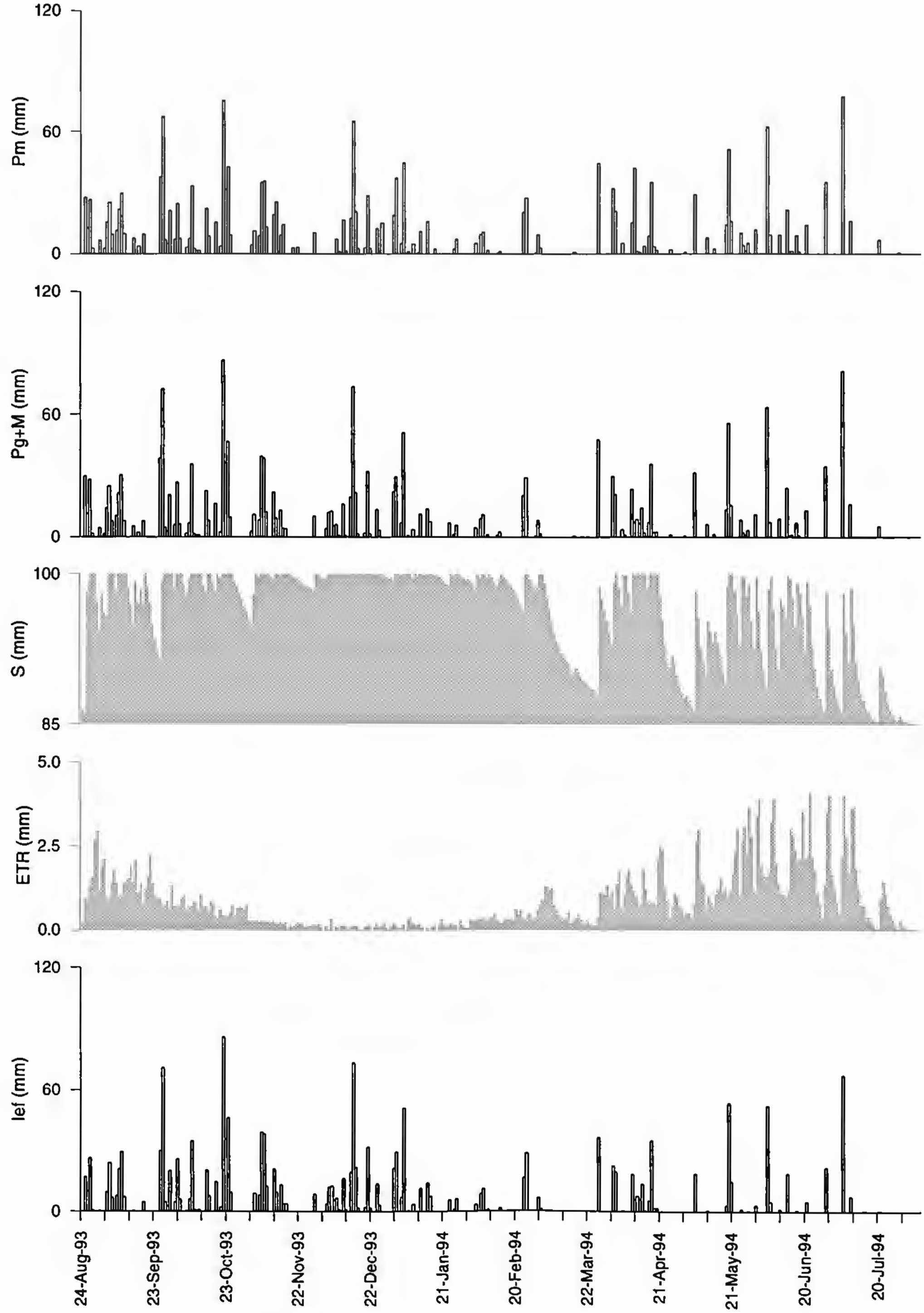
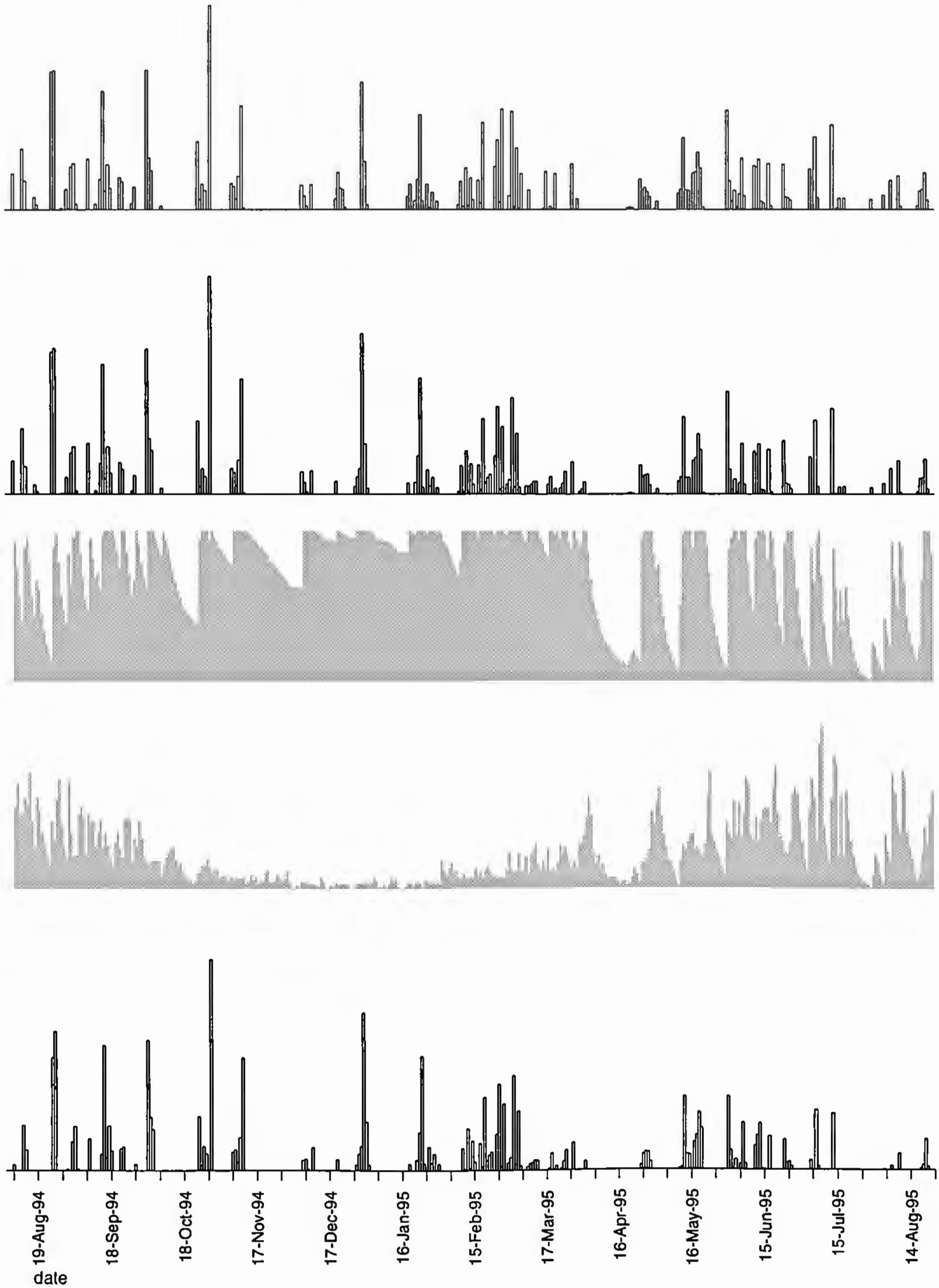

Pm (mm)
120
60
0
Pg+M (mm)
120
60
0
S (mm)
100
85
ETR (mm)
5.0
2.5
0.0
Ief (mm)
120
60
0
24-Aug-93
23-Sep-93
23-Oct-93
22-Nov-93
22-Dec-93
21-Jan-94
20-Feb-94
22-Mar-94
21-Apr-94
21-May-94
20-Jun-94
20-Jul-94

Figure 22: Comparison of the effective infiltration evaluation model's components



tion, which differs from the potential evapotranspiration according to the level of soil moisture. This component is indicated in the graph as well.

As the model's final result I represented also the daily values of primary effective infiltration in the Nanos precipitation zone. One may demonstrate the conditions typical of precipitation zones of Hrušica and Podkraj in a similar manner.

The comparison of obtained values reveals how particularly important is the effect of the application of the effective infiltration evaluation model on the seasonal arrangement of the amount of infiltration. The difference between the measured precipitation and the effective infiltration is thus characteristically greater in spring than in autumn, since it predominantly reflects the changes in climatic and vegetational conditions (Fig. 23). The lower share of the effective infiltration during spring is primarily the consequence of the exuberant vegetation growth, which is reflected in the increased effect of the interception by the vegetation cover and in the increased share of the actual evapotranspiration.

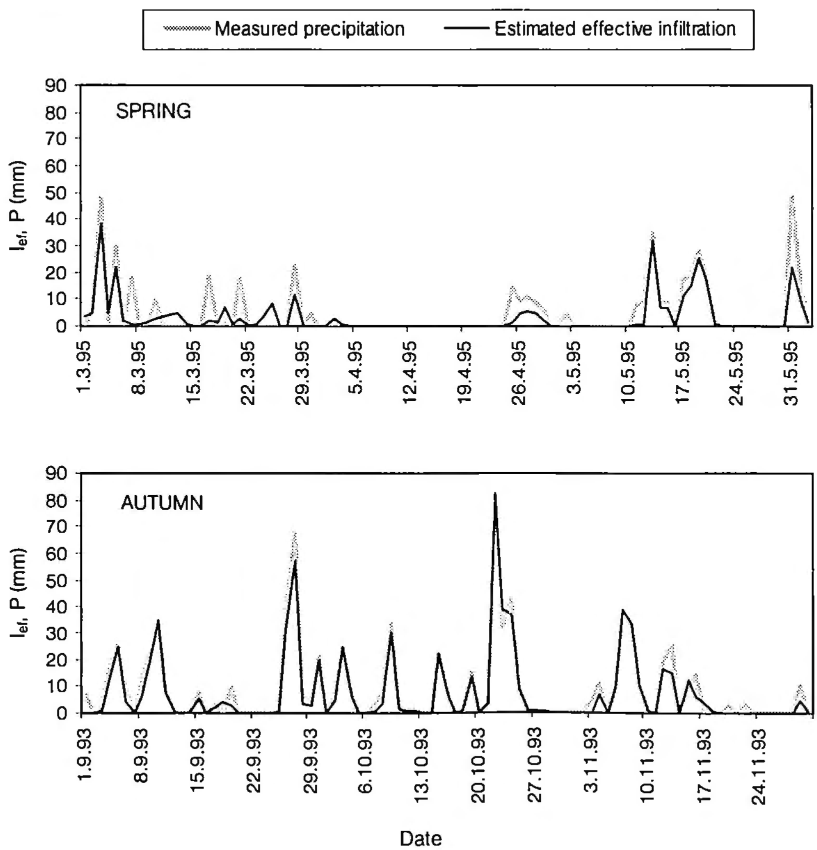


Figure 23: Comparison between the measured precipitation and the effective infiltration in different seasons

TESTING THE MODEL'S SENSITIVITY TO CHANGES OF INDIVIDUAL PARAMETERS

Finally, I tested also the model's sensitivity to changes of calibration parameters. The analysis demonstrated that the estimation of the effective infiltration proves characteristically sensitive primarily to changes of the canopy capacity and of the hydrological properties of the soil (the difference between the field capacity and the wilting point), whereas with other parameters proves to be negligible. In case of the dwindling of the canopy capacity by a half, the entire quantity of the effective infiltration rises by 5 %, whereas in case of a twofold increase the I_{ef} attains only 91 % of its basic value (Fig. 24).

The second characteristic parameter is the difference between the field capacity and the wilting point, which represents the soil moisture deficit or the soil's ability to store water. In case this difference is reduced the infiltration proportionately rises and vice versa. Noteworthy also is a comparison of the daily values, whereby we may perceive that the effect of the change in deficit is reflected only in certain soil moisture conditions (Fig. 25).

The ascertained minor sensitivity of the model to changing parameters may be explained by the difference in the relative amounts of precipitation and of processes which

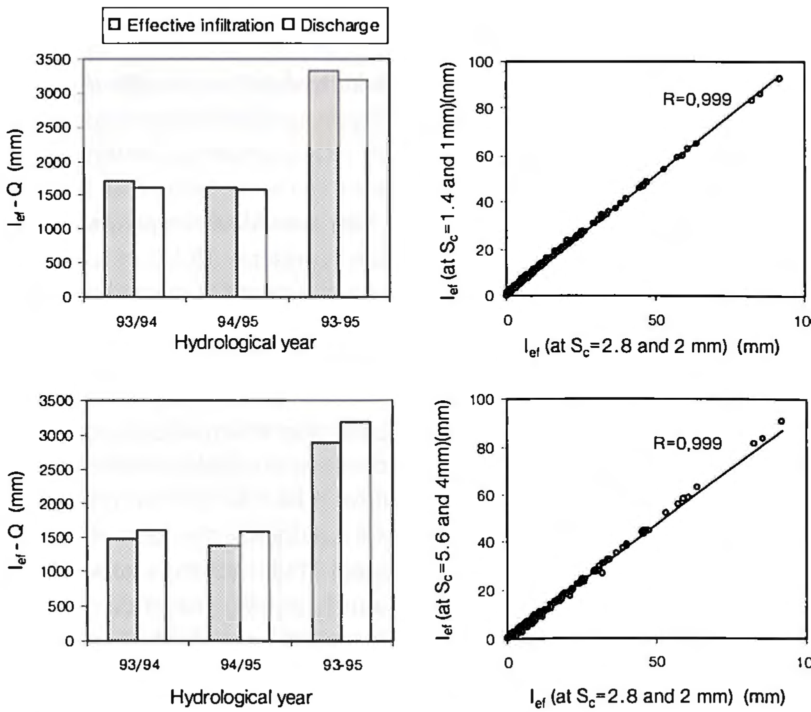


Figure 24: The effect of the change in canopy capacity on the evaluation of effective infiltration

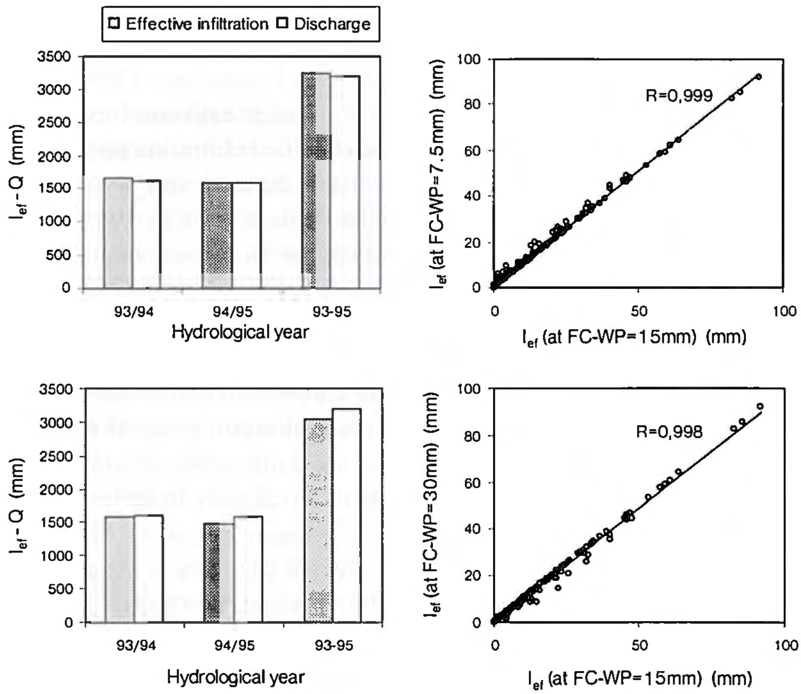


Figure 25: The effect of the changes in the soil moisture deficit on the effective infiltration evaluation

affect them in the air, vegetation and in the soil. The dominant component is the measured precipitation, since the share of interception represents 16.5 %, whereas the evapotranspiration does not exceed a quarter of the entire amount of precipitation. It is also typical of karst areas that the quantity of water which gets stored in the soil and makes up for the moisture deficit, proves to be relatively insignificant.

Nevertheless, the comparisons demonstrated that the above-mentioned processes exert an important effect on the amount of precipitation which actually infiltrates into the soil and should therefore be taken into account in the evaluation of the recharge function. Despite the dominant role of precipitation, which exhibits fairly characteristic high frequency and intensity in the given climatic conditions, the form of the effective infiltration function changes noticeably. On account of this we may also assume that in drier conditions with a lower share of precipitation the significance of the impact on the precipitation would further increase, and the sensitivity of the established model to changes of individual parameters would also consequently become greater. In general I may assert that the significance of the inclusion of the evaluation of effective infiltration into the hydrological models is probably even larger than the undertaken research managed to indicate.

SLOW AND FAST COMPONENT OF RECHARGE

In setting up the model of the effective infiltration evaluation the processes that affect the infiltration of the precipitation water into the rock were taken into consideration, whereas the response of springs depends to a large extent also upon the characteristics of the flow and storage of the infiltrated water within the rock. Numerous studies have demonstrated that the significant role in these processes is played by the epikarst zone (Kiraly *et al.* 1995, Jeannin & Grasso 1995, Jeannin & Grasso 1997, Sauter 1992, Mohrlok & Sauter 1997). Owing to its properties, part of the water is, after precipitation, rapidly transferred through the well permeable karst network to the saturated zone. The rest of it, however, remains in the base of the epikarst zone and subsequently slowly percolates through the less permeable zones towards the water table. Thus we may speak of distinct fast and slow recharge components. The first brings about as its consequence the increase of the discharge within a few days, and the second within a few weeks or months. On the basis of these findings I decided that in the model of the karst aquifer in the recharge area of the Vipava springs I presuppose the existence of a certain mechanism, which enables separation into fast and slow recharge.

To evaluate the share of both components one may make use of various methods. In my research of the recharge area of the Vipava springs I tested two of them, which are both presented below (Jeannin & Grasso 1995). The base flow method is founded upon the volumetric comparison between base and total flow, whereas in the method of hydrological balance the water balance was defined over short periods with an estimation of effective infiltration compared to fast flow. The second method is more approximate in its nature and difficult to carry out; nevertheless it provides vital information about the temporal variability of the division into the slow and fast recharge.

EPIKARST ZONE

The epikarst zone represents the upper part of the unsaturated zone, which is in this area more densely fissured due to the water's higher aggressiveness, tension release, tectonic processes and differences in temperature. Its principal characteristics are substantial storage capacity and high permeability. The base of epikarst zone may be a capillary barrier within narrow fissures or more frequently clays, as the insoluble product of dissolution processes. Such conditions lead toward the formation of a perched aquifer and to horizontal flow of water in direction of zones with higher permeability (sinkholes, channels, larger fissures), which drain the water into the saturated zone (Williams 1983).

The epikarst zone is a very complex hydrogeological unit and may assume various roles during infiltration and processes of the groundwater flow. It may reduce the surface runoff by infiltration or the storage of the precipitation water and the melted snow.

Depending on its horizontal permeability it may also rapidly drain the stored water towards the widened fissures or karst channels and in this way form a more or less permanently saturated zone situated close under the surface (Mangin 1975). In general terms, we may distinguish between two basic recharge components. The slow recharge includes a lengthier retention of water within the less permeable epikarst zones, whereas the fast one includes the flow along the primary drainage routes.

Among others the effects of the epikarst zone on the springs hydrograph were studied in greater detail by Kiraly and his co-researches (1995), who, by means of elaborated numerical models and taking into account various conditions, discovered that without some sort of concentrated recharge one cannot simulate the typical reactions of karst springs. The rise of the water table in the less permeable fissured matrix cannot push enough water into karst channels to result in an intensive, typically karstic response at the spring. On the basis of obtained results they presumed that the share of the fast recharge was approximately 40 %. The significant portion of the old water, and that was confirmed also by other methods (e.g. physicochemical properties of water at the spring indicate that this water has been prior to its outflow for a longer time stored in the aquifer), does not contradict this statement. In the period before the start of the rainfall the certain quantity of the old water may be stored in the epikarst zone, within the unsaturated zone or in the well permeable channel network (at least in channels below the spring's level); the wave of the infiltrated water, however, will push it ahead toward the spring, which in turn, due to the increased hydraulic gradient, will react with the rise of its discharge. The fast recharge component thus comprises the old water, which has been previously stored within the karst system, as well as freshly infiltrated water.

BASE FLOW METHOD

The spring hydrograph analysis represents one of the most important research methods within the field of hydrology; by selecting some of its particular properties, however, it has been favourably accepted also by karst hydrology. The recording of the spring's discharge is the unique reflection of the aquifer's reaction to the recharge. Particularly the characteristics of the recession part provide essential information about the storage and structural properties of the aquifer, which recharges the spring. For this reason the spring hydrograph analysis offers good possibilities for obtaining a potential insight into the nature and functioning of the karst system (Ford & Williams 1989).

One of the outcomes of the spring hydrograph analysis is also the separation of the flow into several components. It is through the karst springs, that the water, which infiltrated into underground karst system and subsequently remained within it for different periods of time, surges up to the surface. With regard to the origin and the time of water retention it may be divided into several components. By hydrograph analysis we usually evaluate two components, namely base and direct flow. The base flow is defined as the outflow of the water, which has been for longer period of time stored in zones of lower permeability within the aquifer, whereas the direct flow signifies the discharge of water, which was after infiltration drained through the channel network toward the spring without being retained for longer time. The problems that may occur in applying this method occur primarily due to the overlapping of the different effects of precipitation events. The interpretation of the recession curve's characteristics is for that reason frequently based upon subjective evaluations.

The division of the flow into several components has been used also in application of the base flow method, which I adopted in order to ascertain the shares of the slow and fast recharge (Jeannin & Grasso 1995). As appears obvious from its name it is based upon the base flow evaluation and its comparison with the overall discharge within the limited periods of hydrological years. The first difficulty occurs at the selection of the most adequate approach for the determination of the base flow, since none of them is completely objective and the selected mode of analyses is inevitably reflected in the obtained results. In all cases I compared the estimated overall volume of the base flow in the period of two hydrological years 1993-1995 with the total volume of discharge and determined the share of base flow for the considered interval as the share of the slow recharge.

In evaluating the base flow I tested 4 different approaches, which are described in the literature. First of all, I determined the lowest limit for the value of this component and at the same time adopted the lowest measured discharge as the base flow. With respect to the ratio between the volumes of the base and entire flow in the period of two hydrological years (1993-1995) I estimated that the recharge comprised 15 % share of the slow component and 85 % of the fast one.

Owing to the fact that this minimum method does not yield realistic values, I applied the method described by Barnes (Brenčič 1997), wherein the base flow is determined on the basis of the line that within individual hydrological years connects the lowest discharge values in the semi-logarithmic diagram. In the hydrogram of the hydrological year, wherein the discharges tend to decrease toward the end of the year, its incline representing the recession of the groundwater. The coefficient determined in this manner is the lowest among all those that may be defined from the hydrological year's hydrogram, whereas the area below the recession line provides the lowest values of the base flow volumes. Comparison with the total discharge in the period of two hydrological years demonstrates that in such circumstances the share of the slow recharge amounts to 24 %, while that of the fast recharge to 76 %.

I finally undertook the separation of the hydrogram by applying the method in which we link up to the straight line the point where the discharge starts to rise and the end point of the discharge decrease (Jeannin & Grasso 1995). Determining the starting point of the discharge increase did not pose any difficulties, whereas some problems, however, cropped up in defining the end point of its decrease. The method presented is founded upon the assumption that the recession curve in the semi-logarithmic scale consists of several linear sections, usually three of them. It is assumed that the sections with the gentlest slope, which are described by the recession coefficients α, reflect primarily the outflow from the less permeable aquifer zones. On the basis of this we may

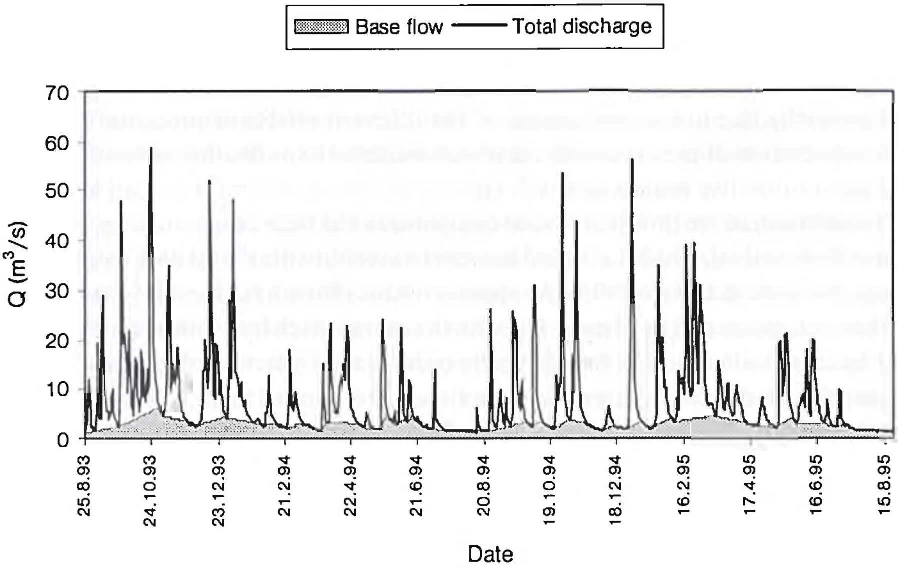


Figure 26: Evaluation of base flow of the Vipava springs on the basis of joining starting points of the rise of the discharge and the end points of its decrease

chose for the end point of discharge decrease the point at which the discharge characterised with the lowest value α is predominant (>90 %, >95 % or >99 %). This condition is fulfilled only once or twice a year. Therefore the end point may be approximated to the intersection point between two straight lines in the semi-logarithmic scale, which are characterised by recession coefficients α_2 and α_3. At this point the discharge is assumed to be composed of approximately 50 % of each of the two components and it therefore represents the starting point, wherefrom the base flow begins to prevail over the direct one. If we consequently join both characteristic points, the area below the resulting straight lines enables us to evaluate the base flow volume for the period of two hydrological years (Fig. 26). On the basis of the comparison with the entire discharge, however, the share of the slow recharge was ascertained as 38 %, while that of the fast recharge as 62 %.

The fourth approach is also founded on the same principle, whereby I defined end points of discharge decrease on the basis of the mean values of recession coefficient, determined for Vipava springs for the period from 1961 to 1990 (Schumann 1996). According to the mean value of coefficients α_2= 0.3380 d^{-1} I presumed that the end point was attained at the moment when the discharge of the springs dropped off to less than 340 l/s in a single day (Fig. 27). The obtained results correspond perfectly with the results of the previously mentioned method, since the estimated share of the slow recharge amounted to 39 %, while that of the fast one to 61 %.

For that reason I may conclude that the fast recharge within the recharge area of the Vipava springs accounts for no less than around 60 %. Since this evaluation is based

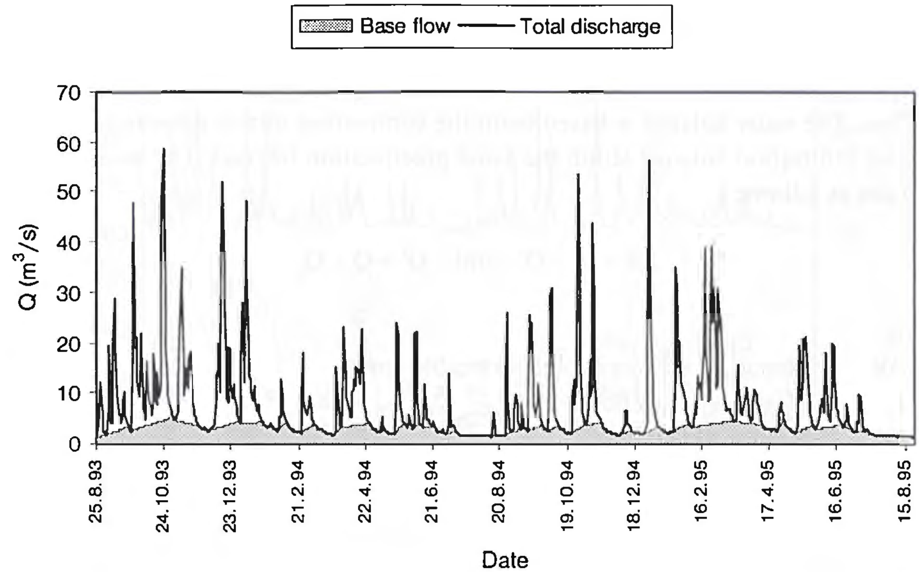


Figure 27: Evaluation of the base flow considering the mean values of recession coefficient α_2 in the 30-year period

upon the determination of the base flow, its accuracy evidently depends on the precision of the applied method of the separation of the base and direct flow. Although direct comparison with the results from Vipava is unfeasible due to the difference in the karst features, I may nevertheless quote some findings about the share of the base flow from the referenced literature. Atkinson (1977) estimated in case of the spring Cheddar Spring in the area of Mendip Hills in England that the share of the base flow in the entire annual discharge amounted to 46 %; for the spring Klokun in Croatia, however, Bonacci (1987) stated that the share of the base flow through the longer period of time was 25 %, whereas the annual values ranged between 11 % and 40 %. Jeannin and Grasso (1995) calculated that within the period of three hydrological years the share of the base flow represented 47 % of the entire discharge.

METHOD OF HYDROLOGICAL BALANCE

The method of hydrological balance is the second method that I availed myself of in the separation of the recharge components. It is based on the comparison between the direct flow volume and the effective infiltration and makes possible also the evaluation of the temporal variability of this separation (Jeannin & Grasso 1995). The analysis comprises the setting up of the water balance within individual precipitation intervals, which include precipitation events or groups of precipitation events. The share of the slow and fast recharge is subsequently determined for each of the selected precipitation intervals. Initially, the base flow within each interval is separated. The area below the discharge curve, the base flow excluded, represents parameter Q', which is also called volume of fast flow. The water balance is based upon the comparison of this parameter with the effective infiltration volume within the same precipitation interval. The balance equation runs as follows:

$$\Delta R = I_{ef} - Q' \quad \text{and} \quad Q' = Q - Q_b \qquad (10)$$

where:

ΔR	change of storage in less permeable zones
I_{ef}	effective infiltration
Q'	volume of fast flow
Q	total discharge
Q_b	base flow

This method enables us to estimate the portion of the water which is transported quickly (the measured volume Q' represents the fast reaction of the aquifer system to the recharge) and the portion of water that is transported slowly (the change of storage in the less permeable zones represents the change of the presumed base wave, which corresponds to the outflow from the less permeable zones).

In the process of determining the slow and fast recharge component in the recharge area of the Vipava springs I divided the period of two hydrological years from 1993 to 1995 in accordance with the precipitation distribution and the form of the discharge curve into 40 precipitation intervals of different lengths, with each of them ending up by a period of a few days without the occurrence of rain. Usually, they comprise several precipitation events. As an input recharge component I adopted the value of the effective infiltration and I subsequently ascertained for each precipitation interval values of parameters ΔR and Q', which represent the share of the slow and fast recharge component.

The obtained results are presented as point values for each precipitation interval, which enables also the assessment of the temporal variability of the recharge components shares (Fig. 28). For the sake of comparison, the diagram displays also daily values of the discharge of Vipava springs. The figure makes it evident that the fast recharge is predominant, with an exception of lengthier periods of low waters.

Results are presented also in the form of percentages of both recharge components (Fig. 29). Once again we may notice the prevailing share of the fast recharge except for the short intermediate periods, wherein the share of the slow recharge may be larger.

In order to demonstrate these comparisons in a clearer way the figure 30 indicates also the ratio between the fast and the slow recharge component within individual intervals.

In the diagram of cumulative curves the individual points represent the cumulative values for the selected precipitation intervals (Fig. 31). The lower curve demonstrates

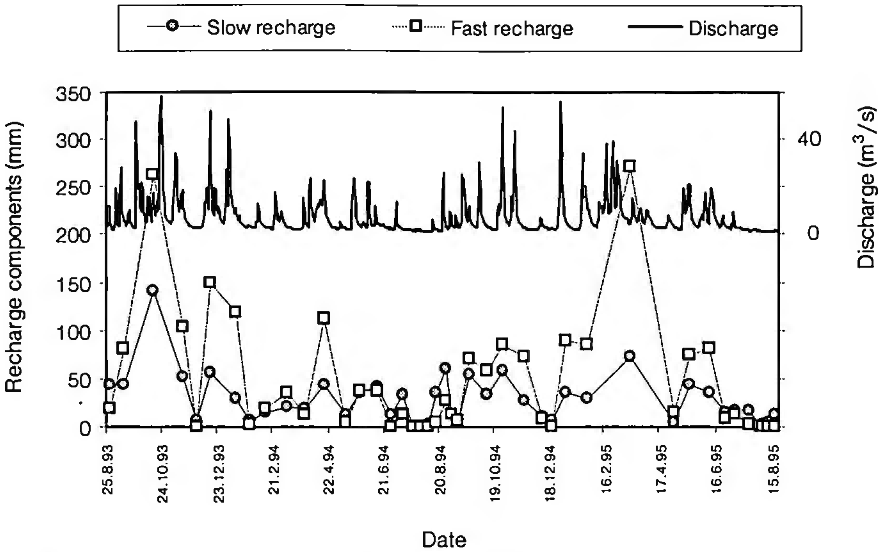


Figure 28: Fast and slow recharge values in individual precipitation intervals

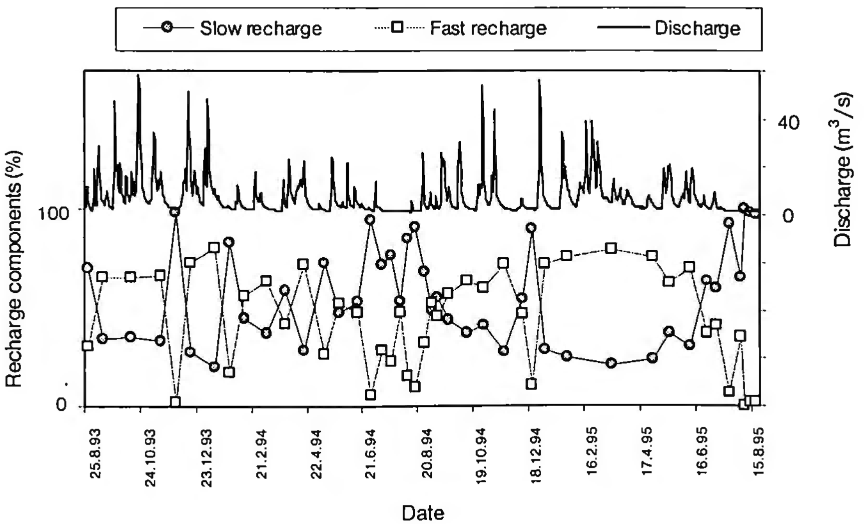


Figure 29: Percentages of the fast and slow recharge in individual precipitation intervals

the cumulative sum of the slow recharge, whereas the upper the cumulative sum of slow and fast recharge. Accordingly, the area under the lower curve represents the total amount of water which has infiltrated during the period of two hydrological years into the less permeable aquifer zones, whereas the area between both curves represents the amount of water which has infiltrated during the same period through the karst network. The

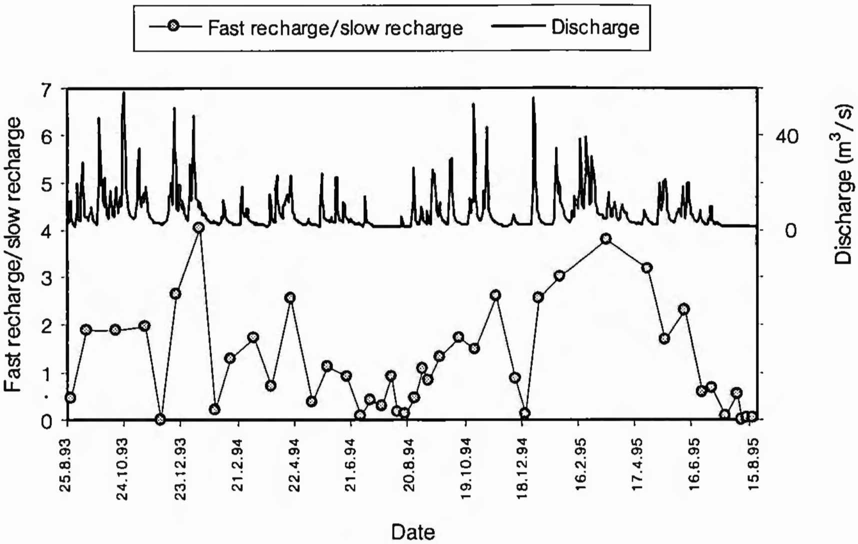


Figure 30: Ratio between the fast and the slow recharge component within individual intervals

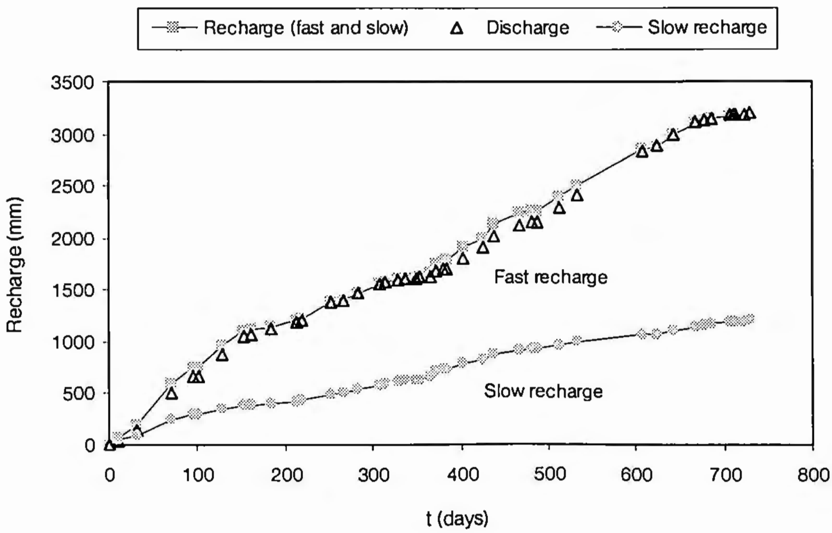


Figure 31: Cumulative curves of the recharge components

entire area under the upper curve stands for the total recharge value. The figure displays also the cumulative curve of the discharge, which closely matches the curve of the entire recharge. With exception of the initial values, where the slow recharge is still predominant, the shares of the fast recharge range from 59 % to 65 %, whereas the final value of the cumulative curves corresponds to the 38 % share of the slow and 62 % share of the fast recharge, which I evaluated for the entire period of two hydrological years by means of the base flow method.

The estimated values depend on the manner and accuracy of the recharge evaluation, on the selected method of the base flow separation and, of course, on the method applied for the evaluation of different recharge components. However, due to the fact that in the planned analysis of the relationship between recharge and discharge the significant information already represents the data on the size order of the individual components shares, I considered the obtained results to be suitable for the further study and processing. Nevertheless, one should remain duly cautious and monitor the effects of these parameters on the proposed evaluation.

INPUT FUNCTION OF THE RECHARGE-DISCHARGE SYSTEM

Described methods were applied to various processes, which characteristically influence the amount and distribution of the recharge. With respect to the ascertained characteristics I elaborated on this basis three different recharge functions, which represent the input component in the overall input-output model. First of all, I took into account the measured precipitation. As in this way some influences which affect the precipitation before or during the infiltration are neglected, I replaced them in the second phase with the effective infiltration. Dealing with effective infiltration an additional consideration was given to various processes taking place in the air, vegetation and within the soil, which are characteristically influencing the amount of precipitation, which actually infiltrates into the rock. Finally, I divided the recharge also into the slow and fast components, assuming that there should exist a certain hydrological mechanism typical of the epikarst zone, which causes such a division.

In all three cases I defined the recharge process within the recharge-discharge model with the uniform, lumped function of the average value for the entire recharge area of Vipava springs. The testing of the adequacy of the used functions and the capabilities of the established models to simulate real conditions, however, are presented next.

DISCHARGE

The discharge of karst aquifers is primarily related to the outflow of the groundwater through large or small-sized karst springs, whereas only a fairly minor share of the overall amount may be represented by the diffuse outflow. The main outflow is thus associated with individual points and for that reason the evaluation of the discharge function proves to be much simpler. By means of adequate methods it is possible to measure discharges accurately within different time intervals.

The studied karst aquifer is discharged mostly through the permanent and intermittent Vipava springs, whereas the share of smaller springs at the southern foot of Nanos proves to be negligible. The discharge of 7 permanent Vipava springs is measured at the gauging station in Vipava town approximately 500 m downstream from the springs (Fig. 6). In June 1993, within the network of the 7th SWT project, a limnigraph was set up at this profile, while discharges had been measured already earlier by staff gauge. Measurements were performed by the Hydrometeorological Survey, which also provided me with all the required data on mean daily discharges in the period from 1985 to 1995. To verify the eventual effects of the change in the measurement techniques on the measured values, I applied the double mass method (Bonacci 1994). I compared the cumulative values of Vipava's mean daily discharges at the gauging station in Vipava and at the Dornberk station (15 km to the west, in the lower course of the Vipava river), where discharges were measured on a continuous basis by a limnigraph (Fig. 32). Since the change of the measurement technique does not cause the straight line of dependence between cumulative values of discharges to break up, I assessed the continuity of the discharge measurements as acceptable. The sensitivity of the applied method is perhaps not great, yet it enables us to perceive characteristic changes in the technique and location of measurement.

The gauging station at the measurement profile Pod farovžem was put into operation within the framework of the 7th SWT project from 14 September 1993 onward, by means of which measurements of the overall discharge of springs Vipava 6 and 7 were carried out. Available also were the data on the Bela's discharge in Sanabor and on its water levels in Vipava town, which I dealt with together with the results of additional individual measurements in the sub-chapter on the surface and groundwater interaction of the Bela stream and Vipava springs.

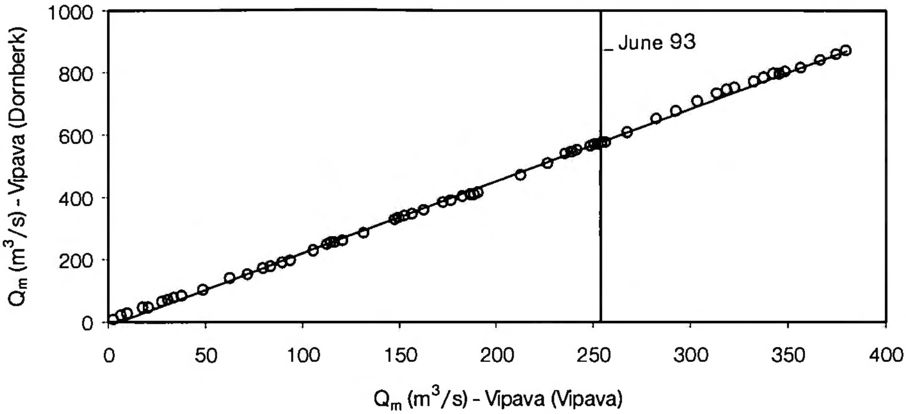


Figure 32: Comparison of cumulative curves of mean monthly discharges at two gauging stations at Vipava from 1990 to 1995

CHARACTERISTIC DISCHARGES OF VIPAVA SPRINGS

The survey of characteristics of permanent Vipava springs' discharges is based upon three groups of data. The first one comprises the 30-year interval from 1961 to 1990 and allows the long-term statistical evaluation of the hydrological regime. The smallest measured discharge amounted to 727 l/s, whereas the biggest was 70 m^3/s. The mean discharge was equal to 6.78 m^3/s; but for approximately 260 days per annum, the quantity of water that emerges from springs was lower than this mean value.

Similar characteristics yielded also the analysis of the period of 10-hydrological years from 1 November 1985 until 23 August 1995, to which were related also the calibration and validation of the established recharge-discharge models. Thus the minimum discharge was Q_{min} = 727 l/s, the mean discharge was Q_m = 6.48 m^3/s and the maximum one amounted to Q_{max} = 66 m^3/s.

From the considered period I extracted also the calibration interval of two hydrological years from 1993 to 1995. Due to the brevity of the time interval, somewhat larger divergences from the long-term average values in evaluation of characteristic discharges are to be expected. Thus the lowest measured discharge was equal to 1.19 m^3/s, while the greatest was 55.7 m^3/s. The mean discharge of 7.54 m^3/s indicated the period with above average quantity of outflowing water.

Noteworthy also is the comparison of mean monthly discharges for all three intervals (Fig. 33). Some small differences are visible already between characteristics of the 10-year and 30-year periods; in both cases however, the typical hydrological regime is well reflected with its autumn and spring peaks following extensive precipitation and/or an additional recharge due to snowmelt in the recharge area, and with its minimum discharges in July and August. Yet, as in the case of comparison of the characteristic

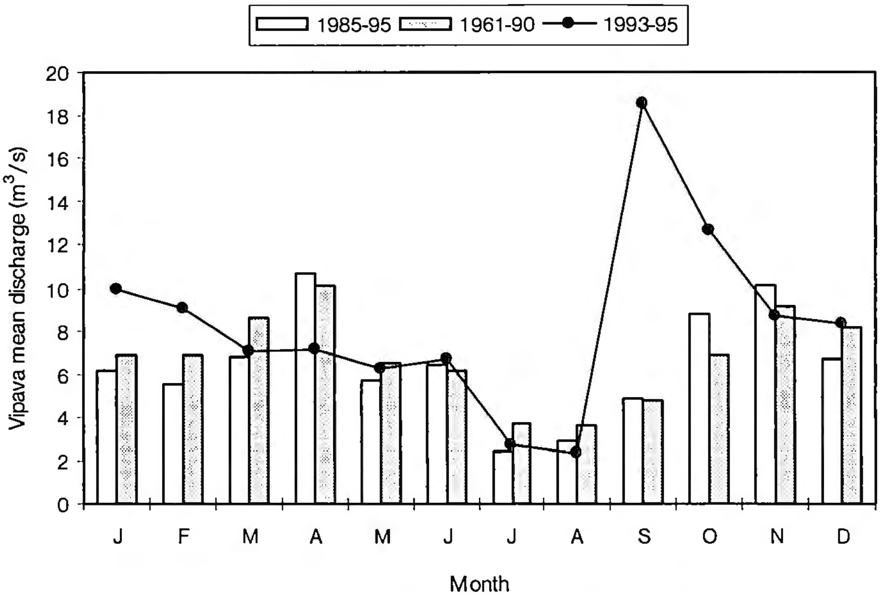


Figure 33: Mean monthly discharges of Vipava springs in different time intervals

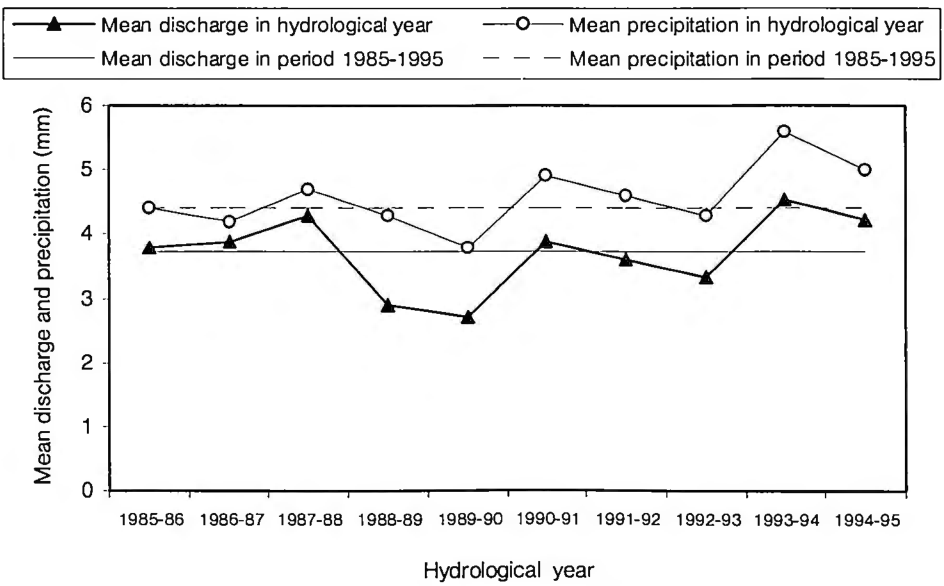


Figure 34: Comparison of mean discharges and precipitation for individual hydrological years in 10-year period

discharges, the shortest interval somehow stands out, wherein the peculiar hydrological properties were not lost to the statistical average. Such peculiarities are, for instance, very high waters in the beginning of autumn in September, and the decline in mean monthly discharges from winter months onward to those of spring.

I compared also mean discharges and precipitation for individual hydrological years within the 10-year period (Fig. 34). In this comparison as well, the interval between 1993 and 1995 stands out as being above average in its wetness. Of considerable interest also is the conspicuous change in difference between precipitation and discharges in individual hydrological years, which points toward certain additional influences on the correlation of precipitation-discharge.

OUTPUT FUNCTION OF THE RECHARGE-DISCHARGE SYSTEM

The output function of the recharge-discharge system was determined on the basis of the measured overall daily discharges of 7 permanent Vipava springs. In addition to this, the influence of the surface and groundwater interaction of the Bela stream and Vipava springs was also taken into consideration. Assuming that the water from the Bela flows also into Vipava springs, I appropriately reduced the measured discharges of Vipava springs by the ascertained difference between the Bela's discharge in Sanabor and in Vipava. Conversely, I added to the measured overall discharges of Vipava springs the calculated share of the outflow through temporary springs for days when they become active and start to flow into Bela.

The corrected total discharge of Vipava springs thus represents the discharge function, which describes the entire runoff of the studied karst aquifer.

RECHARGE-DISCHARGE MODELS

RAINFALL-RUNOFF RELATION

The connection between precipitation and the runoff from the basin represents in hydrology one of the most studied relations. Although, in general, already the basic comparison of two time-series may demonstrate that the discharges depend on precipitation, to ascertain this dependence more accurately, however, proves much more demanding. And this applies with a particular relevance to karst, where this comparison is characteristically influenced by large variability of the conditions of flow and water storage within the karst aquifer. The karst springs of Vipava react to extensive rainfall with the short-term high peaks, which are followed by a rapid decline in discharge and a longer period of medium or low waters (Fig. 35).

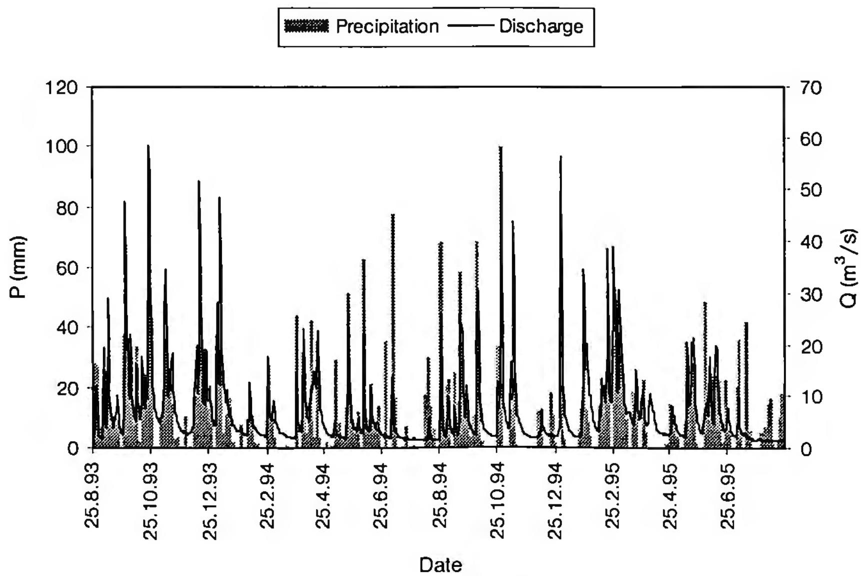


Figure 35: Comparison of daily precipitation at the Nanos precipitation station and daily discharges of Vipava springs in the period 1993-1995

The representation in the scatter plot also confirms certain connections, yet at the same time the deviation from the regression curve indicates the significant role of certain additional processes which affect it (Fig. 36).

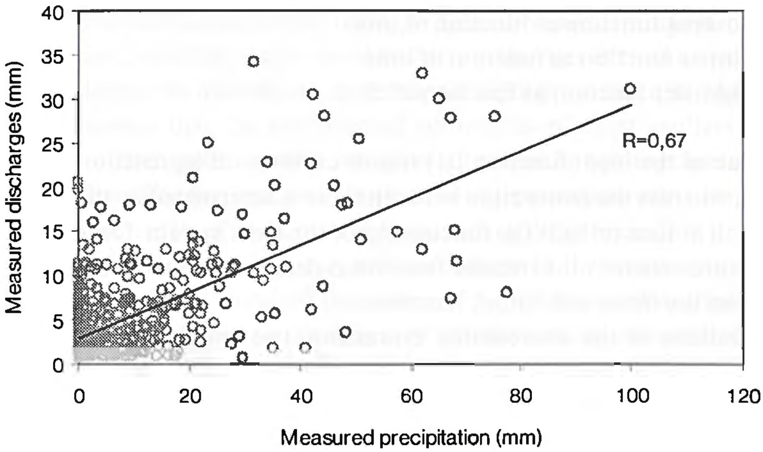


Figure 36: Scatter plot of daily precipitation and discharges in the karst aquifer in the recharge area of Vipava springs

In chapter on the recharge, I already focused upon some of these processes, which influence the precipitation before and during infiltration in greater detail. Nevertheless, many among them remain inaccessible to direct analysis and for that reason I used in their evaluation the black-box method, whereby we may, on the basis of the comparison between input and output function, infer the characteristics of processes that take place within the karst system. Properties of the recharge and its determination as the input signal on the one hand, and the discharge as the output signal on the other, are already described in previous chapters, and here the results of the application of black-box method are presented.

RECHARGE-DISCHARGE MODELS

In the black-box method the processes between the recharge and discharge are presented mathematically, without precise understanding of the physical background. All parameters in the system that affect the filtration of the input signal are united in the transfer function, whereas the relationship between the input and output signals is defined by the function which we call convolution. Its characteristics are represented in various hydrological studies; their fundamentals, however, are summarised from the general mathematical literature:

$$O(t) = Z(t) * I(t) \quad (11)$$

where:

$O(t)$	output function as function of time
$I(t)$	input function as function of time
$Z(t)$	transfer function as function of time

Each value of the input function I(t) has its corresponding reaction in the output function O(t), whereas the connection between them is determined by the transfer function Z(t), which in turn reflects the functioning of the karst system. Deconvolution is a reverse procedure, whereby the transfer function is determined on the basis of the comparison between the input and output functions.

For the validity of the above-stated expression, two conditions of the stationary status and linearity of the system should be fulfilled. The first condition stipulates that the system's response does not depend on time and that the equal transfer function describes the dependence between O(t) and I(t) as well as that between $O(t-t_1)$ and $I(t-t_1)$. In order that the second condition may be fulfilled, the law of proportionality (to the multiple of the input function corresponds the same multiple of the output function) and the law of superposition (the input function, which is equal to the sum of two sub-functions, corresponds to the output function, which is equal to the sum of two output functions, obtained for each input sub-function). If these conditions are met, the uniform, temporally invariable linear system of the dependence may be expressed in the integral form:

$$O(t) = \int_0^t Z(t-\tau) \cdot I(\tau) d\tau \quad (12)$$

where:

τ	time of impulse response of the system
$Z(t-\tau)$	transfer function

The main impediment for the use of these relationships in the analysis of the karst systems represents the fact that the above-enumerated conditions for the validity of the equation may actually not be fulfilled. Despite this the method proved to be adequate in numerous studies of the karst aquifers, assuming that non-linearity is not too large. For two isolated, finite series that are usually related, the convolution integral can be written in a discrete form:

$$O(j) = \Delta t \cdot \sum_{k=0}^{j} (Z(j-k) \cdot I(k)) + \varepsilon(j) \quad (13)$$

where:

Δt	the time between data points
ε	error

In this case there is incorporated also in the function a certain error, mostly due to model assumptions that are not strictly met and measurement errors in input and output functions.

Also the assessment of the characteristics of the relationship between the recharge and discharge in the aquifer in the recharge area of Vipava springs is based upon the represented basic equation; due to some specific properties of the karst systems, however, and considering the availability of the data I slightly modified it. My starting point was the assumption that the hydrological complexity of karst aquifers is primarily a consequence of changeable conditions of recharge and of heterogeneous properties of groundwater flow. For that reason I applied the basic equation with corresponding corrections to three models of recharge-discharge, which differ according to the input function used. First of all, I took into account in equation 13 the measured precipitation; in the next stage however, I included the values of the effective infiltration. Precisely the processes, which are related to the effects of climate and vegetation and the soil moisture balance, are one of the crucial reasons for the non-linearity in the karst system. Finally, I took into consideration also, according to the ascertained differences in the flow and storage of the infiltrated water, the effect of a certain mechanism within the epikarst zone, which causes the division of the recharge into the fast and slow components. I have rewritten the equation for this case in the following form:

$$Q(j)=\sum_{k=0}^{j} Z_f(j-k)\cdot R_f(k)+\sum_{k=0}^{j} Z_s(j-k)\cdot R_s(k)+\varepsilon(j) \qquad (14)$$

where:

$Q(j)$	output function - discharge
$R_f(k)$	input function - fast recharge
$R_s(k)$	input function - slow recharge
$Z_f(j\text{-}k)$	transfer function for fast recharge
$Z_s(j\text{-}k)$	transfer function for slow recharge
$\varepsilon(j)$	error

For each of the three input-output models of the karst system in the recharge area of Vipava springs I expressed each daily discharge value in the period of two hydrological years from 1993 to 1995 by means of the selected equation as a function of measured precipitation or of the evaluated effective infiltration or of components of the slow and fast recharge, and corresponding transfer functions. In this way I obtained the system of linear equations, wherein the unknown quantities are the components of transfer functions. To simplify the equation, I determined, on the basis of the presumed duration of these functions, the number of units in the equation. The evaluation of their duration was based upon the results of the comparison between input and output functions with the cross-correlation method. I selected the time interval, wherein the precipitation still exerted statistically significant influence on the discharges; due to the comparison of the obtained results however, I adopted for the first two models two different lengths of the transfer functions (Petrič 2000b, Martin *et al.* 1997). In this manner I obtained altogether 5 versions of the basic recharge-discharge model. For resolutions of the established systems of linear equations I used the least square method (Vidav 1976) and for each model I determined the corresponding transfer functions with which the closest match between the input and output signal was attained, and where the residual error proved to be the lowest.

TESTING OF MODELS

MODEL MEASURED PRECIPITATION-MEASURED DISCHARGES

To begin with, I tested the adequacy of the model measured precipitation-measured discharges of springs, whereby the effects on the precipitation were not taken into account, neither were the effects of the Bela surface stream on the overall discharge. For both functions the measured data were adopted, which were provided by the Hydrometeorological Survey. Besides, I adopted for precipitation, with respect to the allocation of the precipitation zones Nanos, Hrušica and Podkraj, mean daily values for the entire recharge area. The basic equation 13 is expressed in the following form:

$$Q(t) = P_m(t) \cdot Z_m(0) + P_m(t-1) \cdot Z_m(1) + \ldots + P_m(t-n_m) \cdot Z_m(n_m) + \varepsilon \qquad (15)$$

where:

$Q(t)$	measured discharge at time t
$P_m(t)$	measured precipitation at time t
$Z_m(n_m)$	transfer function at time n_m
n_m	duration of transfer function
ε	error

I thus represented each daily value of the discharge in time t as a function of precipitation, which was recorded in the previous time interval between t and $(t-n_m)$, and of the corresponding transfer function with its duration within the same interval. With regard to the ascertained characteristics of the cross-correlation between precipitation and discharges, I tested two different durations of this interval, i.e. 7 and 30 days.

I thus set up the system of linear equations for the entire period of two hydrological years. The unknown quantities are values of transfer functions Z_m: $Z_m(0)$, $Z_m(1)$,..., $Z_m(n_m)$; the known values, however, are the measured daily discharges and precipitation: $Q(t)$, $P_m(t)$, $P_m(t-1)$,..., $P_m(t-n_m)$.

The resolving of the system of linear equations is based on the least squares method (Vidav 1976). Due to random errors in the function values for Q and P_m we may adapt to them, as the most adequate, the function, for which the following expression has the lowest value:

$$F = \sum_{t=1}^{N} (Y(t) - Q(t))^2 \tag{16}$$

where:

- Y(t) value of the set discharge function in time t
- Q(t) measured discharge value in time t
- N number of measured discharge values in the entire observation period

The term may be written as the function of parameters Z_m:

$$F(Z_m(0), Z_m(1), ..., Z_m(n_m)) = \sum_{t=1}^{N} (Z_m(0) \cdot P_m(t) + Z_m(1) \cdot P_m(t-1) + ... + Z_m(n_m) \cdot P_m(t-n_m) - Q_t)^2 \tag{17}$$

The resolution of the established expression is the matrix equation with the following form:

$$\begin{Vmatrix} \Sigma P_t^2 & \Sigma P_t \cdot P_{t-1} & \Sigma P_t \cdot P_{t-2} & & \Sigma P_t \cdot P_{t-n} \\ \Sigma P_t \cdot P_{t-1} & \Sigma P_{t-1}^2 & \Sigma P_{t-1} \cdot P_{t-2} & & \Sigma P_{t-1} \cdot P_{t-n} \\ \Sigma P_t \cdot P_{t-2} & \Sigma P_{t-1} \cdot P_{t-2} & \Sigma P_{t-2}^2 & \cdots & \Sigma P_{t-2} \cdot P_{t-n} \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ \Sigma P_t \cdot P_{t-n} & \Sigma P_{t-1} \cdot P_{t-n} & \Sigma P_{t-2} \cdot P_{t-n} & & \Sigma P_{t-n}^2 \end{Vmatrix} \cdot \begin{Vmatrix} Z_0 \\ Z_1 \\ Z_2 \\ \vdots \\ Z_n \end{Vmatrix} = \begin{Vmatrix} \Sigma P_t \cdot Q_t \\ \Sigma P_{t-1} \cdot Q_t \\ \Sigma P_{t-2} \cdot Q_t \\ \vdots \\ \Sigma P_{t-n} \cdot Q_t \end{Vmatrix} \tag{18}$$

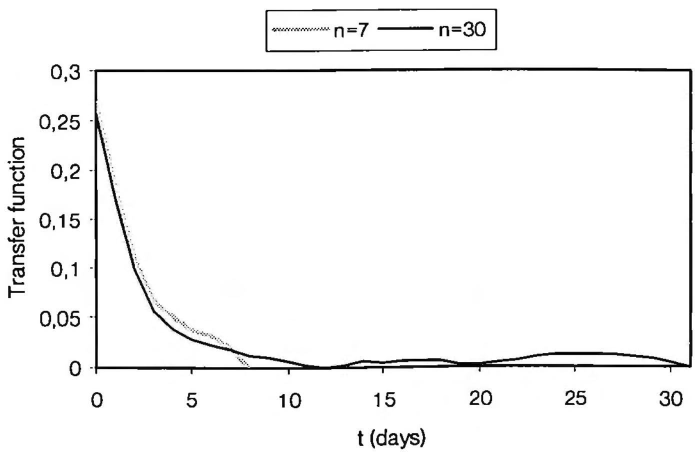


Figure 37: Comparison of transfer functions with durations of 7 and 30 days for the correlation between the measured precipitation and discharges

For the purposes of simplification, parameters $P_m(t)$ are replaced with P_t, $Z_m(n_m)$ with Z_n, $Q(t)$ with Q_t and n_m with n. The unknown quantity is represented by the vector with the coefficients of transfer function Z. Solution is the product of the last unit and

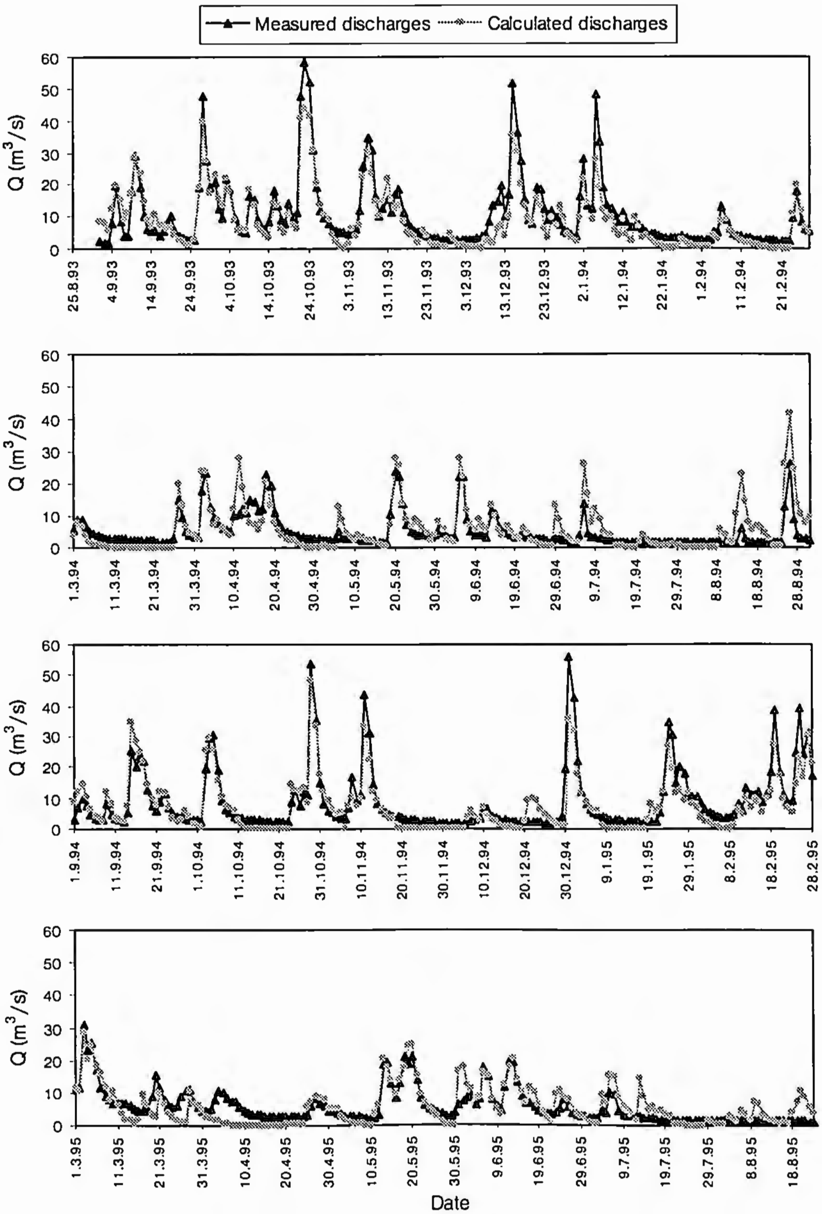


Figure 38: Comparison of measured and calculated discharges for the period 1993-95, determined by the model measured precipitation-measured discharges with the transfer function's duration of 7 days

the inverse matrix of the first unit from the matrix equation. Values Z_0, Z_1, ... Z_n represent coefficients of the sought transfer function within the time interval from 0 to n, i.e., within the entire presumed time of the transfer function's duration.

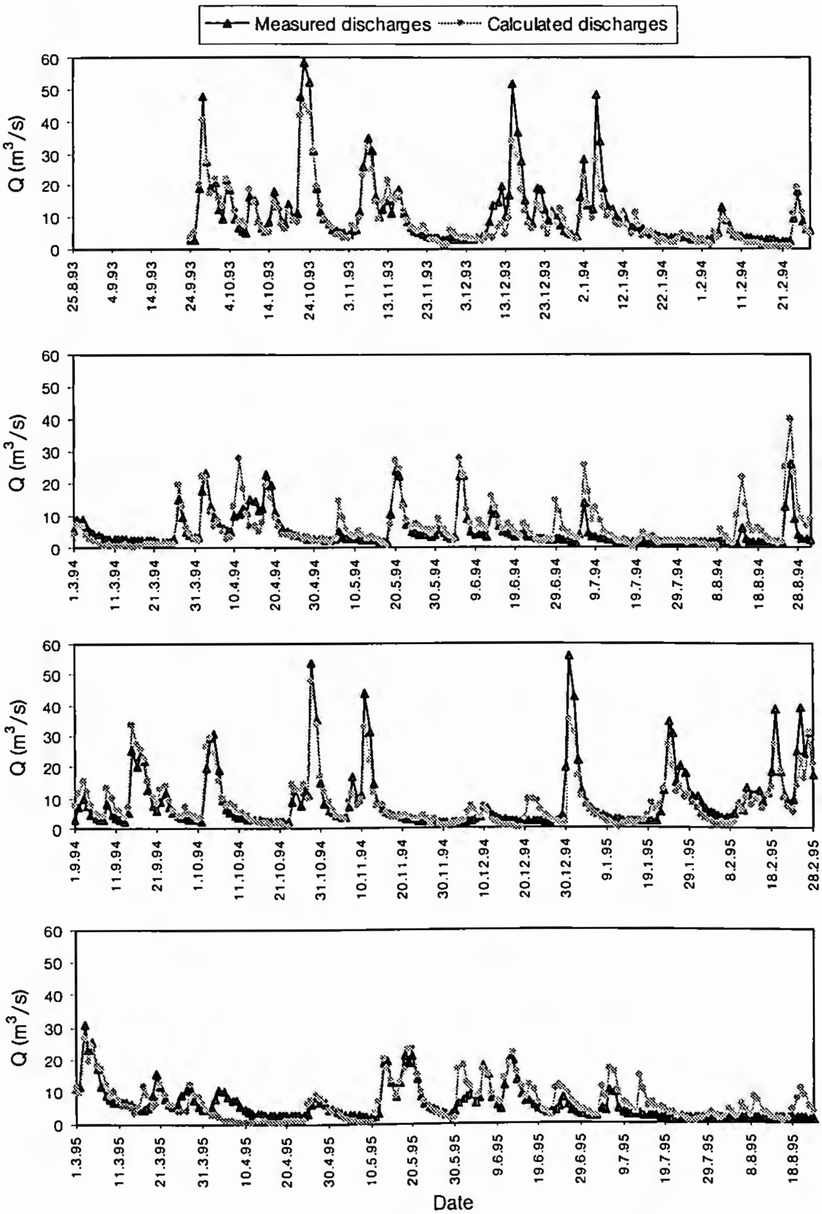


Figure 39: Comparison of measured and calculated discharges for the period 1993-95, determined by the model measured precipitation-measured discharges with the transfer function's duration of 30 days

Taking into account the daily data of values for the period of two hydrological years from 1993 to 1995, I determined, according to the previously described method, two transfer functions for the presumed values n=7 days and n=30 days, which describe the correlation between the measured precipitation in the recharge area of the Vipava springs and their overall discharges (Fig. 37).

On the basis of already known values of measured precipitation and the transfer functions, I conversely calculated values of discharges for the entire period from 1993 to 1995. The comparison with the measured values is presented in figures 38 and 39.

It became apparent already when using the most simplified comparisons, that taking into consideration the previous precipitation and by calculating the corresponding transfer function, one could fairly accurately determine the relation between the precipitation and discharge. Nevertheless, deviations between both functions, which were the consequence of different factors, still remained; and I attempted to determine them in greater detail by setting up the following models. As expected, the matching is slightly closer in calculation that includes the longer duration of the transfer function. Differences occur primarily in longer periods of low waters, because the transfer function with its mere 8 units (duration 7 days) is not sensitive enough to them.

MODEL EFFECTIVE INFILTRATION-DISCHARGE

In the next step I adopted as an input component the values of effective infiltration, which I determined on the basis of the established model of the soil moisture balance, whereby I also took into account processes taking place in air, vegetation and in the soil, which affect the infiltration (Petrič 2001). In the discharge function I took into account

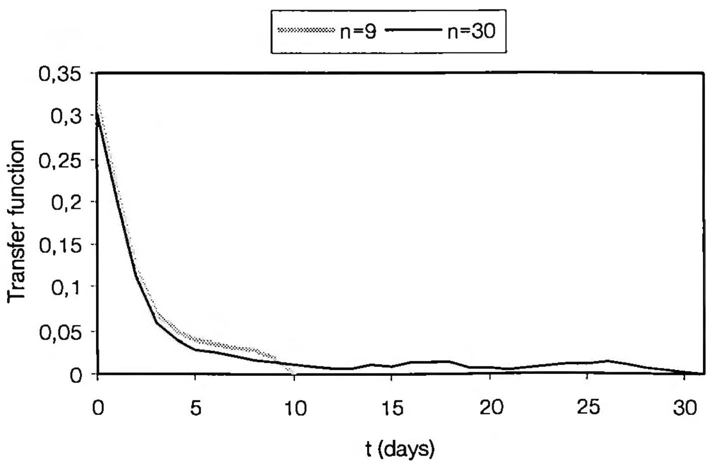


Figure 40: Comparison of the transfer functions with the durations of 9 and 30 days for the correlation between effective infiltration and discharge

as the output component, besides the measured discharges of the Vipava springs, also the effects of the interchange with the Bela surface stream. Both procedures are presented in previous chapters. As the basis serves also in this case the equation 13; considering previously described simplified terms it assumes the following form:

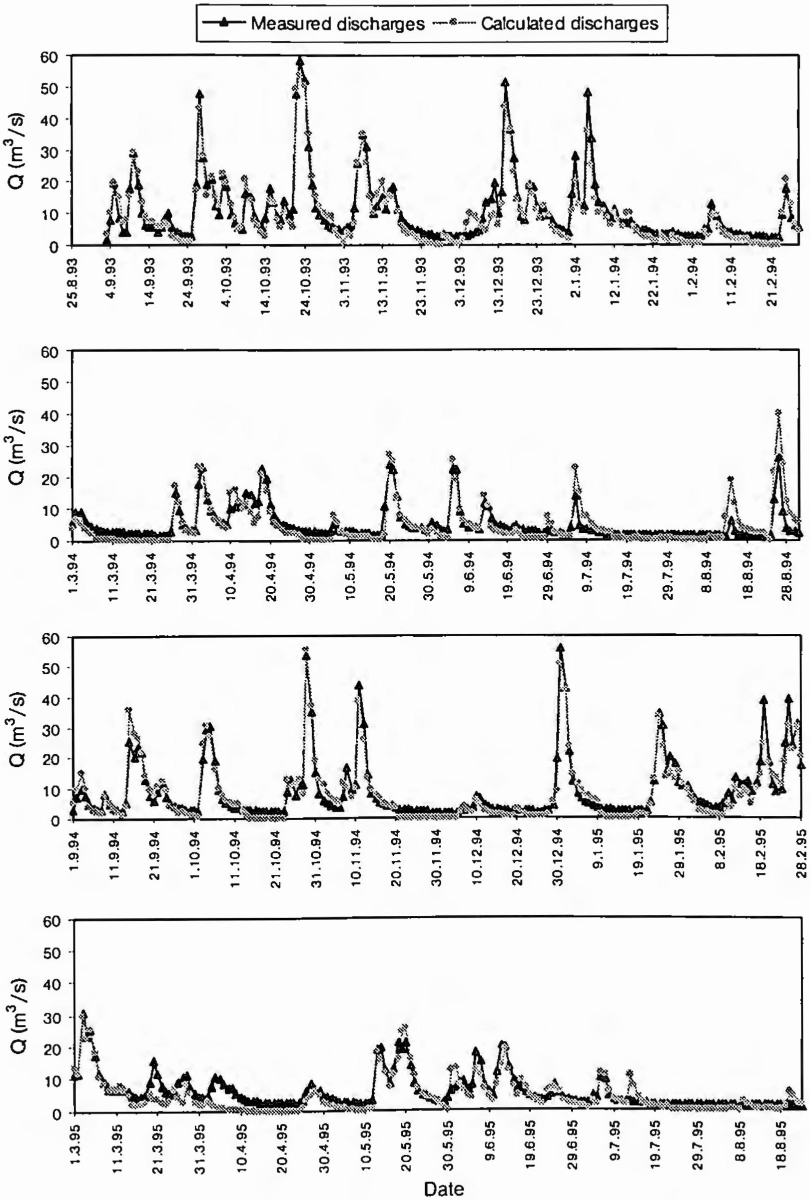


Figure 41: Comparison of measured and calculated discharges for the period of two hydrological years from 1993 to 1995, determined by the model effective infiltration-discharge with the transfer function's duration of 7 days

$$Q(t) = I_{ef}(t) \cdot Z(0) + I_{ef}(t-1) \cdot Z(1) + \ldots + I_{ef}(t-n) \cdot Z(n) + \varepsilon \qquad (19)$$

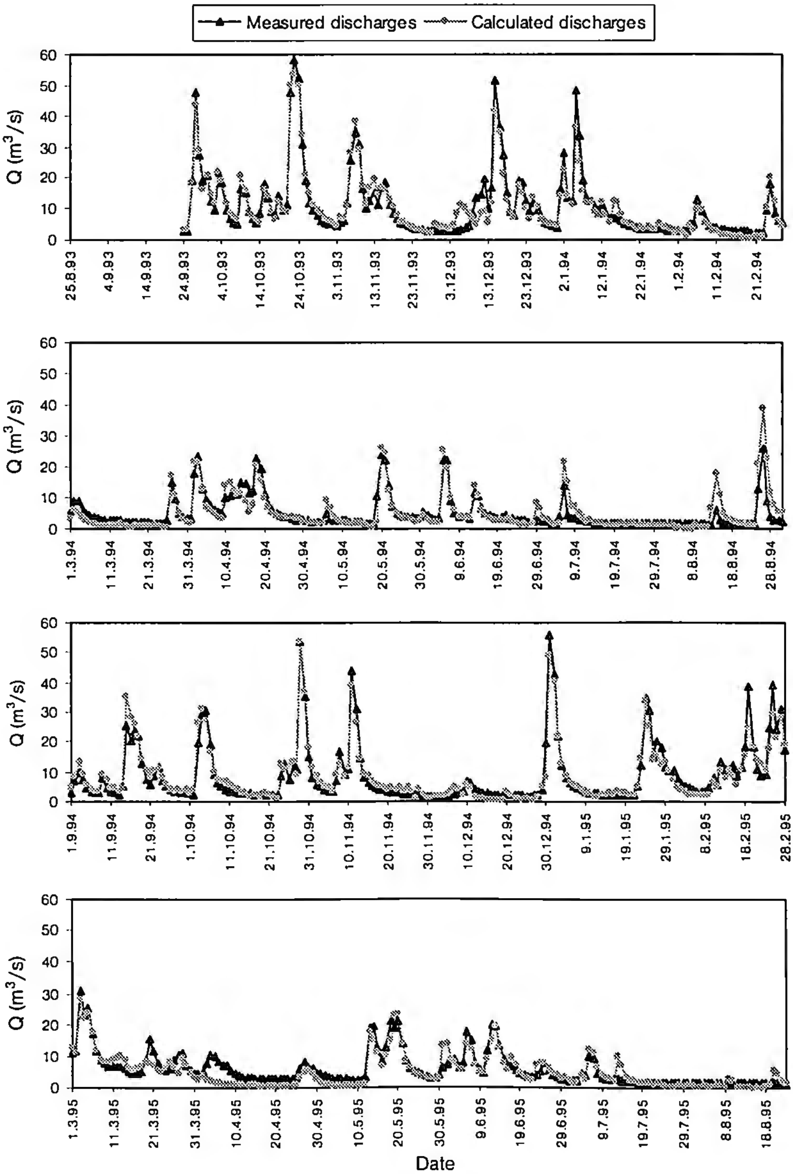


Figure 42: Comparison of measured and calculated discharges for the period of two hydrological years from 1993 to 1995, determined by the model effective infiltration-discharge with the transfer function's duration of 30 days

where:

Q(t)	discharge at time t
$I_{ef}(t)$	estimated effective infiltration at time t
Z(n)	transfer function at time n
n	duration of transfer function
ε	error

I determined the coefficients of the transfer functions with durations of 9 and 30 days on the basis of this equation and according to the method which was described in the first model (Fig. 40).

Using these values and also estimated values of daily effective infiltration, I calculated the discharge values of Vipava springs for the period of two hydrological years from 1993 to 1995 (Figs. 41 and 42).

By adopting the effective infiltration as the input function, the better connection between the input and output signal of the karst system in the recharge area of Vipava springs is attained. By testing the soil moisture balance and taking into account the effects of interception by the vegetation cover, evapotranspiration, snowfall and snowmelt as well as water storage in the soil, one of the most significant causes for the nonlinearity of the considered system has been removed or at least reduced. This amelioration is particularly effectively reflected in the low waters period, when the effects of the above mentioned factors on the precipitation prove to be the greatest. Once again the matching is closer in case of the longer duration of the transfer function. Nevertheless, there still remain some divergences between measured and calculated discharge values, which in the next phase I tried to reduce by taking into account the differences between slow and fast recharge.

MODEL SLOW AND FAST RECHARGE-DISCHARGE

On the basis of findings of numerous investigations which we may find in literature I finally presupposed in the recharge-discharge model also the existence of a certain mechanism within the epikarst zone, which enables such differentiation into slow and fast recharge (Petrič 2000a and 2000c). By means of the hydrological balance method and on the basis of the comparison of the effective infiltration with the base and direct flow of Vipava springs, I determined the daily values of slow and fast recharge. Subsequently, on the basis of equation 15, and by taking into account the simplified expressions for the dependence between discharge and the recharge components, I expressed the established model as follows:

$$\begin{aligned} Q(t) = {} & R_s(t)\cdot Z_s(0) + R_s(t-1)\cdot Z_s(1) + \ldots + R_s(t-n_s)\cdot Z_s(n_s) + \\ & + R_f(t)\cdot Z_f(0) + R_f(t-1)\cdot Z_f(1) + \ldots + R_f(t-n_f)\cdot Z_f(n_f) + \varepsilon \end{aligned} \tag{20}$$

where:

$Q(t)$	discharge at time t
$R_s(t)$	slow recharge at time t
$Z_s(n_s)$	transfer function for slow recharge at time n_s
n_s	duration of transfer function for slow recharge
$R_f(t)$	fast recharge at time t
$Z_f(n_f)$	transfer function for fast recharge at time n_f
n_f	duration of transfer function for fast recharge
ε	error

According to the previously described method I ascertained the coefficients of the transfer function for the fast recharge with the duration of 9 days and for the slow recharge with the duration of 38 days (Fig. 43).

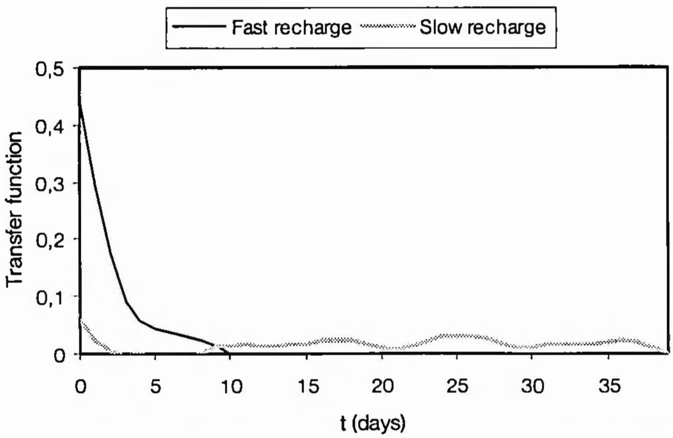


Figure 43: Transfer functions for the correlation between slow and fast recharge and discharge

With respect to the shape of both curves I may presume that springs already respond on the fast recharge by increased discharge in the first days after the precipitation event. The slow recharge, however, is distributed over a longer time period, which is in this case limited by the presumed duration of the transfer functions. In the initial part its values range around 0. Such conditions correspond with the finding which claims that due to the increased potential in the karst channels, which is a consequence of the fast recharge, the outflow from the less permeable zones proves to be negligible. Positive values in the continuation, however, reflect the gradual oozing out of the water which has been infiltrated into the system as slow recharge.

Some oscillations which occurre are hard to clarify accurately. At least to some extent, they are a consequence of errors in the estimation of the recharge and discharge functions, as well as of the assumption about the system's linearity, which does not entirely correspond to the real conditions.

Let me conclude with an assertion that there is certain correlation between the calculated form of the transfer function and the determined conditions of the flow and storage of the fast and slow recharge. Nevertheless, on the basis only of the undertaken

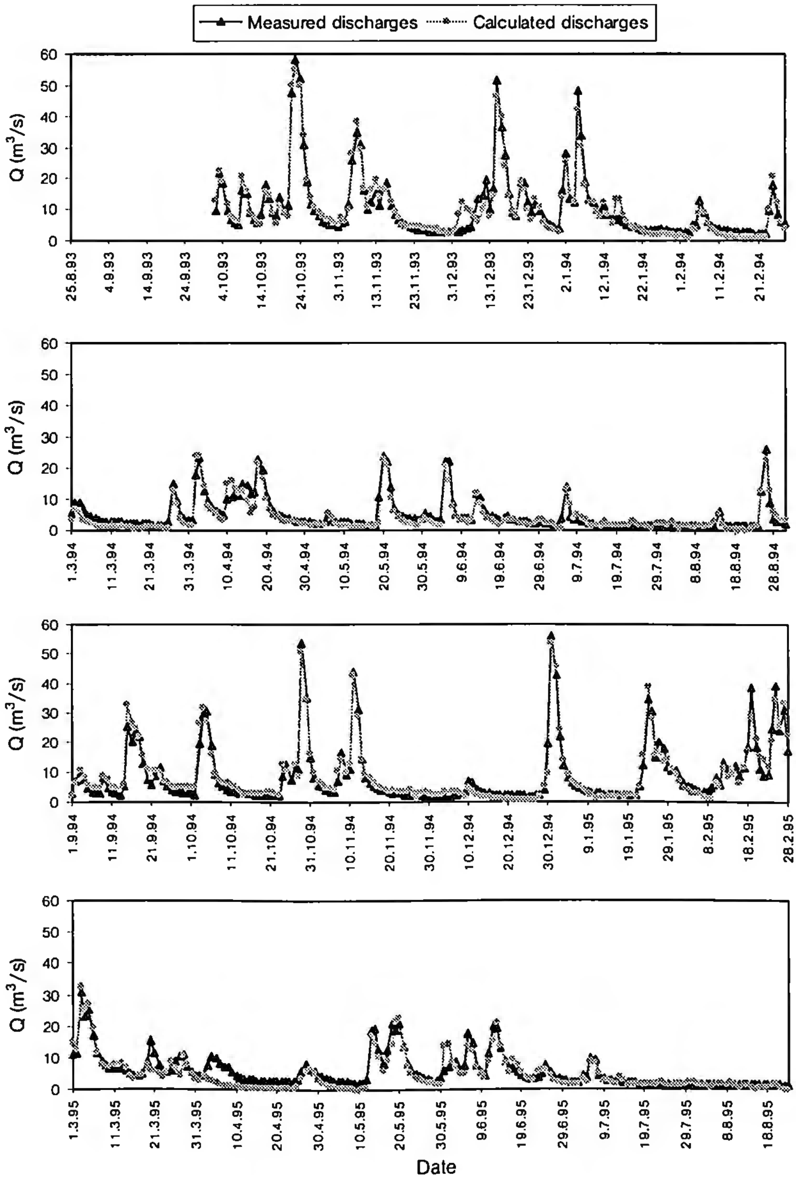


Figure 44: Comparison of measured and calculated discharge for the period from 1993 to 1995, determined by the model slow and fast recharge-discharge

qualitative comparison of the presumed interconnection this cannot be quantitatively determined.

As in previous instances I used the transfer functions for the slow and fast recharge together with data on the daily values of both recharge components also for the calculation of the discharge within the period of two hydrological years 1993-1995 (Fig. 44).

Correspondence between measured and calculated discharge values has with the division of recharge into slow and fast components even increased, which favours the assumption about the duality of the system's functioning: i.e. about the rapid flow through the karst drainage network and the lengthier retention of water due to its storage in less permeable zones. Despite this there still occur certain divergences, which may be a consequence of errors in the evaluation of the recharge or shares of both recharge components.

TESTING OF THE TRANSFER FUNCTIONS STABILITY

The testing of the transfer functions stability is based upon the use of the altered data base. I carried it out for the model slow and fast recharge-discharge; instead of the entire period of two hydrological years, however, I used in determining both transfer functions the data for just one hydrological year.

The comparison demonstrated that the obtained transfer functions match fairly well with one another and that the problem of their instability is not present in the case considered. This particularly applies to the fast recharge, whereas more differences occur at the slow recharge component (Fig. 45).

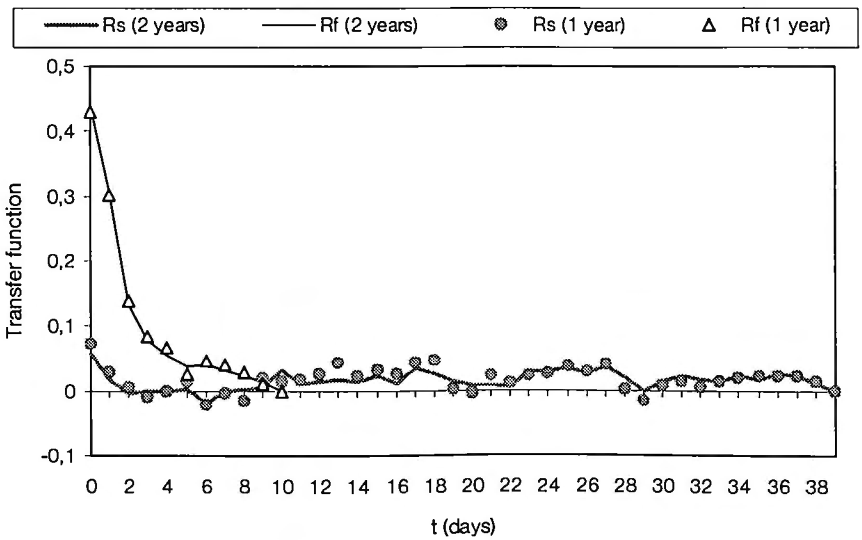


Figure 45: Comparison of the transfer functions of the slow and fast recharge, determined according to the data covering the period of one or two hydrological years

The correlation between daily discharge values, which were calculated on the basis of the above transfer functions for 1 or 2 years is also very high (Fig. 46).

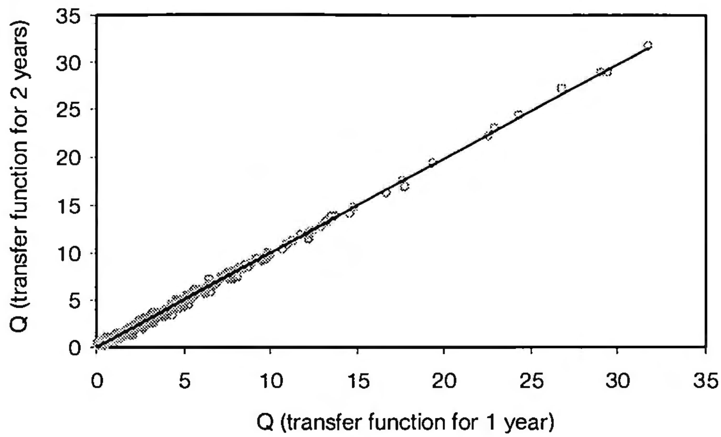


Figure 46: Comparison of daily discharge values, calculated on the basis of the transfer functions for 1 or 2 years

STATISTICAL ANALYSIS OF THE OBTAINED RESULTS

I evaluated the adequacy of individual models by statistical comparison of measured and calculated discharge values. The model's results are exposed to random as well as systematic errors. We would talk of the random errors in cases when the model does not display any trend of exaggeration or underestimation for several successive time intervals. At systematic errors, however, the error's sign persists through several time intervals. Both types of errors may appear as a consequence of the irregularity or deficiency in the structure of the set up model. Naturally, we have to take into account also the possibility of errors in input data, which are virtually unavoidable in the evaluation of the recharge function on the basis of precipitation and other meteorological parameters. Errors crop up also in measuring springs' discharges, which are finally compared with the results of the established model. Random errors in data will bring about as their aftermath also random errors in the results themselves. Systematic errors, however, will not show up as errors that were made during the comparison of measured and calculated discharges, but will reflect in the established model's parameters (Aitken 1973).

In order to evaluate these errors, various statistical methods were developed. Matching between two time series could be tested by calculation and by comparison of certain statistical parameters of both series or more directly by calculating dimensionless coefficients of correspondence. To compare the established recharge-discharge models, I first of all calculated characteristic discharges, and subsequently I used also scatter plots, objective functions, coefficients of determination and efficiency as well as the residual mass curves.

CHARACTERISTIC DISCHARGES

For the basic evaluation of springs' characteristics the so-called characteristic discharges are used, whereby for the determined time period we express different statistical discharge values, such as the minimum one (the smallest measured one), the mean one (the average value of discharges) and the maximum one (the largest measured discharge). The comparison between the measured and calculated values for the established recharge-discharge models is presented in the table (Table 2).

Table 2: Comparison of characteristic discharges for different recharge-discharge models

	Q_{min} (m^3/s)	Q_{max} (m^3/s)	Q_{avg} (m^3/s)	% of measured Q_{avg}
Measured values	1.269	58.703	7.426	100
Precipitation-discharge (duration of transfer function 7 days)	0.000	48.846	6.710	90.4
Precipitation-discharge (duration of transfer function 30 days)	0.000	47.815	7.397	99.6
Effective infiltration-discharge (duration of transfer function 9 days)	0.058	55.313	6.495	87.5
Effective infiltration-discharge (duration of transfer function 30 days)	0.200	54.023	7.170	96.6
Slow and fast recharge-discharge	0.139	54.929	6.987	94.1

In all models the more significant divergences appear at extreme water levels, whereas mean discharges are all within the interval of 15 % divergence from the given value of the measured discharges. Results are in any case better when taking into account longer duration of the transfer functions. But it would be very difficult to bring forward one out of three basic models as the most adequate one just on the basis of the comparison of characteristic discharges.

SCATTER PLOT AND CORRELATION COEFFICIENT

One of the methods that prove to be fairly simple is that of the correlation coefficient, which gives us the degree of correspondence between measured and calculated values and is used also as the accuracy standard. For that reason I made scatter plots of dependence between measured and calculated discharge values for all the considered cases. Correlation coefficients were determined as well. As anticipated, the matching is the least close when the measured precipitation is considered as the input function. The results are somehow less positive also at the presumed shorter duration of the transfer functions. Both correlation coefficients are 0.89 and 0.88, respectively (Fig. 47).

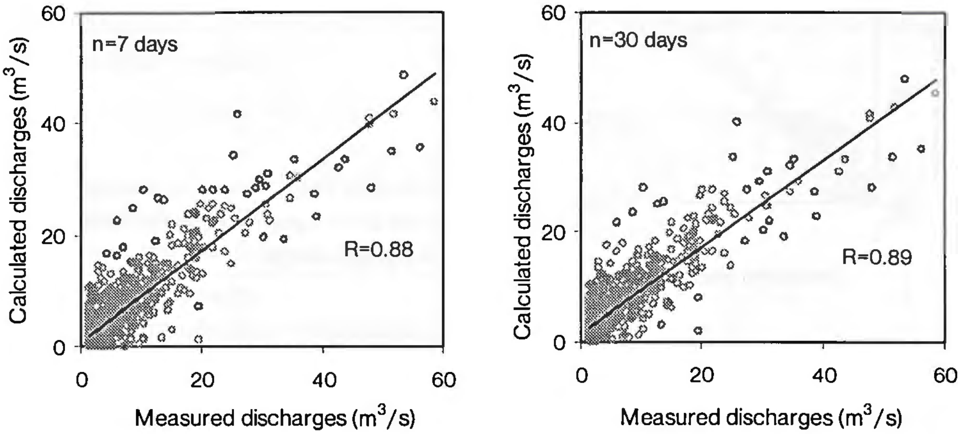


Figure 47: Comparison of measured and calculated discharges for the model measured precipitation-measured discharge

The improved correspondence is noticeable in case when the function of the effective infiltration has been adopted as an input signal and when the correlation coefficient has been calculated at 0.94 and 0.95, respectively (Fig. 48).

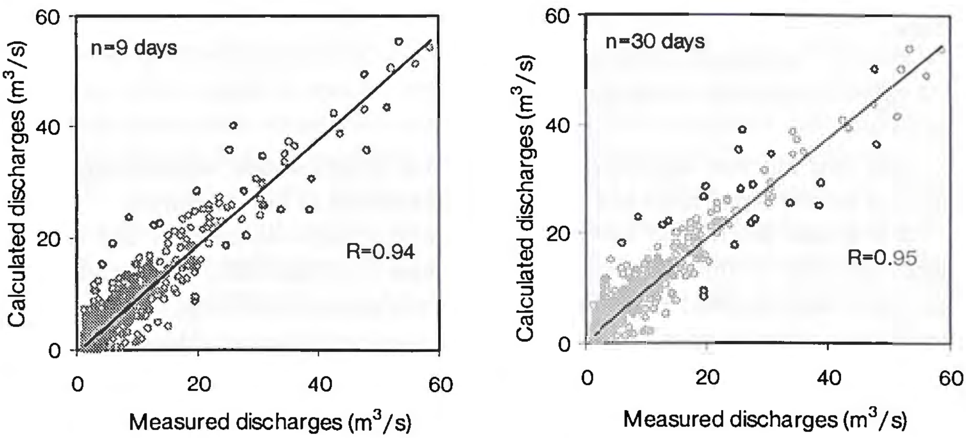


Figure 48: Comparison of measured and calculated discharges for the model effective infiltration-discharge

Even better, however, is the correspondence with the correlation coefficient 0.97 when considering the division of the recharge into slow and fast components (Fig. 49).

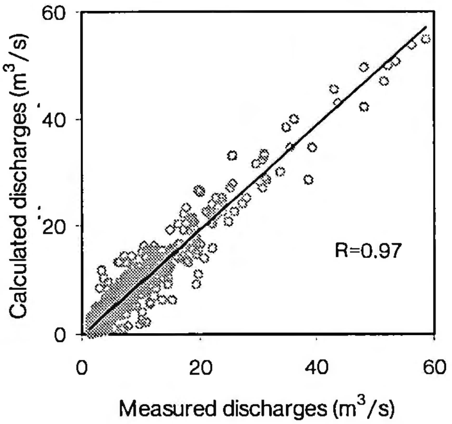


Figure 49: Comparison of measured and calculated discharges for the model slow and fast recharge-discharge

OBJECTIVE FUNCTIONS

The second possibility provides the calculation and the comparison of so-called objective functions (Chiew *et al.* 1993):

$$OBJ1 = \sum_{i=1}^{n} (Q_{si} - Q_{mi})^2 \tag{21}$$

$$OBJ2 = \sum_{i=1}^{n} (Q_{si}^{0.2} - Q_{mi}^{0.2})^2 \tag{22}$$

where:

Q_s calculated discharge
Q_m measured discharge

The first function chiefly reflects conditions at high waters, whereas the second one is of greater significance at evaluating the simulation of low discharges.

I thus also determined for all models objective functions for daily and monthly discharge values. In the table 3 values of parameters OBJ1 and OBJ2 in their relation to the lowest value obtained in the model slow and fast recharge-discharge are represented. Due to their dependence on the quantities of the used data, absolute values may differ by even several size orders. With this kind of relative comparison, however, I was able to assess with which type of input function the match between the measured and calculated discharge proves to be the closest.

Results demonstrated that the introduction of the effective infiltration function instead of the measured precipitation represents a considerable improvement. The presupposed longer duration of the transfer functions also, exerts a positive effect on the results. This is especially obvious when comparing daily values in OBJ2 function, which reflects conditions at low waters. The capability of the established model to provide the discharge evaluation is in general enhanced by the separation into the slow and fast components, whereas the results are slightly less positive only at the simulation of daily values at low waters.

Table 3: Comparison between objective functions for daily and monthly values for different recharge-discharge models

	Daily		Monthly	
	OBJ1	OBJ2	OBJ1	OBJ2
Precipitation-discharge (duration of transfer function 7 days)	3,5	6,6	4,7	2,6
Precipitation-discharge (duration of transfer function 30 days)	3,2	1,5	4,2	2,4
Effective infiltration-discharge (duration of transfer function 9 days)	1,9	2,8	2,3	2,2
Effective infiltration-discharge (duration of transfer function 30 days)	1,5	0,9	1,6	1,5
Slow and fast recharge-discharge	1,0	1,0	1,0	1,0

COEFFICIENT OF DETERMINATION AND COEFFICIENT OF EFFICIENCY

Coefficients of determination and of efficiency are another two of the dimensionless parameters, which could be used for testing the correspondence between measured and calculated values in the established model. These analyses are usually based upon the comparison of sum totals of individual values, and for that reason I compared the measured and calculated monthly discharges. An additional problem in evaluation of the obtained coefficients could be also from a too small sample, since I had at my disposal for the period of two hydrological years the monthly values that covered only 23 months.

Coefficient of determination D is calculated in accordance with the following equation (Aitken 1973):

$$D = \frac{\Sigma(Q_m - Q_{mavg})^2 - \Sigma(Q_m - Q_{reg})^2}{\Sigma(Q_m - Q_{mavg})^2} \tag{23}$$

where:

Q_m measured discharges
Q_{mavg} average value of measured discharges
Q_{reg} discharges estimated on the base of regression curve

In case of perfect correspondence the coefficient D would have value 1, whereas in practice calculated coefficients are usually lower.

The coefficient of efficiency E (Loague & Freeze 1985, Aitken 1973) also has similar form and value up to the theoretical maximum of value 1:

$$E = \frac{\Sigma(Q_m - Q_{mavg})^2 - \Sigma(Q_m - Q_s)^2}{\Sigma(Q_m - Q_{mavg})^2} \qquad (24)$$

where:
Q_s calculated discharges

Coefficient of determination D measures the degree of the correspondence between measured and calculated values, whereas coefficient of efficiency E describes the model's ability to reproduce the measured values. With the use of the coefficient of efficiency the evaluation of bias is also made possible. If the correlation between the measured and calculated values proves to be high and the regression curve deviates from the straight line y = x, the coefficient of efficiency is lower than the coefficient of determination.

Values of the coefficient of determination D and those of the coefficient of efficiency E for all considered cases are represented in table 4. On the basis of relatively high values of the first parameter we might infer the close matching between the calculated and the measured discharge, particularly in cases when the input function in the system is defined as the effective infiltration and when it is presupposed that the duration of the transfer function will take a longer time. Slightly less positive, however, is the evaluation of the adequacy of the established models with regard to the coefficient of efficiency. Reduced value reflects the deviation from the straight line y = x, therefore the error due to the bias of the calculated discharge in the sense of exaggerated or underestimated values.

On the basis of the extensive study of comparisons of monthly discharge simulations, Chiew and his co-researchers (1993) concluded that the assessment of the discharge might be evaluated as "entirely acceptable" if the coefficient of efficiency exceeded 0.9 and the mean calculated discharge remained within 10 % of the mean measured discharge. Results are "acceptable" if the coefficient of efficiency exceeds 0.6 and when the mean calculated discharge remains within 15 % of the mean measured discharge. By adopting these standards I may conclude that the "entirely acceptable" model is the one where the input function was divided into two components, while the others are also "acceptable" yet not in their entirety. The exception is the model where precipitation was adopted as the input function and the presupposed duration of the transfer functions was 7 days.

Table 4: Table of statistical coefficients for different recharge-discharge models

	D	E	R
Precipitation-discharge (duration of transfer function 7 days)	0,81	0,58	0,43
Precipitation-discharge (duration of transfer function 30 days)	0,90	0,65	0,50
Effective infiltration-discharge (duration of transfer function 9 days)	0,92	0,78	0,78
Effective infiltration-discharge (duration of transfer function 30 days)	0,99	0,87	0,82
Slow and fast recharge-discharge	0,98	0,90	0,92

RESIDUAL MASS CURVE

A somewhat different approach to the evaluation of the correspondence between measured and calculated values was applied to the residual mass curve analysis (Aitken 1973). The significant difference lies in the fact that, due to the cumulative mode of the calculation, the previous events are also taken into account and thus we are, using this method, able to detect the systematic error.

To carry out the comparison of the established models I used also in this case the monthly values. First of all I determined the residuals by deducting from individual monthly values the mean monthly discharge. I cumulatively summed up the obtained residuals and represented the succession for the monthly residuals with curves in the diagram (Fig. 50).

The efficiency of the set up model is reflected in the correspondence with the residual mass curve for measured and calculated values. This comparison once again demonstrates that the best results are obtained in the model with the division of the recharge into two components, although even in this case divergences point to certain degree of error.

To evaluate these errors we may use the coefficient of residual mass curve R, which is defined as follows (Aitken 1973):

$$R = \frac{\Sigma(D_m - D_{mavg})^2 - \Sigma(D_m - D_s)^2}{\Sigma(D_m - D_{mavg})^2} \qquad (25)$$

where:

D_m departure from the mean for the observed residual mass curve
D_{mavg} mean of the departures from the mean for the observed residual mass curve
D_s departure from the mean for the estimated residual mass curve

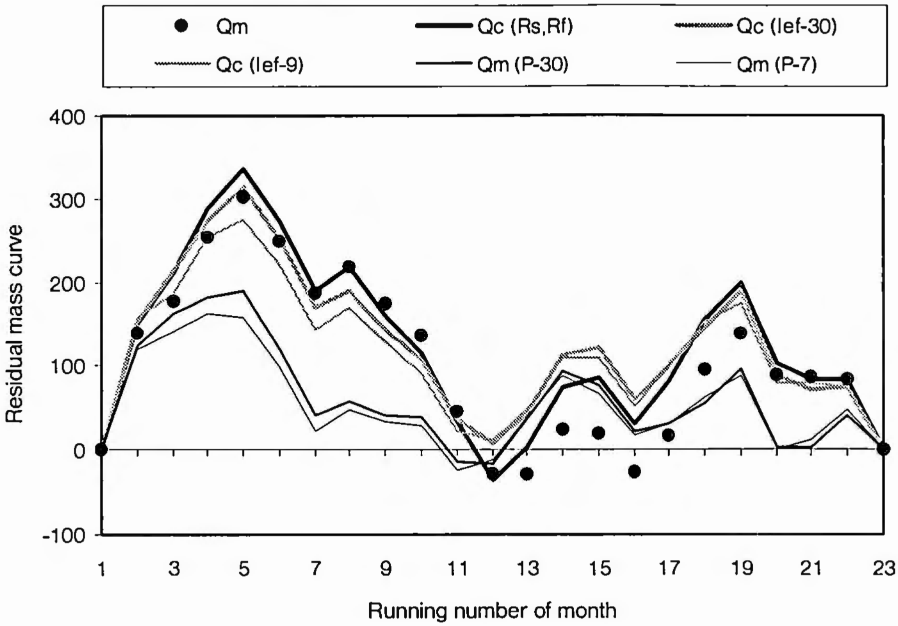


Figure 50: Residual mass curve for different recharge-discharge models

In case of perfect correspondence the coefficient's value is equal to 1; in practice, however, coefficients are, according to the degree of matching, correspondingly lower. The advantage of the evaluation using this parameter, when compared to the use of coefficients of determination and efficiency, lies in the fact that it measures the connection of discharges' sequence and not only of individual events. The value of the coefficient of residual mass curve was for most of the explored cases lower than that of the previously mentioned coefficients, the only exception being the model with the slow and fast recharge component, whereby its higher value only confirmed the advantages of this model when compared to others (Table 4).

COMPARISON OF ESTABLISHED MODELS

Accordingly, I applied different ways of comparison between the input and output signal for the evaluation of the characteristics of the relation between the recharge and discharge of the studied karst aquifer. By gradually changing the input function, I endeavoured to find the most appropriate form of the recharge-discharge model, which would most faithfully reflect the actual circumstances. As the measure of the adequacy of the set models I adopted the accuracy of the simulation, which refers to the capability of the transfer functions to reproduce discharges on the basis of which they were determined.

Differences between models are obvious already in time-series diagrams of the comparison between the measured and calculated discharge (Figs. 38, 39, 41, 42, 44). To confirm this initial evaluation, however, I used also some other statistical methods (Figs. 47 - 50, Tabs. 2 - 4).

In the first model, I compared directly the total discharge of Vipava springs with the measured precipitation in the recharge area and found out that with this basic model one could not satisfactorily describe the dependence of the input and output signal of the studied system. It became manifest that the result is significantly influenced also by the presupposed duration of the transfer function, which I determined with regard to the cross-correlation curve between input and output signal. I selected the time interval wherein the precipitation still exerted the statistically characteristic effect on discharges. When comparing the analyses' results with the presupposed two different durations of the transfer function, it became clear that in the case of the shorter duration the consequential error became too large. Particularly significant deviations occurred in longer periods of low waters, when the short-term transfer function was not sensitive enough to describe the conditions in the time interval without recharge. The enlargement of the number of transfer function's units may signify the improvement in its sensitivity, yet at the same time it also entails far lengthier and complex calculation procedures. For that reason I decided, on the basis of the results obtained, that the transfer function with the time span of approximately one month was entirely acceptable.

Owing to the fact that, in keeping with our expectation, it turned out that the interconnection between precipitation and springs' discharges is not so simple and is influenced also by some other factors, I particularly concentrated upon the effects on the precipitation before and during the infiltration. The significant difference occurrs already between measured precipitation and that part of precipitation, which actually infiltrates into karst. I subsequently replaced the precipitation function with the function of the effective infiltration whereby, in addition to the corrected values of measured precipitation, also the effects of the interception on the vegetation cover, evapotranspiration, snowfall and snowmelt, water storage in the soil and the secondary infiltration were taken into account. The discharge function has been dealt with as well, whereby the measured discharges of Vipava were corrected according to the hydrological interchange with the Bela's surface stream. By setting up the model effective infiltration-discharge, I attained significantly improved correspondence between the measured and calculated discharge values. In this case it once again turned out that the transfer function with the duration of approximately 1 month proved to be the most apposite in the given conditions.

In the last model I assumed that in the unsaturated zone the part of the infiltrated water rapidly flow alongside well-developed fissures and channels and is not retained in the karst system for a longer period of time. In this case we are talking about the fast recharge; whereas with the slow recharge component, we describe the remaining part of the infiltrated water, which is retained by the epikarst zone and is afterwards only slowly flowing through the less permeable zones. Using the hydrological balance method, I assessed the temporal variability of the division into slow and fast recharge. Thus I ascertained corresponding input functions, which I subsequently compared with the aquifer's discharge. By taking into consideration the division of the recharge function, the match between the measured and calculated discharges was additionally slightly closer. In this case the statistical coefficients were high enough to evaluate the discharge simulation as entirely acceptable. It goes without saying that some divergences between the measured and calculated values will still remain. The reason for this is not only in the system's deficiency and in the applied assumptions for its elaboration, but also in errors in determining the input and output functions. Despite the fact that detailed evaluation of the effective infiltration was made, due to the limitations in the measurement of individual parameters certain assumptions were still used which might have negatively influenced the quality of the obtained results. A similar conclusion would apply also to the used method of ascertaining the slow and fast recharge components.

Also of considerable interest was the comparison between the transfer function for the model effective infiltration-discharge and both transfer functions for model slow and fast recharge-discharge. All three are presented in the figure 51, and additionally the overall transfer function is represented as the sum total of transfer functions for the slow and fast recharge, whereby we have taken into account the average share of the fast recharge (62 %) and the slow one (38 %) within the entire period of two hydrological years from 1993 to 1995. This overall transfer function very closely matches values that were obtained at the basic comparison between effective infiltration and discharge. Differences occur particularly in time t>30 days due to the limitations of the duration of the basic transfer function. With regard to the ascertained characteristics, I may assume that there is no significant difference in the estimated overall discharge value for the entire period. Some differences, however, occur in comparison of daily values and are

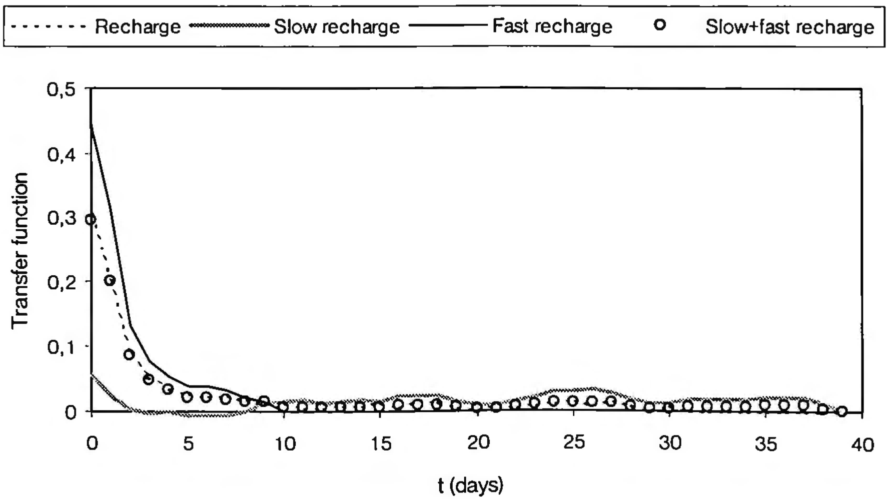


Figure 51: Comparison of different transfer functions

characteristically dependent on the changes in the ratio between the slow and fast recharge in individual precipitation intervals. This, in turn, signifies that the procedure of the separation and the estimated shares of both recharge components significantly affect the final result of the comparison between the recharge and discharge.

VALIDATION OF THE MODEL

The model slow and fast recharge-discharge thus turned out to be the most apposite for the description of conditions in the karst aquifer in the recharge area of Vipava springs for the considered period of two hydrological years from 1993 to 1995. In order to confirm its adequacy, I undertook also the validation procedure. This is the process of the evaluation of the model's efficiency on the basis of the comparison of measured and calculated discharge values for the interval of input data, which were not used at setting up and the calibration of the model. With this aim in view, I used the data for the period of eight hydrological years from 1 October 1985 to 24 August 1993, which were once again provided by Hydrometeorological Survey. For the purposes of comparison, I undertook the validation also for the model effective infiltration-discharge.

Due to the fact that within the period from 1985 to 1993 some of the parameters were not measured, I had to introduce into the model for the estimation of effective infiltration certain modifications. The problems cropped up at determining the secondary infiltration, since the gauging stations on sinking streams from the non-karst area in years from 1985 to 1993 were still not in operation. With regard to the insignificant share of this component in the overall recharge value, I simplified the calculation by adopting for the entire karst and non-karst recharge area that covers 149 km^2 the set

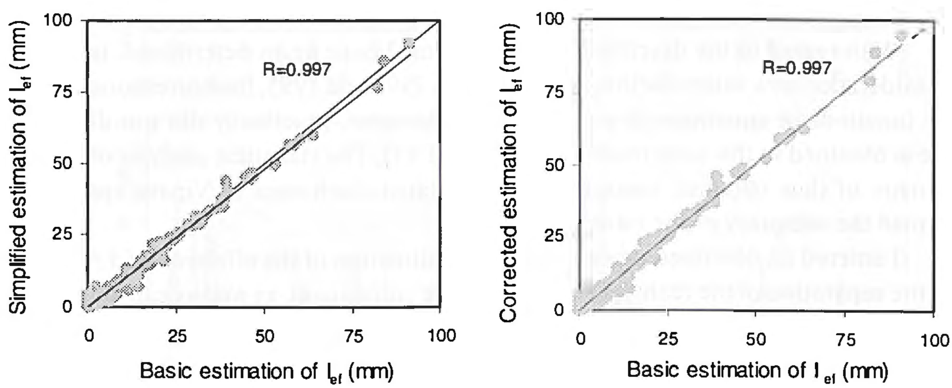


Figure 52: Comparison of results of the basic simplified and the corrected simplified model for the estimation of the effective infiltration

model for the estimation of effective infiltration. Owing to this simplified method the values of effective infiltration might have been slightly underestimated, and for that reason I adopted in my further evaluation the corresponding correction factor (Fig. 52).

On the basis of thus modified model I calculated the daily values of the effective infiltration for the entire period of 10 hydrological years from 1985 to 1995, whereas applying the above described hydrological balance method, I, subsequently and on the basis of these values, determined also the slow and fast recharge component.

I simplified also the determination of the discharge function, given that for the considered period of eight hydrological years the data on Bela's discharges were not available. As an output component I adopted the measured discharges of Vipava springs, since the comparison between the corrected discharge values and measured discharges in the period 1993-1995 displayed only minor divergences.

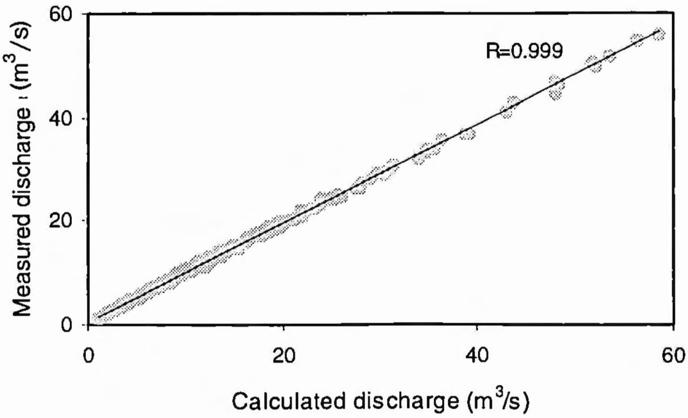


Figure 53: Comparison between the corrected discharges and measured Vipava's discharges in the period from 1993 to 1995

With regard to the described simplifications, I once again determined, taking into consideration new values for the period between 1993 and 1995, the corresponding transfer functions in equations 19 and 20, which, however, practically did not differ from those obtained in the basic model (Figs. 40 and 43). The statistical analysis of the comparison of thus obtained measured and calculated discharges of Vipava springs confirmed the adequacy of the established models.

I entered all described procedures in the estimation of the effective infiltration and in the separation of the recharge in slow and fast component, as well as calculated transfer functions, into the PREPAD document in Microsoft Excell software tool. By means of corresponding formulas and modules the document united the model for the estimation of the effective infiltration and the recharge-discharge models (model effective infiltration-discharge and model slow and fast recharge-discharge), which on the basis of the required input data enabled the calculation of daily discharges of Vipava springs. I used it for the simulation of discharges in validation interval of 8 hydrological years. The comparison between the calculated and measured values for the model slow and fast recharge-discharge is presented in the figure 54.

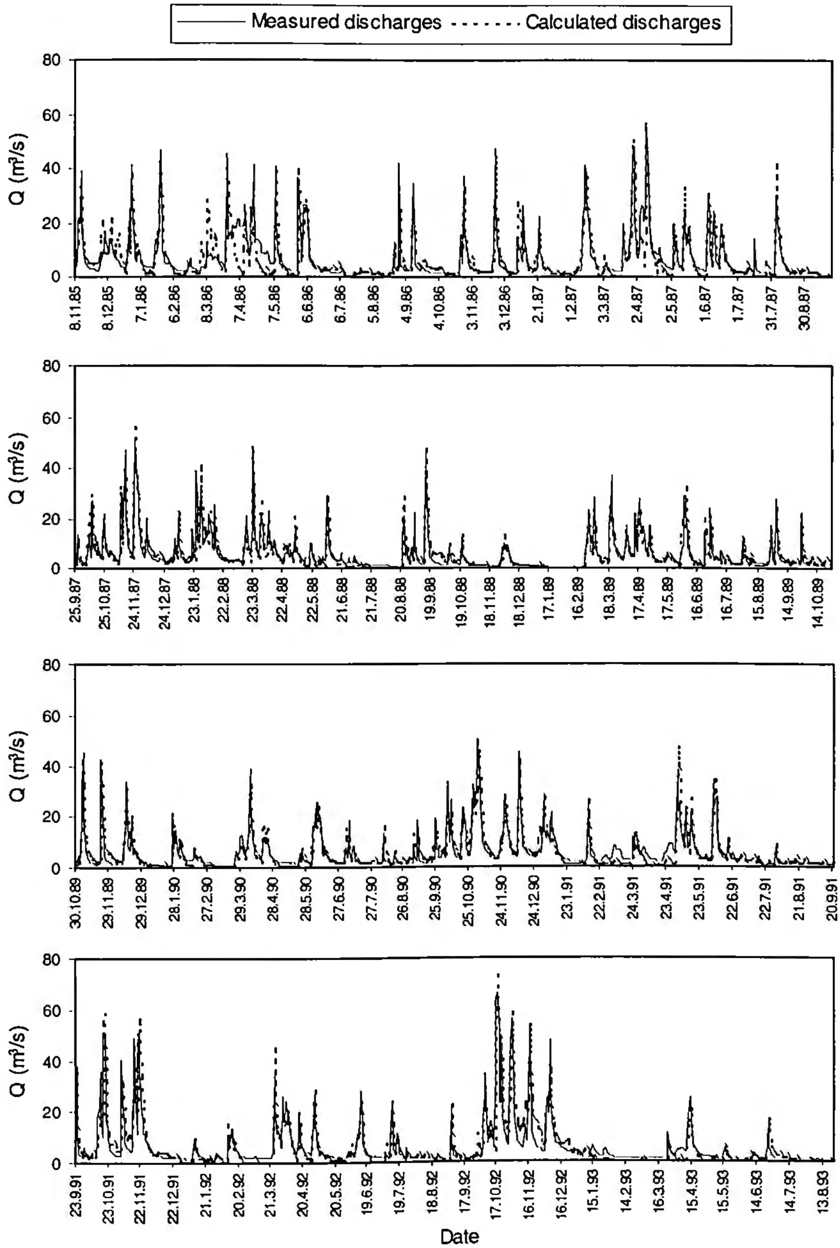


Figure 54: Validation of the model slow and fast recharge-discharge for the period 1985-1993

Characteristic values of the measured and simulated discharges are displayed in the table (Table 5).

Table 5: Table of characteristic discharges in the validation period 1985-1993

	Q_{min} (m^3/s)	Q_{max} (m^3/s)	Q_{avg} (m^3/s)	% of measured Q_{avg}
Measured values	0.727	66.000	6.166	100
Model effective infiltration-discharge	0.174	87.818	6.274	101.8
Model slow and fast recharge-discharge	0.002	72.438	6.076	98.6

Results of the simulation were analysed by statistical methods, which are described in previous subchapter. Scatter plots for daily and monthly values, and residual mass curve are presented on figures 55 and 56. For comparison the later was made also for the model effective infiltration-discharge.

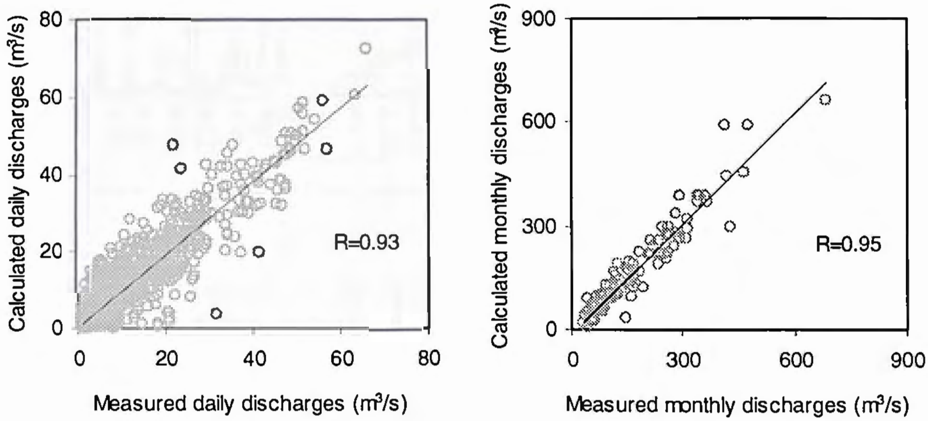


Figure 55: Scatter plots of comparison between measured and calculated daily and monthly discharges in the validation period 1985-1993

In the table 6, other statistical parameters of the comparison between measured and calculated daily and monthly discharges of Vipava springs in the period of 8 hydrological years for both models are also represented.

When compared to the results of model calibrations in the period from 1985 to 1993 the statistical parameters are, as expected, of slightly lower quality. The best for the validation period 1985-1993, however, proves to be the model with the division of the recharge into the slow and fast components. With respect to the coefficient E, also the model effective infiltration-discharge could be assessed as acceptable; quite considera-

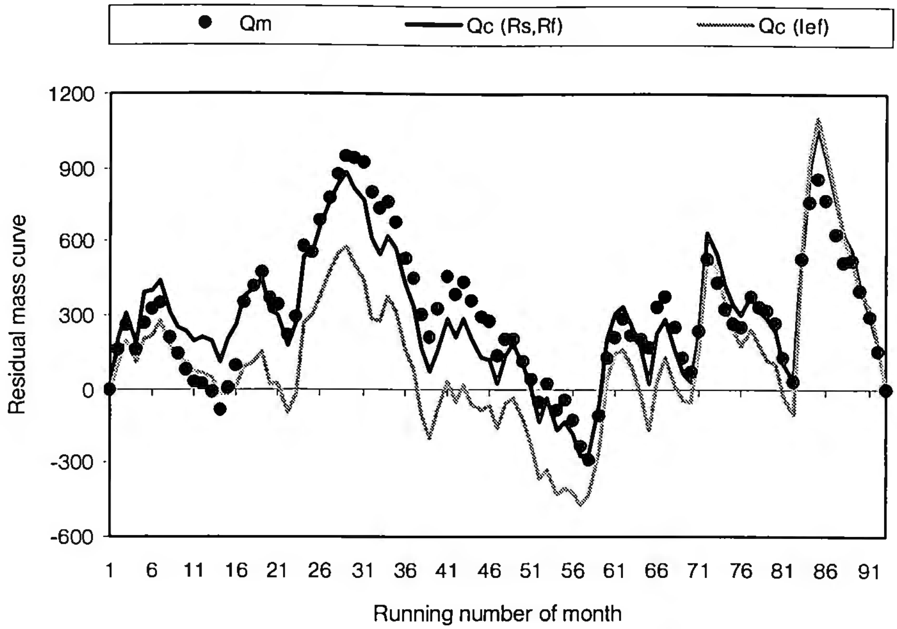


Figure 56: Residual mass curve for the validation period 1985-1993

Table 6: Table of statistical coefficients in the validation period 1985-1993

Daily values

	r	OBJ1	OBJ2
Model effective infiltration-discharge	0,90	1,3	0,8
Model slow and fast recharge-discharge	0,93	1,0	1,0

Monthly values

	r	OBJ1	OBJ2	D	E	R
Model effective infiltration-discharge	0,93	1,6	1,5	0,995	0,81	0,57
Model slow and fast recharge-discharge	0,95	1,0	1,0	0,997	0,89	0,85

ble divergence of the residual mass curve coefficient R, however, suggests the existence of a systematic error.

Validation of the model slow and fast recharge-discharge therefore confirmed that it ensures enough accurate simulation of the relation between the recharge and discharge of the karst aquifer in the recharge area of Vipava springs and it also enables one to infer the characteristics of the functioning of the studied karst system on the basis of the obtained results. Due to the separation of the recharge according to the hydrological balance method, which is founded upon the comparison between the recharge and discharge for the entire precipitation intervals, the model could not be used for the simulation of discharges merely on the basis of data on precipitation, on snowpack depth, and on meteorological parameters. On the other hand this possibility is provided by the model effective infiltration-discharge, but in this case significantly lower accuracy of prediction as well as the existence of certain systematic error were detected.

One of the possible reasons for lower quality of validation process results may be the inappropriate selection of the time interval of the model's calibration. I opted for the period of two hydrological years 1993-1995 due to the most extensive data base. This interval, however, regarding the hydrological conditions, deviated the most from the annual average, since it covered a very wet period. For that reason the evaluation of the effect of the calibration's interval selection on the adequacy of the obtained models seemed reasonable.

EVALUATION OF THE EFFECT OF THE CALIBRATION'S INTERVAL SELECTION ON THE MODEL'S CHARACTERISTICS

For purposes of verification of homogeneity and sufficiency of the available data base, I consequently elaborated also the comparison of results for the case when the calibration's interval was changing. With such cross-comparing technique (Kompare *et al.* 1997) we reduce the possibility that only a local optimum would be ascertained at the calibration for the selected group of data; such an optimum would, despite the high level of correspondence, not reflect the actual conditions to a satisfactory degree through the longer observation period. For that reason I determined also, in the case of the aquifer in the recharge area of Vipava springs, calibration intervals of hydrological years 1988-1990, 1990-1992, and 1989-1994 for the transfer functions; at the validation, however, I adopted in all three cases the remaining hydrological years from the entire period 1985-1995.

Adhering to the previously described method, and taking into account the separation of the recharge into slow and fast components, I determined transfer functions for all three new intervals. With the aim of easier comparison of their forms, I united the transfer functions for slow and fast recharge (taking into consideration the average value of fast recharge - 62 % and the slow one - 38 %) (Fig. 57). Differences between functions for various intervals are very minor, whereas divergences occur chiefly at the peak level.

I finally applied calculated transfer functions for the selected periods of hydrological years also to the simulation of discharges for the longer time period. On the basis of functions from years 1988-1990, 1990-1992, and 1989-1994, I evaluated discharges in the intervals 1985-1988 and 1990-1995, 1985-1990 and 1992-1995, as well as 1985-1989 and 1994-1995. First two groups of data comprise the period of 8 hydrological years,

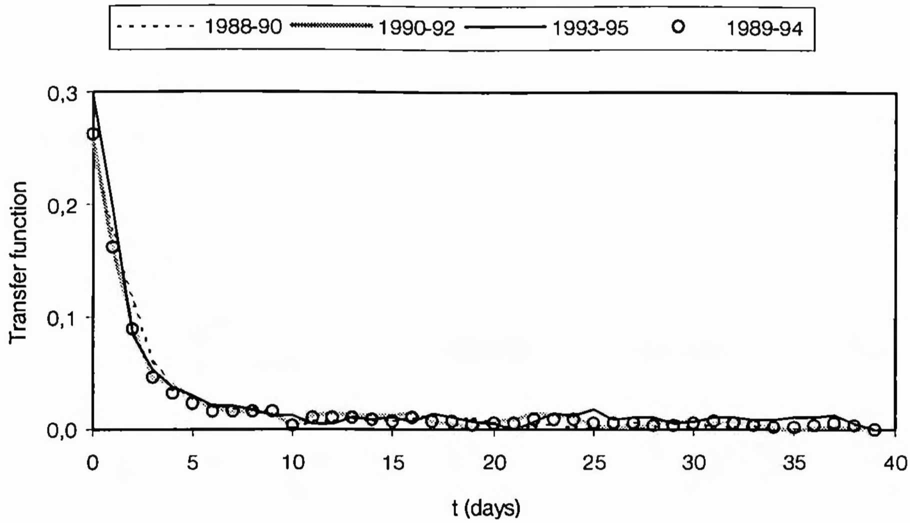


Figure 57: Comparison of transfer functions for different calibration intervals

while the third one the period of 5 years. For purposes of the facilitated reciprocal comparison, I broadened also the third group to the interval between 1985-1990 and 1992-1995. I determined the coefficient of determination D, coefficient of efficiency E and the coefficient of the residual mass curve R (Table 7).

Table 7: Table of statistical coefficients, taking into account different calibration intervals

	D	E	R
1993-95	0,93	0,81	0,57
1988-90	0,93	0,81	0,43
1990-92	0,93	0,83	0,66
1989-94	0,93	0,82	0,67

Intervals 1990-1992 and 1989-1994 most markedly stand out from the table due to their higher coefficient of the residual mass curve. In order to be able to evaluate the obtained results even more accurately, I compared also the hydrological characteristics of selected intervals. I expressed the mean values of discharges, precipitation and effective infiltration for individual hydrological years within the diagram, using the same units (Fig. 58). Already at first sight it is obvious that precipitation is characteristically higher than discharges. This difference primarily reflects processes taking place in air, vegetation and in the soil, which I took in consideration in the estimation of effective infiltration and for which reason the correspondence between average values of the effective infiltration and discharges is already improved. In this evaluation we should, naturally, not overlook the fact that the model for the estimation of effective infiltration was calibrated according to the total discharge of Vipava springs within the period of two hydrological years 1993-1995. For that reason the matching is the closest precisely in the calibration interval, whereas in other intervals the effective infiltration proved to be larger or lower than discharges. If we exclude the possibility of larger errors in the model for estimation, we might interpret these deviations as the result of differing conditions of flow and storage within the karst aquifer. The hydrological year in the sense of the water balance is namely not an enclosed entity, since the effects of different degrees of wetness may remain active and are transferred through considerably longer time periods in the form of certain super-slow recharge. Some basic characteristics of the functioning of the karst systems may be thus inferred already from the differences among mean values, whereas for more accurate determination of processes more detailed analysis is required, wherein also the processing and comparison of the individual components should be included.

In addition to these general characteristics the diagram displays also the average values of differences between mean values of effective infiltration and discharges for the selected intervals. The biggest difference appeared in the period 1988-1990, lower in 1990-1992, the lowest and negative, however, in 1993-1995.

On the basis of this comparison we may conclude that the ascertained differences are reflected also in the previously described results of statistical analyses of models

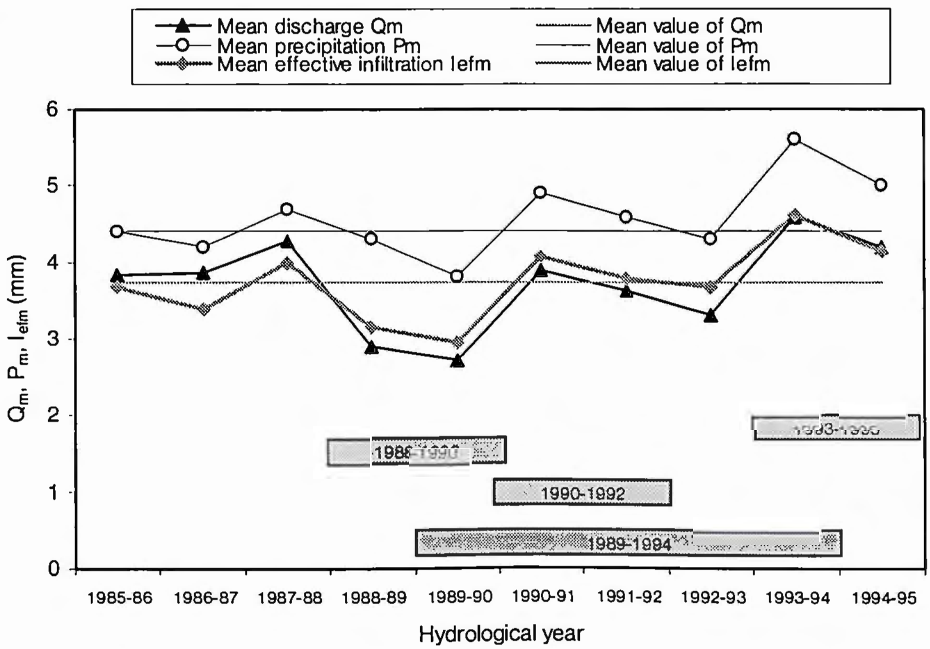


Figure 58: Comparison of hydrological characteristics of individual hydrological years in the period 1985-1995

with different calibration intervals. Larger surpluses of the effective infiltration are reflected in proportionately lower values of the transfer function (Fig. 57). The best results in the simulation of discharges, however, yields the model, which was calibrated according to the interval, wherein the hydrological characteristics came closest to the average. In the case considered these were intervals 1990-1992 and 1989-1994 (Table 7).

Despite ascertained minor differences and linking the model's adequacy to the hydrological conditions within the calibration interval, I may, with regard to the results of the undertaken evaluation, in general conclude that the effect of the selection of this interval on the model's characteristics proved to be small. The extant data base is therefore sufficient and homogeneous enough.

CHARACTERISTICS OF RECHARGE-DISCHARGE RELATIONS IN KARST AQUIFER

CHARACTERISTICS OF THE RECHARGE-DISCHARGE MODELS

In the described research the possibilities in studying the characteristics of karst aquifers were analysed by taking into consideration the principles of the black-box method, whereby we attempt to explain the functioning of these systems on the basis of the comparison between the input and output function, without separately dealing with the aquifer's characteristics at the individual points within the system. With regard to the aspired aims and the available data, I slightly adapted the method, following the assumption that the hydrological complexity of the karst aquifers is primarily a consequence of very variable conditions of recharge and heterogeneous properties of the groundwater flow. I combined processes that determine these conditions and properties into a conceptual model, wherein the karst system was dealt with as a group of several interconnected sub-systems. To be able to compare influences of individual sub-systems 3 different input-output models were set. By changing the input signal I tried to draw as near to the real conditions as possible. In the first one the measured precipitation and springs' discharges were compared, whereas the karst system between the input and output was treated as a whole. The functioning within the system was expressed by the transfer function, which transforms the input signal into the output one.

In the second model I particularly exposed the sub-system of effective infiltration. I described its operation with the soil moisture balance model, wherein processes of interception on the vegetation cover, snowfall and snowmelt, evapotranspiration, water storage in the soil and the secondary infiltration were included. In this manner, the just mentioned processes taking place in air, vegetation and in the soil, which significantly affect the actual quantity and temporal distribution of infiltration, were considered already in the determination of the input component. The response of karst springs to it, however, is described by the transfer function.

In the third model I took into account also characteristics of the sub-system of unsaturated zone. The form of the input function is based upon findings about the hydrodynamical role of the epikarst zone and about its functioning as the controlling factor, that determines the temporal distribution of the recharge. Numerous studies have demonstrated that part of the infiltrated water during high waters is rapidly transferred into the network of channels, whereas the remainder is stored in the epikarst base and subsequently recharges less permeable zones of aquifer. I tried to express these characteristics by the division into fast and slow recharge. On the basis of the comparison between daily values of the effective infiltration and shares of direct and base flow through karst springs of Vipava within individual precipitation intervals I evaluated, by applying the hydrological balance method, for each corresponding precipitation event, the ratio between fast and slow recharge. For each one of the components I subsequently adapted the corresponding transfer function in the input-output system.

In testing the set up hypothesis I compared the adequacy of individual models. I evaluated the accuracy of simulation, which is related to the transfer function's ability to reproduce discharges, on the basis of which the transfer function was determined. By application of various statistical methods I thus compared the measured and calculated discharge values. With respect to the closeness of matching, I assessed the appropriateness of the set up models, whereas with regard to their structure and properties and with respect to the form and characteristics of transfer functions, I conjectured about the role of the considered sub-systems in the flow and storage of water within the karst system. It became evident that the inclusion of the sub-system of effective infiltration substantially improved the model, whereas the ability of the established model to evaluate discharges was further increased by considering the distinction between the slow and fast recharge components. In such a case the calculated statistical coefficients are high enough to enable us to assess the established model slow and fast recharge-discharge as entirely acceptable. It goes without saying that some divergence between the measured and calculated values will still remain. The reason for that is not solely in the model's deficiency but moreover in errors in measurement and in evaluation of its input components.

CHARACTERISTICS OF RECHARGE-DISCHARGE RELATIONS IN KARST AQUIFER

Despite certain limitations of the described method, which simplifies the actual conditions in the karst aquifer, we may nevertheless, with regard to the satisfactory correspondence of the measured and calculated discharges of Vipava springs, draw certain conclusions about the main characteristics of the functioning of the studied karst system. The improvement in the model's results, brought about by the introduction of the effective infiltration function instead of the precipitation, highlighted the significant influence exerted by vegetation and processes in air and in the soil on the quantity and the temporal distribution of water, which actually enters into the aquifer. The simulation's accuracy was further enhanced by division of the recharge into its slow and fast component, which points in favour of the assumption about the duality of the system functioning: i.e. about the rapid flow through the karst drainage network on the one hand, and lengthier retention of water in the system due to the storage within the less permeable zones on the other.

Characteristics of the flow and storage within the karst system may be inferred also from the form of transfer functions. High values in the first part of the transfer function for the fast recharge indicate that the springs already react to it by an increase in their discharge within the first few days after the precipitation event. After the peak in the time t=0, the influence of the fast recharge decreases at first quickly and after three days at a slightly slower rate. The slow recharge, however, is distributed over a longer time period, which in the case considered is limited also by the presupposed duration of the transfer function. In the initial stage its values are ranging around 0. Such conditions are well matched with a finding that, due to the increased potential in the karst channels which is a consequence of the fast recharge, the outflow from the less permeable zones proves to be negligible. Positive values in continuation, however, reflect the successive outflow of water, which was infiltrated into the system as the slow recharge. As with other transfer functions of longer duration, oscillations may occur also in this case and they point toward the periodical increase of the influence of slow recharge on the discharge of springs. At least partly they are certainly a consequence of errors in estimation of discharge functions and recharge, and also of the assumption about the system's linearity, which does not entirely correspond to real conditions.

ROLE OF THE ACCURATE ESTIMATION OF EFFECTIVE INFILTRATION

Special attention was focused on the sub-system of effective infiltration. In addition to precipitation as the basic source, the effects of interception on vegetation cover, evapotranspiration, snowfall and snowmelt, storage of water in the soil, as well as secondary infiltration of sinking streams which collect their surface water in the flysch marginal area, were also included. Owing to the deficiency of the data on parameters which influence these processes, certain assumptions and the calibration with regard to the overall combined discharge of Vipava springs in the period of two hydrological years 1993-1995 were used in the model for the estimation of effective infiltration. Such an approach may somehow diminish the quality of results obtained, yet it nevertheless confirmed the important role of the described processes in the study of hydrodynamic characteristics of karst aquifer. The comparison of values obtained demonstrated that the application of the model of estimation of effective infiltration has a particularly significant influence on the seasonal distribution of the amount of infiltration. The difference between measured precipitation and effective infiltration is accordingly greater in spring than in autumn, since it mainly reflects changes in conditions of climate and vegetation. The lesser share of effective infiltration during spring is primarily a consequence of the start of the exuberant vegetation growth, which is reflected in the increased influence of the interception on the vegetation cover and the increased evapotranspiration.

Due to the fact that errors in the input function values without the accurate estimation of effective infiltration already exert characteristic negative effect on results of the further analysis of the functioning of karst systems, it is obligatory to dedicate special attention to this component and to its most accurate evaluation.

CHARACTERISTICS OF THE SECONDARY RECHARGE FROM SURFACE STREAMS ON KARST

Noticeable results were yielded also by a more detailed analysis of the surface and groundwater interaction of the Bela stream and Vipava springs. The assumptions about the inflow of the Bela's water into the Vipava springs were effectively confirmed by a tracing test, by comparison of physicochemical characteristics of the water and by measuring discharges at several profiles along the Bela surface stream. The flow is mostly directed toward the spring Vipava 7 (approximately 60 % of the returned tracer), but dependent on hydrological conditions and in different quantities also toward other permanent Vipava springs. It was demonstrated that the hydrological response changed, dependent on the amount of the recharge from the karst and flysch recharge area. High waters in the immediate karst recharge area of Vipava springs limit the inflow from the direction of Bela, whereas conversely, at low waters the impact of the secondary recharge from flysch recharge area is increased, not only in the spring Vipava 7 but even more conspicuously in all other permanent Vipava springs. The share of water originating from the Bela in Vipava 7 ranges around 20 % and rises when the intensity and the amount of precipitation in flysch recharge area exceeds those of the karst one.

Results of the investigations of the correlation between the surface stream Bela and Vipava springs thus confirmed that the extent of the recharge of karst springs from the surface flow is significantly dependent on the hydrological conditions.

HYDRODYNAMIC FUNCTION OF THE EPIKARST ZONE

The characteristics of the functioning of karst systems may be indirectly conjectured also from the conclusion that the best results were yielded by the model with the division into the slow and fast recharge component. We could relate this ascertained feature to the existence of a certain mechanism that enables rapid entrance of the infiltrated precipitation water into karst drainage network and brings about as its consequence a typical reaction of karst springs, i.e. their rapid and intensively increased discharge. On the other hand, such a mechanism enables a part of infiltrated precipitation to be temporarily stored during high waters and subsequently sustains the slower emptying of the aquifer also in period of low waters. Numerous studies described in the literature have ascribed such a role to the epikarst zone.

These findings about the hydrodynamic function of epikarst which, due to its typical structure, influences the temporal recharge distribution, were, using the new research method and the altered approach to the study of the functioning of the karst systems, confirmed also by my research. After the precipitation event a part of the infiltrated water rapidly flows as the fast recharge through primary karst drainage channels to the water table. The remainder is retained in the epikarst's base and subsequently in the form of the slow recharge, sustains the inflow of water toward the saturated zone of the karst aquifer for longer time intervals in the period of low waters.

POTENTIAL USE OF THE ESTABLISHED RECHARGE-DISCHARGE MODELS FOR THE SIMULATION OF DISCHARGES OF VIPAVA SPRINGS

The validation of recharge-discharge models pointed also towards the possibility of their use for simulation of discharges of Vipava spring on the basis of data on precipitation and meteorological parameters in the recharge area. Although, the best results were initially yielded by the model slow and fast recharge-discharge, yet owing to the applied method of separation of recharge components, it is not suitable for simulation. The method of hydrological balance is based upon comparison between the effective infiltration and the discharge for the entire precipitation intervals. In order to use the model in simulation, we should first of all explain and quantitatively define the characteristics of the recharge division on the basis of the comparison of input parameters and not on the basis of the discharge curve analysis, which represents the model's output component.

However, we do not encounter such problems in the model effective infiltration-discharge, since the calibrated model of the estimation of effective infiltration is already included in it. The required data are thus measured precipitation, the snowpack depth, and the temperature and humidity of air, wind velocity and the sunshine hours. The problem that, nonetheless, remains is the lower accuracy of this simulation, which reduces the model's utility for the prediction of discharges in hydrological analyses.

CONCLUSIONS AND POTENTIAL FOR FURTHER RESEARCH

Ascertained characteristics of the recharge-discharge relations as well as conclusions related to the impact of individual components of input function on the functioning of the karst system were already represented in previous sub-chapter. At this point, I will just summarise them in order to answer the questions posed in the introduction:

- I evaluated the adequacy of recharge-discharge models on the basis of statistical analysis of correspondence between measured and calculated discharges of Vipava springs. "Entirely acceptable" proved to be the model slow and fast recharge-discharge, whereas other models were also "acceptable", yet at a somewhat lesser degree. I may thus conclude that the modified black-box method ensures the setting up of models which describe the system's reaction to the recharge in a satisfactory manner. Divergences between measured and calculated discharges, which do occur anyway, are, however, a consequence of errors in evaluation of input and output parameters as well as of the applied assumptions in the elaboration of the model, which do not conform to the actual conditions within the karst aquifers.

- The applied method turned out as adequate also for the evaluation of the hydrodynamic characteristics of karst aquifer. The improvement of the model's results by introducing the effective infiltration function instead of precipitation underlined the significant influence of the vegetation and processes taking place in air and in soil, on the amount and temporal distribution of water which actually enters the karst rock. The simulation's accuracy was further increased by division of the recharge into slow and fast components. All this speaks in favour and advances the assumption about the duality of the karst system's functioning - i.e. about the rapid flow through the karst drainage network and the lengthier retention of water due to the storage in less permeable zones, as well as about the existence of a mechanism within the epikarst zone, which enables such a temporal distribution of the recharge.
- The adequacy of tested models confirmed the appropriateness of the established conceptual recharge model in karst aquifers. The recharge is described by the flow of the infiltrated water, which reaches the water table and brings about as its consequence the increase of the quantity of stored water. The basic source is in general precipitation, which is, however, affected by numerous processes that are taking place in air, vegetation and in soil, which significantly alter the quantitative and temporal distribution of the water's inflow into the epikarst zone. Since without the estimation of effective infiltration, errors that may appear already in input function values exert a characteristically negative impact on the results of the further analysis of the functioning of karst systems, this component and its maximally accurate evaluation deserves special attention. The next phase of the recharge includes the flow of water through the unsaturated zone. The increase of the simulation's accuracy in the last model confirmed the assumption that due to the typical structure of epikarst zone the recharge ought to be divided into the slow and fast component. A part of the infiltrated water quickly flows through the primary karst drainage channels as a fast recharge to the water table, whereas the remainder is retained within the epikarst base and subsequently as the slow recharge for longer time periods sustains the inflow of water into the saturated zone of the karst aquifer.

The research undertaken thus managed to introduce some answers to the questions raised, yet at the same time it opened also many new ones. The potential for further studies point in various directions. Although our focused attention was already by now consecrated particularly to the most accurate possible determination of the recharge function, many assumptions were used in its estimation. Of significant interest would thus prove the study of the impact of the described processes in the air, vegetation and in soil on the actual infiltration of precipitation into the karst aquifer, which should also be supported by field measurement.

Even more unknown quantities are connected with the functioning of the epikarst zone. Its hydrodynamic role and its effects on the transport of substances are frequently conjectured on the basis of results from indirect studies. For that reason the explorations at experimental polygons are increasingly gaining in relevance, since they enable us to closely monitor and control conditions of the recharge, flow and storage. In the region of High karst one such a polygon has already been set up and field measurements investigating the hydrodynamic characteristics of the unsaturated zone were also carried out (Čenčur Curk 2002, Trček 2001, Trček *et al.* 2001, Veselič & Čenčur Curk 2001), therefore the possibility of the inclusion of their findings into the conceptual model of the recharge-discharge system appears highly interesting.

I already underlined the significance of karst aquifers as the source of potable water in the introduction. In our quest for the most adequate ways of their protection ever more attention is dedicated also to the elaboration of hydrological models, with which we could simulate the flow and transport within the karst systems and, subsequently on the basis of obtained results draw a plan of eventual protection measures. The established model effective infiltration-discharge turned out to be acceptable for the simulation of discharges, yet it does not enable the simulation of the transport. In order to ensure more detailed analysis of this process it would be mandatory to include into the study also tracing tests with natural and artificial tracers, whereas their results should be processed by the black-box method.

The second path of potential research conducts us to the use of the deterministic models. We studied possibilities of setting up such a model at the experimental study polygon in the recharge area of Vipava springs within the framework of the project »STALAGMITE: Sustainable management of groundwater in karstic environments« which is a part of the INCO-Copernicus programme (EC Project IC15-CT98-0113). In collaboration with the English research team from Water Resource Systems Research Laboratory, Department of Civil Engineering, University of Newcastle upon Tyne, we adapted for this particular karst aquifer the existent hydrological model SHETRAN (Ewen *et al.* 2000, Adams & Younger 1997, Adams & Parkin 2001). The SHETRAN model is physically-based in so far as most of the parameters have some physical meaning and was first developed for porous aquifers. The modifications made to simulate karstic aquifers are: the coupling of a pipe network model to a variably-saturated 3-D groundwater component to simulate flow under pressure in saturated conduits, the coupling of surface water features (e.g. sinking streams and spring discharges) to the conduit system, and the addition of a preferential "bypass" flow mechanism to represent fast vertical infiltration through a high conductivity epikarst zone. The lack of data on the hydrodynamic parameters and the geometry of the karst drainage network represented a significant problem in application of the model to the karst environment. For that reason, in the process of calibration different conceptual models were tested (Parkin *et al.* 2002). Already basic comparisons demonstrated that without some sort of concentrated rapid infiltration the simulation of characteristic peaks in hydrograph of karst springs proved impossible. In view of that the justifiability of the use of epikarst »bypass« mechanism was confirmed; further difficulty, however, faced the setting up of the corresponding computer procedure for its simulation. The physical process of fast recharge is still poorly understood and very difficult to characterise, so a simplified module was built into the SHETRAN to represent this process. The results obtained are not satisfactory and additional improvements are necessary. First steps in the direction of setting up the numerical hydrological model for the study of the functioning of karst systems in the recharge area of Vipava springs have thus already been taken. Nevertheless, additional research and a long-term process of model improvement will be required, before it may be successfully used in various hydrological studies, as well as in planning the sustainable groundwater management in karstic environments.

REFERENCES

Adams, R. & G. Parkin, 2001: Development of a Coupled Surface-Groundwater-Pipe Network Model for the Sustainable Management of Karstic Groundwater.- In: Beck, B.F. & J.G. Herring (Eds.). Geotechnical and environmental applications of karst geology and hydrology: proceedings of the eighth Multidisciplinary Conference on Sinkholes and the Engineering and Environmental Impacts of Karsts, Louisville, Kentucky, 1-4 April 2001. A.A. Balkema, 195-199.

Adams, R. & P.L. Younger, 1997: Simulation of Groundwater Rebound in Abandoned Mines Using a Physically Based Modelling Approach.- In: Veselič & Norton (Eds.). Minewater and the Environment: Proceedings of the 6th International Minewater Association Congress, Bled, Slovenia 8-12 September 1997. Vol. 2, 353-362.

Aitken, A.P., 1973: Assessing systematic errors in rainfall-runoff model.- Journal of Hydrology, 20, 121-136, Amsterdam.

Allerup, P. & H. Madsen, 1979: Accuracy of point precipitation measurements.- Danish Meteorol. Inst., Climatolog. Pap., No. 5, 84 pp, Charlottenlund.

Armbruster, V. & Ch. Leibundgut, 1997: Short term investigations during a heavy snow-melt event.- Acta carsologica, Karst Hydrogeological Investigations in South-Western Slovenia, 26, 256-259, Ljubljana.

Ashton, K., 1966: The analysis of flow data from karst drainage systems.- Transactions of the Cave Research Group, 7, 163-203.

Atkinson, T.C., 1977: Diffuse flow and conduit flow in limestone terrain in the Mendip Hills, Somerset (Great Britain).- Journal of Hydrology, 35, 93-100, Amsterdam.

Baker, G. & M. Petrič & G. Parkin & J. Kogovšek, 2001: Surface and Groundwater Interaction of the Bela Stream and Vipava Springs in Southwestern Slovenia.- Acta carsologica, 30/2, 16, 217-238, Ljubljana.

Behrens, H. & R. Benischke & W. Käss & M. Zupan, 1997: Results of the Vipava Area - The Second Tracing Experiment in Spring 1994.- Acta carsologica, Karst Hydrogeological Investigations in South-Western Slovenia, 26, 295-301, Ljubljana.

Bonacci, O., 1987: Karst Hydrology. With Special Reference to the Dinaric Karst.- Springer-Verlag, 184 pp, Berlin, Heidelberg.

Bonacci, O., 1994: Oborine: glavna ulazna veličina u hidrološki ciklus.- Geing, 341 pp, Split.

Brenčič, M., 1997: Prispevek k teoriji in praktični obravnavi praznjenja vodonosnikov.-

Magistrsko delo, 168 p, Univerza v Ljubljani, Naravoslovnotehniška fakulteta, Oddelek za geologijo, Ljubljana.

Brown, M.C., 1973: Mass balance and spectral analysis applied to karst hydrologic networks.- Water Resources Research, 9(3), 749-752, Washington.

Buser, S., 1968: Osnovna geološka karta 1:100.000, list Gorica.- Zvezni geološki zavod Beograd, Beograd.

Buser, S., 1973: Osnovna geološka karta 1:100.000. Tolmač lista Gorica.- Zvezni geološki zavod Beograd, 50 pp, Beograd.

Buser, S. & K. Grad & M. Pleničar, 1967: Osnovna geološka karta 1:100.000, list Postojna.- Zvezni geološki zavod Beograd, Beograd.

Calder, I.R., 1977: A model of transpiration and interception loss from a spruce forest in Plynlimon, central Wales.- Journal of Hydrology, 33, 3/4, 247-265, Amsterdam.

Chiew, F.H.S. & M.J. Stewardson & T.A. McMahon, 1993: Comparison of six rainfall-runoff modelling approaches.- Journal of Hydrology, 147, 1-36, Amsterdam.

Chow, V.T., 1964: Handbook of Applied Hydrology.- McGraw-Hill Book Company, 477 pp, New York.

Chow, V.T. & D.R. Maidment, & L.W. Mays, 1988: Applied hydrology.- McGraw Hill Book Company, 527 pp, New York.

Čar, J., 1997: Geological description.- Acta carsologica, Karst Hydrogeological Investigations in South-Western Slovenia, 26, 68-73, Ljubljana.

Čenčur Curk, B., 2002: Tok in prenos snovi v kamnini s kraško in razpoklinsko poroznostjo.- Doktorska disertacija, Naravoslovnotehniška fakulteta, Univerza v Ljubljani, 253 p, Ljubljana.

Diaconu, V. & A. Bulgar & V. Oancea, 1984: The use of the transfer function in establishing the water circulation characteristics in the karst.- Theoretical and Applied Karstology, 1, 225-230, Bucharest.

Dingman, L.S., 1994: Physical Hydrology.- Macmillan Publishing Company, 575 pp, New York.

Doerfliger, N., 1996: Advances in karst groundwater protection strategy using artificial tracer tests analysis and multiattribute vulnerability mapping (EPIK method).- Ph.D. Thesis, Faculty of Sciences, University of Neuchâtel (Switzerland), 308 pp, Neuchâtel.

Dreiss, S.J., 1982: Linear kernels for karst aquifers.- Water Resources Research, 18, 865-876, Washington.

Dreiss, S.J., 1983: Linear unit response functions as indicators of recharge areas for large karst springs.- Journal of Hydrology, 61, 31-44, Amsterdam.

Dreiss, S.J., 1989a: Regional scale transport in a karst aquifer: 1. Component separation of spring flow hydrographs.- Water Resources Research, 25, 117-125, Washington.

Dreiss, S.J., 1989b: Regional scale transport in a karst aquifer: 2. Linear systems and time moment analysis.- Water Resources Research, 25, 126-134, Washington.

Drogue, C. & A. Guilbot, 1977: Représentativité d'un bassin témoin en hydrogéologie

karstique: application à la modélisation des écoulements souterrains d'un aquifère de grande extension.- Journal of Hydrology, 32, 57-70, Amsterdam.
Duffy, C.J. & L.W. Gelhar, 1986: A frequency domain analysis of ground-water quality fluctuations: interpretation of field data.- Water Resources Research, 22(7), 1115-1128, Washington.
Duffy, C.J. & J. Harrison, 1987: The statistical structure and filter characteristics of tritium fluctuations in fractured basalts.- Water Resources Research, 23(5), 894-902, Washington.
Estrela, T. & A. Sahuquillo, 1997: Modeling the response of a karstic spring at Arteta Aquifer in Spain.- Groundwater, 35, 18-24, Westerville.
Ewen, J. & G. Parkin & P.E. O'Connell, 2000: SHETRAN: a coupled surface/subsurface modelling system for 3D water flow and sediment and solute transport in river basins.- ASCE J. Hydrologic Eng., 5(3), 250-258.
Ford., D. & P. Williams, 1989: Karst Geomorphology and Hydrology.- Unwin Hyman, 601 pp, London, Boston, Sydney, Wellington.
Gash, J.H.C. & A.J. Morton, 1978: An application of the Rutter model to the estimation of the interception loss from the Thetford forest.- Journal of Hydrology, 38, 49-58, Amsterdam.
Gash, J.H.C. & J.B. Stewart, 1977: The evaporation from Thetford Forest during 1975.- Journal of Hydrology, 35, 385-396, Amsterdam.
Gospodarič, R., 1987: Zaščita vodnih virov v občini Postojna (brez Malnov).- Tipkano poročilo, 17 p, Biblioteka SAZU, Ljubljana.
Graupe, D. & D. Isailović & V. Yevjevich, 1976: Prediction model for runoff from karstified catchments.- Karst hydrology and water resources, Proc. of the U.S.-Yugoslavian Symp., Dubrovnik 1975, 227-243, Dubrovnik.
Grindley, J., 1967: The estimation of soil moisture deficits.- Meteorol. Mag., 96 (1137), 97-108.
Habe, F., 1970: Predjamski podzemeljski svet.- Acta carsologica, 5, 5-94, Ljubljana.
Habič, P., 1968: Kraški svet med Idrijco in Vipavo. Prispevek k poznavanju kraškega reliefa.- SAZU, Classis IV, Dela-Opera 21, 243 pp, Ljubljana.
Habič, P., 1983: Kraški izviri Vipave in njihovo zaledje.- Acta carsologica, 11, 41-57, Ljubljana.
Habič, P., 1989: Kraška bifurkacija Pivke na jadransko črnomorskem razvodju.- Acta carsologica, 18, 233-264, Ljubljana.
Habič, P., 1997: Geomorphologic review of Trnovsko-Banjška planota.- Acta carsologica, Karst Hydrogeological Investigations in South-Western Slovenia, 26, 38-57, Ljubljana.
Harum, T. & H. Stadler & N. Trišič, 1997: The Electrical Conductivity as Indicator for Hydrodynamic Processes in the Vipava System.- Acta carsologica, Karst Hydrogeological Investigations in South-Western Slovenia, 26, 168-181, Ljubljana.
Howard, K.W.F. & J.W. Lloyd, 1979: The sensitivity of parameters in the Penman evap-

oration equations and direct recharge balance.- Journal of Hydrology, 41, 329-344, Amsterdam.

Janež, J., 1997: Hydrogeology.- Acta carsologica, Karst Hydrogeological Investigations in South-Western Slovenia, 26, 73-81, Ljubljana.

Janež, J. & J. Čar, 1997: Geological conditions and some hydrogeologic characteristics of the Vipava karst springs.- Acta carsologica, Karst Hydrogeological Investigations in South-Western Slovenia, 26, 86-91, Ljubljana.

Janež, J. & J. Čar & P. Habič & R. Podobnik, 1997: Vodno bogastvo Visokega krasa.- Geologija d.o.o., 167 pp, Idrija.

Jeannin, P-Y. & A.D. Grasso, 1995: Estimation des infiltrations efficaces journaliéres sur le bassin karstique de la Milandrine (Ajoie, JU, Suisse).- Bulletin d'Hydrogéologie, 14, 83-93, Neuchâtel.

Jeannin, P-Y. & A.D. Grasso, 1997: Permeability and hydrodynamic behaviour of a karstic environment.- In: Günay & Johnson (Eds.). Karst Waters & Environmental Impacts, 335-342, A.A. Balkema, Rotterdam.

Kiraly, L. & P. Perrochet & Y. Rossier, 1995: Effect of the epikarst on the hydrograph of karst springs: a numerical approach.- Bulletin d'Hydrogéologie, 14, 199-220, Neuchâtel.

Kitching, R. & L. Bridge, 1974: Lysimeter installations in sandstone at Styrrup, Nottinghamshire.- Journal of Hydrology, 23, 219-232, Amsterdam.

Kitching, R. & T.R. Shearer & S.L. Shedlock, 1977: Recharge to Bunter Sandstone determined from lysimeters.- Journal of Hydrology, 33, 217-232, Amsterdam.

Knežević, B., 1976: Optimizacija parametra modela hidrograma oticanja u uslovima krša.- Karst hydrology and water resources, Proc. of the U.S.-Yugoslavian Symp., Dubrovnik 1975, 213-226, Dubrovnik.

Knisel, W.G., 1972: Response of karst aquifers to recharge.- Hydrology Paper 60, Colorado State University, 48 pp, Fort Collins, Colorado.

Kogovšek, J., 1999: Nova spoznanja o podzemnem pretakanju v severnem delu Javornikov (Visoki kras).- Acta carsologica, 28/1, 161-200, Ljubljana.

Kogovšek, J. & M. Knez & A. Mihevc & M. Petrič & T. Slabe & S. Šebela, 1999: Military Training Reserve in Kras (Western Slovenia).- Environmental Geology, 38, 1, 69-76, Tuscaloosa.

Kompare, B. & F. Steinman & U. Cerar & S. Džeroski, 1997: Napovedovanje padavinskega odtoka iz povodja s pomočjo analize podatkov z metodami strojnega učenja iz orodjarne umetne inteligence.- Zbornik referatov 16. Goljevščkovega spominskega dne, Acta hydrotechnica, 15/17, 79-94, Ljubljana.

Kranjc, A. (Ed.), 1997: Karst Hydrogeological Investigations in South-Western Slovenia.- Acta carsologica, 26, 388pp, Ljubljana.

Kranjc, A. & S. Šebela, 1992: Grafične priloge za odlok o varstvu krajevnih vodnih virov v občini Postojna.- Tipkano poročilo, 14 p, Biblioteka SAZU, Ljubljana.

Krešić, N., 1993: Review and selected bibliography on quantitative definition of karst hydrogeological systems.- In: LaMoreaux & Assaad & McCarley (Eds.). Annotated Bibliography of Karst Terranes - Volume 5, International Contributions to Hydrogeology, Vol. 14, 51-87, Heise Verlag, Hannover.

Labat, D. & R. Ababou & A. Mangin, 2000: Rainfall-runoff relations for karstic springs. Part I: convolution and spectral analyses.- Journal of Hydrology, 238, 123-148.

Lerner, D.N., 1997: Groundwater recharge.- In: Saether & de Caritat (Eds.). Geochemical processes, weathering and groundwater recharge in catchments, 400 pp, A.A. Balkema, Rotterdam, Brookfield.

Lerner D.N. & A.S. Issar & I. Simmers (Eds.), 1990: Groundwater Recharge. A Guide to Understanding and Estimating Natural Recharge.- International Contributions to Hydrogeology, Volume 8, 345pp, Verlag Heinz Heise, Hannover.

Loague, K.M & R.A. Freeze, 1985: A Comparison of Rainfall-Runoff Modelling Techniques on Small Upland Catchments.- Water Resources Research, 21, 2, 229-248, Washington.

Lobnik, F., 1991: Pedološka karta Republike Slovenije, sekcija Postojna - opis pedoloških profilov.- Elaborat, Narodna in univerzitetna knjižnica, Ljubljana.

Long, A.J. & R.G. Derickson, 1999: Linear systems analysis in a karst aquifer.- Journal of Hydrology, 219, 206-217, Amsterdam.

Mangin, A., 1975: Contribution a l'étude hydrodynamique des aquiferes karstiques.- Ph.D. These, Univ. Dijon, 124 p, Dijon.

Mangin, A., 1994: Karst Hydrogeology.- In: Gilbert & Danielopol & Stanford (Eds.). Groundwater Ecology, 43-67, Academic Press, Inc., San Diego.

Martin, Ph. & J. Kogovšek & M. Petrič & S. Šebela & C. Martin, 1997: Correlation and spectral analysis.- Acta carsologica, Karst Hydrogeological Investigations in South-Western Slovenia, 26, 144-157, Ljubljana.

Mihevc, A., 1997: Speleological properties of the area.- Acta carsologica, Karst Hydrogeological Investigations in South-Western Slovenia, 26, 57-68, Ljubljana.

Mijatović, B.F., 1990: Kras - hidrogeologija kraških vodonosnika.- Geozavod, 304 pp, Beograd.

Mohrlok, U. & M. Sauter, 1997: Modelling groundwater flow in a karst terrane using discrete and double-continuum approaches - importance of spatial and temporal distribution of recharge.- Proceedings of the 12th International Congress of Speleology, Switzerland - Volume 2, 167-170, Neuchâtel.

Neff, E.L., 1977: How much does rain gage gage?- Journal of Hydrology, 35, 213-220, Amsterdam.

Parkin, G. & P. Arnal & P. Malik & M. Petrič & M. Galabov & B. White, 2002: STALAGMITE-Sustainable Management of Groundwater in Karstic Environment - Final report.- EC project IC15-CT98-0113. Biblioteka SAZU, Ljubljana.

Penman, H.L., 1948: Natural evaporation from open air, bare soil and grass.- Proc. Roy. Soc. London, 193, 120-145, London.

Penman, H.L., 1950: The water balance of the Stour catchment area.- J. Inst. Water Eng., 4, 457-469.

Petrič, M., 1996a: Ocena efektivne infiltracije v študijskem poligonu Tičnice (Estimation of the effective infiltration in the Tičnica basin).- Acta carsologica, 25, 365-390, Ljubljana

Petrič, M., 1996b: Study of relations rainfall-runoff in experimental karst basin.- In: Karst-fractured aquifers - vulnerability and sustainability. Katowice-Ustroń, 169-176, Katowice-Ustron.

Petrič, M., 1998: Odvisnost padavine - pretok izvirov v karbonatem vodonosniku Tičnice (Relation precipitation - spring discharge in the carbonate aquifer Tičnica).- Acta carsologica, 27/1, 325-347, Ljubljana.

Petrič, M., 2000a: Recharge-discharge relations of the Vipava karst aquifer, Slovenia.- In: Sililo, O. (Ed.). Groundwater: past achievements and future challenges: proceedings of the 30 IAH Congress on Groundwater: Past Achievements and Future Challenges, Cape Town, South Africa, 26 November-1 December 2000. 253-257, A.A. Balkema, Rotterdam.

Petrič, M., 2000b: Značilnosti napajanja in praznjenja kraškega vodonosnika v zaledju Vipave.- Doktorska disertacija, Naravoslovnotehniška fakulteta, Univerza v Ljubljani, 151 p, Ljubljana.

Petrič, M., 2000c: Značilnosti odnosa med napajanjem in praznjenjem kraškega vodonosnika v zaledju izvirov Vipave (Slovenija) (Characteristics of the recharge-discharge relation of the karst aquifer in the background of the Vipava springs (Slovenia)).- Acta carsologica, 29/2, 271-292, Ljubljana.

Petrič, M., 2001: The role of accurate recharge estimation in the hydrodynamic analysis of karst aquifers.- Acta carsologica, 30/1, 69-84, Ljubljana.

Placer, L., 1981: Geološka zgradba jugozahodne Slovenije.- Geologija, 24/1, 27-60, Ljubljana.

Placer, L., 1994/95: O zgradbi Soviča nad Postojno.- Geologija, 37, 38, 551-560, Ljubljana.

Pleničar, M., 1970: Osnovna geološka karta 1:100.000. Tolmač lista Postojna.- Zvezni geološki zavod Beograd, 62 pp, Beograd.

Poitrinal, D., 1974: Qu'apporte la deconvolution a l'hydrogeologue?- Mem. Int. Assoc. Hydrogeol., 10 (1), 238-241.

Poitrinal, D. & G. De Marsily, 1973: Relations du type entree-sortie en hydrogeologie procede d'identification de l'operateur.- Bull. Bur. Rech. Geol. Minière, Ser. 2, 3(2), 119-135.

Pristov, J., 1997: The climate of the Trnovsko-Banjška planota.- Acta carsologica, Karst Hydrogeological Investigations in South-Western Slovenia, 26, 30-38, Ljubljana.

Pristov, J., 1998: Vodna bilanca.- In: MOP-Hidrometeorološki zavod Republike Slovenije, Površinski vodotoki in vodna bilanca Slovenije, 41-98, Ljubljana.

Puncer, I. & M. Zupančič & M. Wraber, 1982: Vegetacijska karta Postojna L33-77.- SAZU, Razred za naravoslovne vede, Biološki inštitut Jovana Hadžija, 118 pp, Ljubljana.

Remškar, B., 2001: Vipavska jama.- Naše jame, 43, 107-112, Ljubljana.

Rushton, K.R. & C. Ward, 1979: The estimation of groundwater recharge.- Journal of Hydrology 41, 345-361, Amsterdam.

Rutter, A.J., 1975: The hydrological cycle in vegetation.- In: Monteith (Ed.). Vegetation and the Atmosphere, Vol. 1, Ch. 4, 111-154, Academic Press, London.

Rutter, A.J. & K.A. Kershaw & P.C. Robins & A.J. Morton, 1971: A predictive model of rainfall interception in forests, I. Derivation of the model from observations in a plantation of Corsican pine.- Agric. Meteorol., 9, 367-380.

Sauter, M., 1992: Quantification and forecasting of regional groundwater flow and transport in karst aquifer (Gallusquelle, Malm, SW Germany).- Ph.D. Thesis, Tübingen geowissenschaftliche Arbeiten C13, 150 pp, Tübingen.

Schumann, S., 1996: Evaluations on the basis of discharge time series and conductivity measurements - Hubelj and Vipava springs.- Bericht der Professur für Hydrologie der Albert-Ludwigs-Universität Freiburg i. Br., 69 p, Freiburg.

Sevruk, B., 1982: Methods of correction for systematic error in point precipitation measurement for operational use.- WMO, No. 589, Operational Hydrology, Report No. 21, 91 pp, Geneva.

Sevruk, B., 1986: Correction of precipitation measurements: Swiss experience.- Proc. Correction of Precipitation Measurements, 187-196, Zürich.

Shaw, E.M., 1994: Hydrology in Practice. Third edition.- Chapman & Hall, 569 pp, London.

Smith, D.B. & P.L. Wearn & H.J. Richards & P.C. Rowe, 1970: Water movement in the unsaturated zone of high and low permeability strata by measuring natural tritium.- Proc. of the Symposium on the Use of Isotopes in Hydrology, I.A.E.A., 73-87, Vienna.

Stewart, J.B., 1977: Evaporation from the wet canopy of a pine forest.- Water Resources Research,13, 915-921, Washington.

Šebela, S., 1991: Površinske geološke strukture in njihov vpliv na oblikovanje Predjame.- Magistrsko delo, 115 p, Univerza v Ljubljani, Fakulteta za naravoslovje in tehnologijo, Oddelek za montanistiko, Odsek za geologijo, Ljubljana.

Šebela, S. & J. Čar, 1991: Geološke razmere v podornih dvoranah Vzhodnega rova Predjame.- Acta carsologica, 20, 205-222, Ljubljana.

Šebela, S., 1996: Pregled najpomembnejših speleoloških, hidroloških in geoloških raziskav Predjamskega spleta.- Naše jame, 38, 17-28, Ljubljana.

Šušteršič, F., 1996: Jame v zaledju Predjame.- Naše jame, 38, 29-34, Ljubljana.

Trček, B., 2001: Spremljanje prenosa snovi v nezasičeni coni kraškega vodonosnika z naravnimi sledili.- Doktorska disertacija, Naravoslovnotehniška fakulteta, Univerza v Ljubljani, 125 p, Ljubljana.

Trček, B. & J. Pezdič & M. Veselič & W. Stichler, 2001: Changes in $\delta^{18}O$ composition of the Hubelj spring under different hydrogeological conditions.- In: Seiler & Wöhnlich (Eds.). New approaches characterizing groundwater flow. Proceedings of the XXXI International Association of Hydrogeologists Congress, Munich, Germany, 10-14 September 2001. A.A. Balkema, 207-210.

U.S. Army Corps of Engineers, 1960: Runoff from Snowmelt.- Engineering and Design Manuals, EM 1110-2-1406.

Veselič, M. & B. Čenčur Curk, 2001: Test studies of flow and solute transport in the unsaturated fractured and karstified rock on the experimental field site Sinji Vrh, Slovenia.- In: Seiler, & Wöhnlich (Eds.). New approaches characterizing groundwater flow. Proceedings of the XXXI International Association of Hydrogeologists Congress, Munich, Germany, 10-14 September 2001. A.A. Balkema, 211-214.

Veselič, M. & J. Prestor & P. Junež, 1989: Hidrogeološka problematika rudnika Mežica. Poročilo o v letu 1988 izvedenih raziskavah.- Tipkano poročilo, IGGG, Ljubljana.

Vidav, I., 1976: Višja matematika III.- Državna založba Slovenije, 557 pp, Ljubljana.

Vrevc, S., 1994: Kmetijska tehnologija in širjenje škodljivih snovi v krasu. Preliminarno poročilo o delu v letu 1993.- In: Širjenje škodljivih snovi v krasu-Sledila in modeli v različnih vodonosnikih. Fazno poročilo za leto 1993, 86 p, Biblioteka SAZU, Ljubljana.

Vrhovec, T., 1999: Predjamski sistem.- Bilten Jamarskega kluba Železničar, 21, 5-12, Ljubljana.

Wicks, C. & B. Bohm, 2000: Application of Unit Hydrograph Technique to the Discharge Record at Big Spring, Carter County, Missouri.- In: Sasowsky & Wicks (Eds.). Groundwater Flow and Contaminant Transport in Carbonate Aquifers. A.A. Balkema, 193 pp, Rotterdam, Brookfield.

Wicks, C.M. & J.A. Hoke, 1999: Linear systems approach to modeling groundwater flow and solute transport through karstic basins.- Karst Modeling, Karst Waters Institute Special Publication 5, 97-101, Charlottesville, Virginia.

Williams, P.W., 1983: The role of subcutaneous zone in karst hydrology.- Journal of Hydrology, 61, 45-67, Amsterdam.

Yang, D. *et al.*, 1994: Wind-Induced Error on Snow Measurement.- WMO Intercomparison Results, Annalen der Meteorologie 30, Offenbach am Main.

Zupan, M., 1997: The Fourth Tracing Experiment in Autumn 1995.- Acta carsologica, Karst Hydrogeological Investigations in South-Western Slovenia, 26, 302-304, Ljubljana.

Zupančič, B., 1995: Klimatografija Slovenije 1961-1990, Padavine.- MOP-Hidrometeorološki zavod RS, 366 pp, Ljubljana.

POVZETEK

CILJI IN ZASNOVA RAZISKAVE

Kraški vodonosniki skrivajo velike količine podzemne vode in so kot taki tudi pomemben rezervoar pitne vode. Da bi lahko to naravno bogastvo ohranili ali ga pravilno izkoriščali, moramo ustrezno načrtovati izrabo in preprečiti ali vsaj omejiti negativne vplive. Pri tem pa bomo učinkoviti le, če bomo upoštevali specifične značilnosti kraških vodonosnih sistemov. Zaradi heterogene zgradbe in zapletenega delovanja opredelitev teh značilnosti ni enostavna naloga. Za njeno reševanje so bile razvite številne raziskovalne metode, katerih uporabnost in zanesljivost je za izbrana območja odvisna od različnih faktorjev. Vsaka od njih pa pomeni dodaten korak na poti k spoznavanju zakonitosti pretakanja in uskladiščenja podzemne vode v krasu. Nekaj sem jih uporabila tudi v raziskavi kraškega vodonosnika v zaledju izvirov Vipave v jugozahodni Sloveniji, ki je predstavljena v tej knjigi. To območje s pomembnim vodnim virom je bilo predmet zanimanja strokovnjakov različnih profilov že več kot sto let. S širokim spektrom uporabljenih metod je bila zbrana obsežna baza podatkov in opredeljene osnovne hidrogeološke značilnosti. Z opravljeno raziskavo sem skušala poznavanje teh značilnosti še nadgraditi, hkrati pa dodati nov kamenček v mozaik razumevanja delovanja kraških hidroloških sistemov.

Najbolj poznan in dostopen del kraškega vodnega toka je podsistem površinskega toka, ki vključuje padavine kot vir napajanja in izvire kot točke praznjenja vodonosnika (Sl. 1). Njihova dostopnost omogoča stalna meteorološka in hidrološka merjenja, vedno bolj pomembne tudi s stališča proučevanja hidrodinamičnih značilnosti pa postajajo tudi hidrokemične analize. Logična posledica je razvoj številnih raziskovalnih metod, ki temeljijo na primerjavi vhodnih in izhodnih parametov kraškega vodonosnega sistema. Še posebej zaradi dejstva, da dogajanja v podzemlju večinoma ni možno opazovati neposredno in običajno ne razpolagamo z dovolj obsežno in zanesljivo bazo podatkov o geometriji in hidrodinamičnih parametrih vodonosnika. S tem je omejena uporabnost determinističnih modelov, v katerih so posamezni procesi znotraj sistema definirani z ustreznimi fizikalnimi zakoni. Nasprotno pa metode črne skrinjice obravnavajo kraški sistem kot središče dinamičnih procesov, določenih z vhodnim in izhodnim signalom (Sl. 2). S funkcijskim ali sistemskim pristopom k njihovem proučevanju lahko na osnovi analize odnosov med vhodno in izhodno funkcijo sklepamo na značilnosti delovanja sistema (Mangin 1994). Samo vhodni in izhodni signal imata fizikalni pomen, za povezavo med njima pa uporabljamo empirične oz. matematične funkcije, ki odražajo fizikalne procese v sistemu (Chiew *et al.* 1993). To vlogo imajo lahko t.i. funkcije transferja. Njihova osnovna značilnost je, da pretvorijo vhodno funkcijo v odziv sistema, ki ga opisuje izhodna funkcija. Čeprav funkcije transferja združujejo vplive različnih kompleksnih procesov, dajejo pomembno informacijo o delovanju kraških sistemov (Dreiss 1982). Določimo jih na osnovi merjenih meteoroloških in hidroloških časovnih serij, potem pa lahko z njimi tudi testiramo odziv sistema na različne hidrološke scenarije (Long & Derickson 1999). Metoda temelji na načelu linearnih sistemov. Glede na fizikalno in geometrijsko heterogenost kraških vodonosnikov je zato njena uporabnost v tem okolju vprašljiva, vendar pa je številnim avtorjem v različnih tipih raziskav dala zanimive in sprejemljive rezultate (Knisel 1972, Ashton 1966, Estrela & Sahuquillo 1997, Wicks & Hoke 1999, Labat *et al.* 2000, Wicks & Bohm 2000).

V zaledju izvirov Vipave so bile že v preteklih letih opravljene številne hidrogeološke raziskave, ki so pojasnile osnovne zakonitosti delovanja kraškega sistema, hkrati pa odprle nova vprašanja o njegovih hidrodinamičnih značilnostih. Merjeni so bili večinoma podatki o meteoroloških razmerah in značilnostih kraških izvirov, dosti manj pa je bilo zbranih podatkov o notranji zgradbi vodonosnika in njegovih hidrodinamičnih parametrih. Glede na razpoložljivost podatkov se je zato v nadaljnji raziskavi zdela smiselna uporaba metode črne skrinjice.

Na začetku sem si zastavila 3 osnovna vprašanja:

- Ali lahko za obravnavani kraški sistem postavimo model črne skrinjice, s katerim bo možno z zadovoljivo natančnostjo opisati odziv sistema na napajanje?
- Ali lahko na osnovi primerjave med različnimi vhodnimi in izhodnimi funkcijami kraškega sistema sklepamo o njegovih hidrodinamičnih značilnostih?
- Kakšne so značilnosti funkcije napajanja in kakšna je njena vloga v kraških sistemih?

Da bi dobila odgovore nanje, sem glede na zastavljene cilje in razpoložljive podatke uporabljeno metodo nekoliko prilagodila. Izhajala sem iz predpostavke, da je hidrološka kompleksnost kraških vodonosnikov predvsem posledica zelo spremenljivih pogojev napajanja in heterogenih lastnosti podzemnega toka. V postavljenem konceptualnem modelu sem zato posebno pozornost posvetila procesom, ki te pogoje in lastnosti opredeljujejo. Povezave med elementi posameznih podsistemov sem definirala z enačbami, ki opisujejo fizikalne procese med njimi ali pa z empiričnimi odvisnostmi in efektivnimi parametri. Glede na predpostavljeno obliko vhodne funkcije sem postavila tri različne modele napajanje - praznjenje in se s spreminjanjem značilnosti vhodnega signala skušala čim bolj približati realnim razmeram. Predpostavila sem, da lahko dobimo z natančno oceno funkcije napajanja dovolj dobre vhodne podatke, ki jih je možno uporabiti pri nadaljnji analizi hidrodinamičnih značilnosti obravnavanega kraškega sistema.

V osnovnem modelu sem kot vhodno funkcijo privzela kar merjene padavine. V naslednjem sem jih zamenjala z efektivno infiltracijo, ki vključuje vplive različnih procesov v zraku, vegetaciji in tleh na dejanski vnos vode v kamnino. Upoštevani so bili vplivi prestrezanja padavin v vegetacijskem pokrovu, snežnih padavin in taljenja snega, evapotranspiracije in uskladiščenja vode v tleh, pa tudi sekundarne infiltracije ponikalnic, ki zbirajo površinsko vodo na flišnem obrobju. V tretjem modelu sem simulirala še delovanje hidrološkega mehanizma v epikraški coni, ki omogoča razdelitev napajanja na hitro in počasno komponento. Funkcijo praznjenja pa predstavljajo skupni merjeni pretoki izvirov Vipave.

Pogosto metoda črne skrinjice temelji na primerjavi funkcije napajanja in praznjenja za posamezne padavinske dogodke, v opravljeni raziskavi pa sem jo nekoliko priredila. Primerjala sem podatke za celotno obdobje dveh hidroloških let in tako v analizi upoštevala razmere pri različnih hidroloških pogojih. Za vsak model sem z matematično-statistično primerjavo vhodnega in izhodnega signala določila ustrezne funkcije transferja, ki odražajo procese znotraj obravnavanega sistema. Nato sem z upoštevanjem teh funkcij in merjenih vhodnih parametrov s postavljenim modelom simulirala še vrednosti pretokov izvirov Vipave.

Za merilo ustreznosti modelov sem postavila točnost simulacije, ki se nanaša na sposobnost funkcije transferja, da reproducira pretoke, na osnovi katerih je bila določena. Glede na ujemanje merjenih in izračunanih pretokov sem tako ocenila primernost postavljenih modelov, glede na zgradbo in lastnosti modelov ter obliko in značilnosti funkcije transferja pa sklepala o vlogi funkcije napajanja in njenih komponent pri pretakanju in uskladiščenju vode v kraškem vodonosnem sistemu. Pri uporabljeni metodi sicer ni bilo možno povsem izključiti napak pri določitvi vhodnih in izhodnih parametrov sistema, pa tudi privzetje načel linearnosti ne ustreza povsem realnim razmeram. Kljub temu sem ocenila, da je ob predpostavki zadovoljive točnosti simulacije testiranje njene uporabnosti smiselno, saj omogoča zanimiv in inovativen pristop k proučevanju hidrodinamičnih značilnosti kraških vodonosnikov.

OSNOVNE ZNAČILNOSTI ZALEDJA IZVIROV VIPAVE

Značilna morfološka oblika jugozahodne Slovenije je Visoki kras, ki obsega niz zaokroženih pokrajinskih enot (Sl. 3). Njegov jugovzhodni del z Nanosom in Hrušico predstavlja osrednji del obravnavanega kraškega zaledja izvirov Vipave (Sl. 4). Voda prihaja na površje skozi več stalnih in občasnih izvirov, ki se stekajo v reko Vipavo. Ta je poleg Idrijce največji pritok Soče, ki se izliva v Jadransko morje. V centru mesta Vipave je na razdalji okrog 300 m razporejenih sedem stalnih izvirov Vipave (Sl. 5), ki jih v smeri od juga proti severu označujemo z zaporednimi številkami od 1 do 7 (Sl. 6). Izvir Pod lipco ali Vipava 2 je zajet za vodooskrbo dela Vipavske doline. Proti severu pa je med Vipavo in Vrhpoljem še šest občasnih izvirov.

Izviri imajo značilen kraški hidrološki režim s kratkotrajnimi visokimi pretoki in daljšimi obdobji srednjih in nizkih vod. Ekstremni viški pretokov se pojavljajo hkrati z viški padavin. V obdobju 1961-1990 sta bila po podatkih Hidrometeorološkega zavoda Republike Slovenije za stalne izvire Vipave izmerjena najmanjši pretok 727 l/s in največji pretok 70 m^3/s, srednji pretok v tem intervalu pa je 6,78 m^3/s. Razmerje med nizkimi, srednjimi in visokimi vodami je torej okrog 1:10:100. Vipava ima največje pretoke v aprilu in novembru. Novembrski viški so predvsem rezultat obilnega jesenskega dežja, visoki pretoki v aprilu pa se pojavljajo tudi kot posledica taljenja snega. Najnižje vode so v juliju in avgustu (Sl. 7).

Površinskih voda v kraškem delu zaledja izvirov Vipave ni, so pa številne ponikalnice na njegovem obrobju. V severozahodnem delu Pivške kotline potoki Lokva, Belščica, Ribnik, Mrzlenk ter vode v Stranskih in Šmihelskih ponikvah po krajšem toku na flišnem površju ponikajo v kras. Potok Bela na severozahodnem robu Nanosa vzdolž toka izgublja del vode in napaja stalne izvire Vipave. V strugo Bele pa se stekajo tudi občasni izviri Vipave. V Pivški kotlini predstavlja glavno vodno žilo reka Pivka, ki je s podzemnimi vodnimi tokovi prav tako povezana z izviri Vipave.

Na osnovi poznane geološke zgradbe je možno opredeliti osnovne hidrogeološke enote (Sl. 8). Osrednji del zaledja predstavlja dobro prepusten kraški vodonosnik Nanosa in Hrušice, ki ga gradijo kredni in jurski apnenci. Močno zakraselost nakazujejo površinske kraške oblike in številne kraške jame, predvsem brezna. V geološkem smislu sta Nanos in Hrušica ločena s Predjamskim prelomom, ki pa ne predstavlja hidrogeološke pregrade. Neposreden dokaz za to so opravljeni sledilni poizkusi, ki so potrdili podzemno zvezo ponikalnic Lokve in Belščice z izviri Vipave (Habe 1970, Behrens *et al.* 1997). Debelina karbonatnega paketa je velika in v njem je razvit globoki kras. Nobeno od številnih brezen ne doseže stalnega nivoja kraške vode. Natančnih podatkov o položaju neprepustne flišne podlage ni, z interpretacijo geološke zgradbe (Placer 1981) pa je bilo ocenjeno, da se nahajajo flišne kamnine na območju Nanosa (v severozahodnem delu celo na koti -1300 m) dosti globlje kot v Hrušici (okrog 0 m n.m.v.) (Janež 1997). Podobne značilnosti kraškega vodonosnika ima tudi zahodno obrobje Javornikov, ki se vsaj deloma prav tako odteka proti izvirom Vipave. Nekoliko slabšo prepustnost ima manjši pas jurskih in zgornjetriasnih dolomitov z razpoklinsko poroznostjo na obrobju Hrušice. Kvartarna periglacialna breča in holocenski pobočni grušč ob vznožju Nanosa predstavljata dobro prepustne vodonosnike z medzrnsko poroznostjo. V grušču so številni manjši izviri, ki so pomembni za lokalno vodooskrbo. Vlogo neprepustne pregrade pa ima eocenski fliš, ki se pojavlja v Vipavski dolini, v dolini Bele in v Pivški kotlini. Pri tem je bilo za območje Pivške kotline ugotovljeno, da je kras razvit tudi pod flišnimi plastmi, saj vode iz doline Pivke ter zahodnega obrobja Javornikov odtekajo pod flišem proti izvirom Vipave. Tudi ta podzemna zveza je bila potrjena s sledilnimi poizkusi (Habič 1989, Kogovšek *et al.* 1999, Kogovšek 1999).

Položaj izvirov Vipave je vezan na območje, kjer je neprepustno flišno obrobje najgloblje odstranjeno. Ob nizkih vodah je gladina v stalnih izvirih okrog 98 m. Po močnejših padavinah se dvigne za okrog pol metra, aktivirajo pa se tudi nekateri dotoki do 5 m višje. Ob visokih vodah začnejo delovati občasni izviri med Vrhpoljem in Vipavo na nadmorski višini do 125 m (Habič 1983).

Na Nanosu in Hrušici je preko 200 znanih jam. Prevladujejo brezna z globinami tudi več kot 100 m. Na izvirnem obrobju pri Vipavi je pomembnejša Vipavska jama, v katero vodi umetni rov, ki ob visokih vodah deluje kot pravi bruhalnik. Rov preseka dve večji naravni votlini, iz ene izmed teh votlin pa so jamarji raziskali približno 1,3 km dolg splet epifreatskih kanalov, nastalih vzdolž razpok (Mihevc 1997, Remškar 2001). Večje in bolj pomembne so jame na ponornem območju ob severozahodnem robu Pivške kotline. Največja je jama Predjama, ki ima tri etaže. V spodnji na nadmorski višini 462 m ponika potok Lokva. Še do nedavnega je veljalo, da je jama dolga približno 8 km (Šebela 1996). V zadnjih letih pa so potapljači preplavali nekaj sifonov in odkrili številne nove rove. Odkrili so tudi povezavo s 1300 m dolgo Jamo v Grapi, v katero ponika potok Belščica. Skupna dolžina do sedaj raziskane jame se je tako povečala na nekaj več kot 13 km (Vrhovec 1999). Ostale ponorne jame na tem območju so precej manjše.

NAPAJANJE VODONOSNIKA

Napajanje vodonosnika opisuje tok infiltrirane vode, ki doseže stalni nivo podzemne vode in ima za posledico povečanje količine uskladiščene vode (Lerner *et al.* 1990). Ločimo neposredno napajanje, ki obsega vertikalno prenikanje padavin skozi nezasičeno cono (tudi primarno ali avtigeno napajanje) in posredno napajanje, ki vključuje druge, posredne načine dotoka padavinske vode do vodonosnika (tudi sekundarno ali alogeno napajanje). Funkcija napajanja se spreminja v prostoru in času, zato je določitev njenih vrednosti povezana s številnimi težavami. Neposredno merjenje je v regionalnem smislu praktično nemogoče, zato v praksi uporabljamo različne metode ocene. Na padavine kot osnovni vir napajanja vplivajo različni procesi v zraku, vegetaciji in tleh. Dejanski vnos vode v kamnino zato opisujemo s parametrom efektivna infiltracija. Infiltrirana voda lahko hitro nadaljuje vertikalno pot po dobro prepustni kraški drenažni mreži do zasičene cone, ali pa se za določen čas uskladišči v slabše prepustnih območjih in se potem počasi pretaka proti nivoju podzemne vode. Opisana procesa označujemo z izrazoma hitro in počasno napajanje (Sl. 9).

Ocena efektivne infiltracije

Model ocene efektivne infiltracije temelji na metodi bilance vode v tleh. Zaradi pomanjkanja ustreznih podatkov sem pri njegovi kalibraciji predpostavila, da je znotraj obdobja posameznih hidroloških let skupna efektivna infiltracija I_{ef} v zaledju izvirov Vipave enaka skupnemu iztoku skozi te izvire. Vir vode so padavine, zmanjšane za delež prestreženih padavin na vegetacijskem pokrovu P_g, ob ugodnih klimatskih pogojih pa še dodatno voda zaradi taljenja snežne odeje M (enačba 1). Evapotranspiracija ETR z vračanjem vode v atmosfero opisuje njeno porabo. Na odnos med prispevkom in porabo vplivajo hidrološke karakteristike tal, ki določajo količino uskladiščenja vode v tleh ΔS.

Pri oceni bilance je potrebno najprej določiti obseg zaledja, ki se drenira proti opazovanim izvirom in predstavlja celotno območje napajanja. Postavitev meja temelji na poznavanju geološke zgradbe in rezultatov sledilnih poizkusov, vendar je točna določitev zaradi specifičnih lastnosti kraških vodonosnikov (neznane poti podzemne vode, bifurkacija, spreminjanje obsega zaledja ob različnih hidroloških pogojih, skrit podzemni tok v pokritem krasu) praktično nemogoča. Zato sem tudi pri oceni obsega zaledja izvirov Vipave uporabila nekatere poenostavitve. Osrednji del zaledja obsega kraško območje Nanosa in Hrušice, na osnovi znanih podatkov pa ni mogoče točno opredeliti položaja razvodnice med Vipavo in Ljubljanico na območju Hrušice. S sledilnimi poizkusi je bilo dokazano, da se proti Vipavi stekajo ponikalnice s flišnega območja na severozahodnem obrobju Pivške kotline, kjer lahko mejo zaledja potegnemo po površinskih razvodnicah med Vipavo in Pivko (Habe 1970, Behrens *et al.* 1997). Potrjen je bil tudi omejen in s hidrološkimi razmerami pogojen dotok iz površinskega toka Bele v izvire Vipave (Baker *et al.* 2001). S sledilnimi poizkusi pa so bile ugotovljene še podzemne vodne zveze z dolino Pivke in s kraškim masivom Javornikov (Habič 1989, Kogovšek *et al.* 1999). Glavni tok s tega območja je sicer usmerjen proti izvirom na Planinskem polju, del podzemnih voda pa odteka tudi proti Vipavi. Zaradi vseh opisanih značilnosti sem pri določitvi obsega zaledja uporabila metodo vodne bilance. Na osnovi primerjave podatkov o srednjih vrednostih padavin, realne evapotranspiracije in odtokov v 30-letnem obdobju 1961-1990 sem površino zaledja ocenila na 149 km^2 (Petrič 2000b). Od tega predstavlja 9 km^2 nekraški, 140 km^2 pa kraški del zaledja na območju Nanosa in Hrušice (Sl. 10). Ob pomanjkanju ustreznih podatkov sem namreč privzela, da je zaradi podobnih značilnosti krasa Javornikov ter Nanosa in Hrušice napaka, ki sem jo naredila z neupoštevanjem območja Javornikov kot dela zaledja in s tem precenjenim obsegom zaledja na Hrušici, zanemarljiva.

Ker je bila obstoječa baza podatkov najbolj obsežna v obdobju dveh hidroloških let od 25. avgusta 1993 do 23. avgusta 1995, sem postavljene modele kalibrirala znotraj tega intervala. Pri njihovi validaciji pa sem uporabila še podatke za osem hidroloških let od 1. avgusta 1985 do 24. avgusta 1993. Pri oceni splošnih hidroloških značilnosti sem upoštevala dolgoletna povprečja za obdobje 1961-1990, ki temeljijo na statistični primerjavi merjenih dnevnih vrednosti. Tudi v analizi odnosa med napajanjem in praznjenjem pa so bili uporabljeni dnevni podatki.

Padavine so glavni vir napajanja in predstavljajo osnovo za oblikovanje vhodne funkcije kraškega sistema. Znotraj zaledja je imel v daljšem obdobju Hidrometeorološki zavod postavljene samo 3 padavinske postaje: Nanos (Ravnik), Hrušica in Podkraj, na katerih so bile padavine merjene z dežemeri Helmannovega tipa enkrat dnevno ob 7. uri zjutraj (Zupančič 1995). Na sliki je za te postaje prikazana razporeditev povprečnih mesečnih padavin v intervalu 1961-1990 (Sl. 11). Pomemben delež imajo tudi snežne padavine (Sl. 12). Velik problem predstavljajo napake v merjenju padavin, ki jih lahko vsaj delno odpravimo z metodo korekcije. Tudi za obravnavano območje sem po enačbah 2 in 3 določila korigirane dnevne padavine v vseh treh padavinskih postajah. Vsaki postaji sem znotraj zaledja tudi priredila padavinsko cono, za katero so izmerjene vrednosti v tej postaji reprezentativne (Sl. 10).

Kar okrog 4/5 zaledja izvirov Vipave pokriva gozd (Sl. 13), zato je pomemben tudi delež padavin, ki jih prestreže vegetacijski pokrov. Po definiciji je prestrezanje padavin ali intercepcija proces zadrževanja padavin na vegetacijskem pokrovu, izguba zaradi prestrezanja pa predstavlja delež te vode, ki se je z evaporacijo vrnila v ozračje. Odvisna je od tipa in stopnje razvoja vegetacije ter intenzitete, trajanja, frekvence in oblike padavin. Prestrezanje padavin predstavlja dodatek k izgubi zaradi evapotranspiracije (Dingman 1994). Neposredno je izgube zaradi prestrezanja praktično nemogoče meriti, zato se pogosto uporabljajo različni konceptualni modeli, ki temeljijo na oceni vodne bilance za uskladiščenje v krošnjah dreves in na deblih. Za primer zaledja Vipave sem tako privzela Rutterjev model (Rutter *et al.* 1971), kjer so ločeno obravnavani trije deli: padavine, ki direktno prehajajo skozi drevesni sestoj P ter padavine, ki dosežejo krošnje dreves P_c ali drevesna debla P_t (Sl. 9). Del padavin, ki pade na krošnjo dreves, izhlapi zaradi evaporacije E_c, del pa se drenira do tal D_c. Razmerje med obema procesoma je odvisno od razlike med višino vode na krošnji C_c in kapaciteto krošnje S_c. Podobni odnosi veljajo tudi za bilanco vode, ki doseže drevesna debla. Skupna količina padavin, ki dosežejo tla, je za območje gozdne vegetacije določena kot vsota padavin, ki neposredno dosežejo tla, odtoka iz krošnje in odtoka po deblu. Za negozdna območja pa je privzeto, da padavine neovirano dosežejo tla.

Posebej so obravnavane snežne padavine, ki se uskladiščijo na površini kot snežna odeja debeline D_s in prispevajo k funkciji napajanja šele z določenim časovnim zaostankom, ko se ob ugodnih klimatskih razmerah sneg začne taliti. Njihov delež je v zaledju izvirov Vipave pomemben, saj se prvi sneg lahko pojavi že novembra, pogosto pa se snežna odeja ohrani do maja. Za oceno količine staljenega snega sem uporabila enačbe U.S. Army Corps of Engineers (1960). To so empirične formule (enačbe 4 in 5), ki so bile definirane na osnovi terenskih opazovanj in merjenj na določenih lokacijah, vendar pa sem jih zaradi pomanjkanja boljših podatkov privzela tudi za obravnavano območje. Pri tem je bila seveda storjena določena napaka, ki pa se ji ni bilo mogoče izogniti. Enačbe omogočajo izračun količine staljenega snega za gozdna in negozdna območja ter za taljenje brez ali ob dežju v odvisnosti od srednje dnevne temperature zraka, količine dežja in hitrosti vetra. Glede na znane vegetacijske razmere in merjene meteorološke parametre sem tako s kombinacijo teh osnovnih enačb določila vrednosti parametra M, ki predstavlja dnevne količine staljenega snega.

Te so skupaj s padavinami, ki dosežejo tla P_g, v postavljeni hidrološki bilanci vir vode, evapotranspiracija ETR pa z vračanjem vode v atmosfero opisuje njeno porabo. Vključuje vse procese, pri katerih prehaja voda iz tekočega ali trdnega stanja na ali blizu površine tal v vodno paro ozračja. Zelo pogosto se za njen izračun uporablja Penmanova enačba (enačba 6) ali razne izpeljanke te osnovne enačbe (enačbi 7 in 8). Glede na kakovost in obseg meteoroloških podatkov v zaledju Vipave sem za oceno potencialne evapotranspiracije ETP po literaturi povzela izpeljanko iz osnovne Penmanove enačbe, pri kateri so bili osnovni koeficienti prilagojeni pogojem evaporacije in transpiracije z območij, poraslih z vegetacijo (Shaw 1994). V enačbi so bili uporabljeni 4 meteorološki parametri: temperatura zraka T, relativna vlažnost zraka ρ, hitrost vetra 10 m nad tlemi u_{10} in osončenost n.

Opisane metode omogočajo določitev količine padavin, ki dejansko dosežejo tla, količine staljenega snega in potencialne evapotranspiracije, ocena realne evapotranspiracije ETR in sprememb uskladiščenja vode v tleh pa je odvisna od hidroloških karakteristik tal. Vlažnost tal S predstavlja vodo, ki se zadržuje v tleh zaradi delovanja kapilarnih sil. Je zelo občutljiva na vpliv padavin in evapotranspiracije, zato se ob spremembah teh dveh parametrov stalno pojavljajo tudi spremembe v vlažnosti tal ΔS. Kadar so padavine večje od evapotranspiracije, vlažnost tal narašča, dokler ne doseže kapacitete tal FC. Ta predstavlja vrednost saturacije, pri kateri se pojavi drenaža pod vplivom gravitacije in se začne infiltracija. Ko evapotranspiracija preseže padavine, se začne vlažnost tal manjšati. Pri normalnih atmosferskih pogojih pa evapotranspiracija ne more popolnoma izsušiti tal. Zato se v večini primerov nadaljuje pri maksimalni ali potencialni vrednosti le do trenutka, ko vlažnost tal pade na vrednost koreninske konstante RC. Ta je mera količine vode, ki je na voljo v dosegu korenin, izražena z ekvivalentom dežja. V območju med koreninsko konstanto in točko venenja WP se realna evapotranspiracija nadaljuje na nižji stopnji. Točka venenja je dosežena, ko je vlažnost tal tako majhna, da rastline ne morejo več črpati vode (Howard & Lloyd 1979).

Na osnovi ugotovitev iz literature sem upoštevala še vpliv neposrednega napajanja I_r, ki opisuje pojav, ko pride padavinska voda do vodonosnika skozi razpoke in infiltracija ni pogojena s predhodno zapolnitvijo deficita vlažnosti tal (Rushton & Ward 1979). Privzela sem metodo določitve praga, kjer predstavlja količina padavin, ki presega prag, neposredno napajanje, ostanek pa se porablja za zapolnjevanje deficita vlažnosti tal.

Bolj neposredna je ocena sekundarne infiltracije, saj je možno merjenje pretokov ponikalnic z nekraškega obrobja, ki napajajo kraški vodonosnik. Najpomembnejše v zaledju izvirov Vipave so ponikalnice na severozahodnem robu Pivške kotline: Lokva in Belščica ter nekateri občasni tokovi v Šmihelske ponikve, Stranske ponikve in ponikalnice južno od Bukovja. V okviru projekta 7.SWT je Hidrometeorološki zavod z limnigrafom in vodomerom opremil Belščico pri Bukovju in Lokvo pri Predjami. Za celotno obdobje dveh hidroloških let 1993-1995 so bili tako na voljo podatki o srednjih dnevnih pretokih Belščice, na Lokvi pa so z merjenjem pretokov začeli šele v letu 1994, zato ni podatkov za leto 1993. Za potrebe izdelave ocene napajanja sem jih zato določila na osnovi korelacije s pretoki Belščice, ki ima podoben hidrološki režim. Za ostale, manjše ponikalnice, so bili pretoki ob različnih hidroloških pogojih le približno ocenjeni. Ob predpostavki podobnega hidrološkega režima kot pri Belščici sem njihovo skupno kapaciteto ocenila na 25 % pretoka Belščice. Primerjava ocenjenega skupnega dotoka ponikalnic z roba Pivške kotline s skupnim pretokom izvirov Vipave pokaže, da dosega v obravnavanem obdobju dveh hidroloških let ocenjen delež sekundarne infiltracije le okrog 6 % (Sl. 14). Zato lahko zaključim, da ima napaka zaradi uporabljenih približnih ocen zanemarljiv vpliv na skupno funkcijo napajanja.

Poseben primer je potok Bela, ki jo ob visokih vodah napajajo občasni izviri Vipave, ob nizkih in srednjih vodah pa vzdolž toka ponika in odteka tudi proti stalnim izvirom Vipave. Medsebojni vpliv površinske in podzemne vode potoka Bele in izvirov Vipave je zato obdelan posebej. Potok Bela zbira vodo na zelo slabo prepustnem flišu na severozahodnem obrobju Nanosa, nato pa po prehodu na apnenec vzdolž toka postopno ponika.

Samo ob višjih vodah se površinsko pretaka tudi do mesta Vipave in se potem izliva v reko Vipavo. Že starejše raziskave nakazujejo hidrološko zvezo potoka Bele z izviri Vipave. Ob primerjavi specifične električne prevodnosti posameznih stalnih izvirov Vipave se je pokazalo, da se izvir Vipava 7 značilno razlikuje od drugih (Harum *et al.* 1997). Tudi pri dveh sledilnih poizkusih z injiciranjem sledila v zaledje izvirov Vipave je imel ta izvir drugačno krivuljo koncentracije sledila (Behrens *et al.* 1997, Zupan 1997). Z opazovanjem spreminjanja pretoka Bele je bilo ugotovljeno ponikanje na različnih mestih vzdolž površinskega toka, na terenu pa je bilo opazovano tudi stekanje občasnih izvirov Vipave v površinski tok Bele ob visokih vodah. Načrt dodatnih raziskav je vključeval izvedbo sledilnega poizkusa z injiciranjem sledila v površinski tok Bele ter merjenje pretoka Bele na različnih profilih vzdolž toka. V okviru magistrskega študija na Univerzi Newcastle upon Tyne se je v raziskavo vključil Irec Gerry Baker. Opravil je večji del terenskega merjenja in odvzema vzorcev pri sledilnem poizkusu ter obdelavo izmerjenih vrednosti. Sledilni poizkus je nadzirala Janja Kogovšek z Inštituta za raziskovanje krasa ZRC SAZU. Rezultati so v celoti objavljeni v publikaciji Acta carsologica (Baker *et al.* 2001), na tem mestu pa povzemam nekaj osnovnih ugotovitev o povezavi med površinskim tokom Bele in izviri Vipave. Najprej je bilo 29. maja 2001 izvedeno injiciranje 170 g sledila uranina v površinski tok Bele na mestu, ki je oddaljeno približno 2,8 km od izvirov Vipave. Pretok izvirov Vipave je bil takrat 3,8 m^3/s, po dveh dneh se je pojavila kratka, intenzivna nevihta in 1. junija 2001 je pretok narasel na 22 m^3/s. Vzorce smo vsako uro odvzemali z avtomatskim zajemalnikom ISCO 6700 na izviru Vipava 7, ročno pa enkrat ali dvakrat na dan na vseh ostalih stalnih izvirih Vipave. Na avtomatski zajemalnik smo priključili tudi sondo YSI 600, s katero smo v 5-minutnih intervalih merili specifično električno prevodnost in temperaturo. Oba parametra smo z WTW konduktometrom LF196 merili tudi na ostalih izvirih. Hkrati smo s hidrometričnim krilom OTT C20 v času trajanja poizkusa izvedli 10 meritev skupnega pretoka izvirov Vipava 6 in Vipava 7, dvakrat pa smo dodatno izvedli še ločeno meritev za oba izvira. Za opazovanje spreminjanja pretoka smo vzdolž površinskega toka Bele izbrali še osem profilov za merjenje pretoka. Točke so bile dokaj pravilno razporejene na območju med Sanaborjem in Vipavo (Sl. 16). Hkrati smo z WTW konduktometrom LF196 merili tudi specifično električno prevodnost in temperaturo. Hidrološke razmere v obdobju opazovanja od 29. maja do 30. junija 2001 so prikazane na sliki (Sl. 17). Podatki o dnevnih padavinah so bili izmerjeni na postaji Nanos, ki odraža razmere v pretežnem delu kraškega zaledja izvirov Vipave in na postaji Podkraj, ki je locirana nad flišnim zaledjem toka Bele. Najbolj izrazito se je uranin pojavil v izviru Vipava 7, nekoliko povečane koncentracije so bile zabeležene tudi v izvirih Vipava 6 in Vipava 5, ostali izviri pa so pokazali le manjši odziv (Sl. 18). Zanimiva je primerjava s krivuljo skupnega pretoka izvirov Vipava 6 in Vipava 7. Sledilo se je začelo pojavljati šele potem, ko je pretok po močnejši nevihti 1. junija že začel upadati oz. vzporedno z novim povečanjem pretoka. Vrh je bil dosežen 136 ur po injiciranju, kar da dominantno navidezno hitrost okrog 20 m/h. Tudi naslednji, manjši vrhovi pretočne krivulje se ujemajo s povišanimi vrednostmi koncentracij sledila. Zanimivo je relativno povečanje koncentracij v izvirih Vipava 6 in Vipava 5 ter predvsem v izvirih Vipava 3 in Vipava 2 v primerjavi s koncentracijami v izviru Vipava 7 po padavinah 11. in 12. junija. Ta padavinski dogodek se od prvega, ki je povzročil izrazito povečanje pretokov v začetku junija, razlikuje po razmerju količine padavin med postajama Nanos in Podkraj. V prvem padavinskem dogodku je na obeh postajah padlo preko 40 mm dežja, v drugem pa so bile padavine z več kot 20 mm dokaj intenzivne v postaji Podkraj, praktično zanemarljive pa na Nanosu. Ob upoštevanju dejstva, da je zaledje Vipave značilno večje kot zaledje Bele, je skupni volumen padavin v prvem dogodku večji na planoti Nanosa kot v zaledju Bele in obratno v drugem dogodku. Tretji padavinski dogodek 18. in 19. junija ima spet podobne značilnosti kot prvi, relativno večja pa je spet koncentracija sledila v izviru Vipava 7. Že iz teh primerjav se kaže, da na povezavo med Belo in izviri Vipave značilno vplivajo hidrološke razmere v zaledju. Do podobnih ugotovitev smo prišli tudi z merjenjem pretoka Bele v različnih profilih vzdolž toka. V dveh tednih smo izvedli 8 serij meritev (Sl. 19). V celoti se v krivuljah odraža velika spremenljivost pretokov, saj se tudi znotraj istih odsekov v različnih dneh pojavljajo izgube ali prirastki pretokov. Meritve za 1., 4. in 6. junij imajo zelo podoben trend z izjemo odseka M2-M1 z značilnim vplivom občasnih izvirov Vipave. Končno smo z uporabo linearne enačbe mešanja (enačba 9) ocenili še delež vode iz potoka Bele v izviru Vipava 7. Z metodo separacije toka izvira Vipava 7 smo ugotovili, da se delež dotoka iz Bele giblje okrog 20 %, zanimiva pa sta padec deleža ob nevihti 1. junija in povečanje vpliva dotoka iz Bele ob padavinskem dogodku 11. in 12. junija (Sl. 20). Z opravljenim sledilnim poizkusom so bile potrjene predpostavke o zatekanju vode, ki ponika vzdolž površinskega toka Bele, v izvire Vipave. Tok je v glavnem usmerjen proti izviru Vipava 7 (okrog 60 % povrnjenega sledila), glede na hidrološke pogoje pa v različnih deležih tudi proti ostalim stalnim izvirom Vipave. Pokazalo se je, da se hidrološki odziv spreminja glede na delež napajanja iz kraškega ali flišnega zaledja. Visok vodostaj v neposrednem kraškem zaledju Vipave omejuje dotok iz smeri Bele, obratno pa se ob nizkem vodostaju poveča vpliv dotoka iz površinskega dela Bele ne le v izviru Vipava 7, ampak še bolj izrazito tudi v ostalih stalnih izvirih Vipave. Oviran dotok zaradi povečanega hidravličnega potenciala v kraškem vodonosniku je verjetno tudi razlog za zamik prihoda sledila za prvim viškom pretoka 1. junija. Je pa na visok vodostaj v kraškem zaledju vezano tudi delovanje občasnih kraških izvirov Vipave. Predstavljena raziskava je torej potrdila predpostavke o medsebojnem vplivu med površinskim tokom Bele in izviri Vipave. Izpostavljen je bil velik pomen hidroloških razmer na značilnosti te povezave. Zaradi njene kompleksne narave je delež infiltrirane vode iz površinskega toka Bele in pretok občasnih izvirov Vipave zelo težko količinsko ovrednotiti. Ker pa dotok iz Bele predstavlja dodatek k napajanju kraškega vodonosnika v zaledju Vipave in ker iztok skozi občasne izvire, ki se stekajo v površinski tok Bele in zato niso vključeni v merjenje skupnega pretoka izvirov Vipave, ni upoštevan v funkciji praznjenja, sem vseeno v primerjavo napajanje - praznjenje obravnavanega kraškega sistema v obdobju dveh hidroloških let 1993-1995 vključila tudi ovrednotenje vpliva te povezave. Glede na razpoložljivost podatkov sem oceno vpliva povezave med Belo in izviri Vipave izdelala na osnovi primerjave med pretoki Bele v Vipavi in v Sanaborju (Q_{Bv}-Q_{Bs}).

Predstavljene parametre sem v dokumentu PREPAD v računalniškem programu Microsoft Excel končno povezala v model ocene efektivne infiltracije, ki temelji na predpostavki, da je znotraj obdobja posameznih hidroloških let skupna efektivna infiltracija enaka skupnemu iztoku skozi izvire Vipave. Skupna efektivna infiltracija je vsota primarne in sekundarne. Pri oceni primarne infiltracije sem v metodi bilance vode v tleh upoštevala padavine, ki dosežejo tla, količino staljenega snega, evapotranspiracijo, neposredno infiltracijo in spremembo uskladiščenja v tleh, pri sekundarni pa kar merjene pretoke ponikalnic s flišnega obrobja v severozahodnem delu Pivške kotline. Kalibracijski parametri v modelu so vezani na oceno intercepcije (kapaciteta krošnje, delež padavin, ki nemoteno pridejo skozi vegetacijo in dosežejo tla, delež padavin, ki padejo na debla), neposredne infiltracije (prag) in uskladiščenja v tleh (kapaciteta tal, koreninska konstanta, točka venenja). Vhodni podatki so merjene dnevne padavine in debeline snega na postajah Nanos, Hrušica in Podkraj, srednje dnevne temperature zraka, vlažnosti zraka, osončenost in hitrosti vetra v postaji Nanos ter merjeni dnevni pretoki Lokve in Belščice, korigirani glede na dodatni vpliv ostalih ponikalnic s tega območja. Za kalibracijo modela sem za obdobje dveh hidroloških let 1993-1995 kot izhodne podatke uporabila merjene dnevne pretoke izvirov Vipave, korigirane glede na medsebojni hidrološki vpliv teh izvirov s površinskim tokom Bele. Z izbiro ustreznih vrednosti kalibracijskih parametrov je ujemanje med ocenjenimi vrednostmi efektivne infiltracije in praznjenja skozi izvire Vipave za obe hidrološki leti in za celotno obdobje dveh hidroloških let dobro (Sl. 21). V tabeli so v milimetrih prikazane letne količine efektivne infiltracije oz. praznjenja v hidroloških letih 1993/94 in 1994/95 ter skupno v obdobju dveh hidroloških let 1993-1995 določene kot povprečna vrednost za celotno kraško in nekraško zaledje (Tab. 1). V oklepajih so te vrednosti izražene še kot srednji pretok.

Končno sem kalibriran model uporabila za izračun dnevnih vrednosti efektivne infiltracije v zaledju izvirov Vipave. Primerjavo posameznih komponent v obdobju dveh hidroloških let 1993-1995 sem zaradi preglednosti in zaradi največjega obsega padavinskega pasu Nanosa izdelala za to cono (Sl. 22). Pokazalo se je, da je pomemben predvsem vpliv uporabe modela ocene efektivne infiltracije na sezonsko razporeditev količine infiltracije. Razlika med merjenimi padavinami in efektivno infiltracijo je tako spomladi značilno večja kot jeseni, saj je večinoma odraz sprememb v klimatskih in vegetacijskih pogojih (Sl. 23). Manjši delež efektivne infiltracije spomladi je predvsem posledica začetka bujne rasti vegetacije, ki se odraža z večanjem vpliva prestrezanja padavin na vegetacijskem pokrovu in deleža realne evapotranspiracije.

Nazadnje sem testirala še občutljivost modela na spreminjanje kalibracijskih parametrov. Analiza je pokazala, da je ocena efektivne infiltracije značilno občutljiva predvsem na spreminjanje kapacitete krošnje in hidroloških karakteristik tal (razlika med kapaciteto tal in točko venenja), pri ostalih parametrih pa je zanemarljiva (Sl. 24 in 25). Ugotovljeno majhno občutljivost modela na spreminjanje parametrov lahko razložimo z razliko v relativnih velikostih padavin in procesov, ki nanje vplivajo v zraku, vegetaciji in tleh. Dominantna komponenta so merjene padavine, saj delež prestreženih padavin predstavlja 16,5 %, evapotranspiracija pa tudi ne preseže četrtine skupne količine padavin.

Za kras je tudi značilno, da je količina vode, ki se uskladišči v tleh in zapolnjuje deficit vlažnosti, relativno majhna. Vseeno so opravljene primerjave pokazale, da imajo omenjeni procesi pomemben vpliv na količino padavin, ki se dejansko infiltrira v tla in jih je zato potrebno upoštevati pri oceni funkcije napajanja. Kljub prevladujoči vlogi padavin, za katere je v danih klimatskih razmerah značilna velika pogostnost in intenzivnost, je oblika funkcije efektivne infiltracije značilno spremenjena. Na tej osnovi lahko tudi sklepamo, da bi se v bolj sušnih pogojih z manjšim deležem padavin pomen vplivov na padavine še povečal in posledično bi se povečala tudi občutljivost postavljenega modela na spreminjanje posameznih parametrov. V splošnem je torej pomen vključitve ocene efektivne infiltracije v hidrološke modele verjetno še večji, kot je nakazala opravljena raziskava.

Počasna in hitra komponenta napajanja

S postavitvijo modela ocene efektivne infiltracije so bili upoštevani procesi, ki vplivajo na infiltracijo padavinske vode v kamnino, odziv izvirov pa je v veliki meri odvisen tudi od značilnosti pretakanja in uskladiščenja infiltrirane vode znotraj nje. Številne študije so pokazale, da ima pomembno vlogo pri tem epikraška cona (Williams 1983, Kiraly *et al.* 1995, Jeannin & Grasso 1995, Jeannin & Grasso 1997, Sauter 1992, Mohrlok & Sauter 1997). Zaradi njenih značilnosti se del vode po infiltraciji padavin hitro prenese skozi dobro prepustno kraško mrežo do zasičene cone. Ostanek pa se zadrži v bazi epikrasa in nato počasi odteka skozi slabše prepustne cone proti nivoju podzemne vode. Govorimo torej lahko o hitri in počasni komponenti napajanja. Prva ima za posledico povečanje pretoka v nekaj dneh, druga pa v nekaj tednih ali mesecih. Na osnovi teh ugotovitev sem se odločila, da tudi v modelu kraškega vodonosnika v zaledju izvirov Vipave predpostavim obstoj nekega mehanizma, ki omogoča razdelitev na hitro in počasno napajanje. Za oceno deležev obeh komponent napajanja so v uporabi različne metode. Preizkusila sem metodo baznega toka, ki temelji na primerjavi volumna baznega in celotnega toka ter metodo hidrološke bilance, pri kateri v obdobju visokih vod primerjamo efektivno infiltracijo in volumen odtoka visokih vod (Jeannin & Grasso 1995). Druga metoda je bolj približna in težje izvedljiva, vendar pa daje tudi pomembno informacijo o časovni spremenljivosti razdelitve na počasno in hitro napajanje. Temelji na izdelavi vodne bilance znotraj posameznih padavinskih intervalov, ki vključujejo padavinske dogodke ali skupine padavinskih dogodkov. Odstotni delež počasnega in hitrega napajanja je nato določen za vsakega izmed izbranih padavinskih intervalov. Znotraj vsakega intervala je najprej ločen bazni tok (Sl. 26 in 27). Območje pod krivuljo pretoka brez baznega toka predstavlja parameter Q', ki ga imenujemo volumen hitrega toka. Na osnovi primerjave tega parametra z volumnom efektivne infiltracije v istem padavinskem intervalu (enačba 10) lahko ocenimo delež vode, ki se transportira hitro (merjeni volumen Q' predstavlja hiter odziv vodonosnega sistema na napajanje) in delež vode, ki se transportira počasi (sprememba rezerv v slabše prepustnih conah ΔR predstavlja spremembo predpostavljenega baznega vala, ki odgovarja iztoku iz slabše prepustnih con). V procesu določitve počasne in hitre komponente napajanja v zaledju izvirov Vipave sem obdobje dveh hidroloških let 1993-1995 glede na razporeditev padavin in obliko krivulje praznjenja razdelila na 40 različno dolgih padavinskih intervalov, ki se vsak konča z nekajdnevnim obdobjem brez napajanja. Kot vhodno komponento napajanja sem privzela vrednosti efektivne infiltracije in nato za vsak padavinski interval določila vrednosti parametrov ΔR in Q', ki predstavljata delež počasne in hitre komponente napajanja. Dobljeni rezultati so prikazani na slikah 28-31. Ocenjene vrednosti so odvisne tudi od načina in natančnosti ocene napajanja, izbrane metode za določitev baznega toka in seveda od uporabljene metode za oceno posameznih komponent napajanja. Ker pa pri načrtovani analizi odnosa med napajanjem in praznjenjem daje pomembno informacijo že podatek o velikostnem redu deležev posameznih komponent napajanja in odstopanje od točnih vrednosti nima odločilnega vpliva, sem dobljene rezultate ocenila kot primerne za nadaljnjo obdelavo. Pri tem pa je seveda potrebna določena previdnost in spremljanje vpliva teh parametrov na izdelano oceno.

Vhodna funkcija modela napajanje-praznjenje

Z opisanimi metodami so bili obravnavani različni procesi, ki značilno vplivajo na količino in razporeditev napajanja. Glede na ugotovljene značilnosti sem na tej osnovi oblikovala tri različne vhodne funkcije modela napajanje-praznjenje in vsako definirala z enotno, združeno funkcijo povprečne vrednosti za celotno zaledje izvirov Vipave. Najprej sem upoštevala kar merjene padavine. Ker so pri tem zanemarjeni vplivi, ki delujejo na padavine pred ali med infiltracijo, sem jih v drugi fazi nadomestila z efektivno infiltracijo. V njej so dodatno upoštevani različni procesi v zraku, vegetaciji in tleh, ki značilno vplivajo na količino padavin, ki se dejansko infiltrira v kamnino. Končno sem napajanje razdelila še na počasno in hitro komponento ob predpostavki, da epikraška cona deluje kot mehanizem, ki povzroča to razdelitev.

PRAZNJENJE

Praznjenje kraških vodonosnikov je vezano predvsem na iztekanje podzemne vode skozi večje in manjše kraške izvire, le majhen delež v skupni količini pa ima lahko difuzivni iztok. Glavni iztok je torej vezan na posamezne točke, zato je ocena funkcije praznjenja precej bolj enostavna. Z ustreznimi metodami je možno natančno merjenje pretokov v različnih časovnih intervalih.

Obravnavani kraški vodonosnik se prazni predvsem skozi stalne in občasne izvire Vipave (Sl. 6). Pregled značilnosti pretokov stalnih izvirov Vipave temelji na treh skupinah podatkov. Prva obsega 30-letni interval 1961-1990 in omogoča statistično oceno hidrološkega režima v daljšem časovnem obdobju. Najmanjši izmerjeni pretok je bil 727 l/s, največji pa 70 m^3/s. Srednji pretok je 6,78 m^3/s, približno 260 dni na leto pa je količina vode na izvirih manjša od te vrednosti. Podobne značilnosti da analiza obdobja 10 hidroloških let od 1.10.1985 do 23.8.1995, na katerega sta vezani kalibracija in validacija postavljenih modelov napajanje - praznjenje. Tako je minimalni pretok Q_{min}=727 l/s, srednji pretok Q_{sr}=6,48 m^3/s in maksimalni pretok Q_{max}=66 m^3/s. Posebej sem iz tega obdobja izločila še kalibracijski interval dveh hidroloških let 1993-1995. Pri oceni karakterističnih pretokov so zaradi krajšega obdobja nekoliko večja odstopanja od dolgoletnega povprečja pričakovana. Tako je bil najmanjši izmerjeni pretok 1,19 m^3/s, največji pa 55,7 m^3/s. Srednji pretok 7,54 m^3/s kaže na obdobje z nadpovprečno količino iztekle vode. Zanimiva je primerjava srednjih mesečnih pretokov za vse tri predstavljene intervale (Sl. 33). Tipičen hidrološki režim ima viške jeseni in spomladi ob obilnih padavinah oz. dodatnem napajanju zaradi taljenja snega v zaledju ter minimalne iztoke v juliju in avgustu. Za 10-letno obdobje sem primerjala še srednje pretoke in padavine za posamezna hidrološka leta (Sl. 34). Tudi pri tej primerjavi izstopa interval 1993-1995 kot nadpovprečno namočen. Opazno spreminjanje razlike med padavinami in pretoki po posameznih hidroloških letih pa je odraz nekih dodatnih vplivov na odnos padavine - pretok.

Merjene dnevne pretoke izvirov Vipave sem torej privzela kot izhodno funkcijo sistema napajanje - praznjenje. Poleg tega pa sem upoštevala še vpliv njihovega medsebojnega odnosa s površinskim tokom Bele. Pri pogojih, da se v izvire Vipave podzemno stekajo tudi vode iz potoka Bele, sem izmerjene pretoke izvirov Vipave ustrezno zmanjšala za ugotovljeno razliko med pretokom Bele v Vipavi in Sanaborju (Q_{Bv}-Q_{Bs}). Obratno pa sem za dneve, ko začnejo delovati občasni izviri in se stekajo v Belo, to razliko kot delež iztoka skozi občasne izvire prištela k izmerjenim skupnim pretokom izvirov Vipave. Na ta način določena funkcija praznjenja torej opisuje celotni iztok iz obravnavanega kraškega vodonosnika.

MODELI NAPAJANJE - PRAZNJENJE

Zveza med padavinami in odtokom iz bazena je v hidrologiji ena izmed najbolj proučevanih odvisnosti. Čeprav običajno že osnovna primerjava dveh časovnih serij pokaže, da so pretoki odvisni od padavin, pa je bolj natančno to odvisnost težko opredeliti. Še posebej to velja za kras, kjer nanjo značilno vpliva spremenljivost razmer pretakanja in uskladiščenja vode v kraškem vodonosnem sistemu. Kraški izviri Vipave se ob močnejših padavinah odzovejo s kratkotrajnimi visokimi valovi, ki jim sledi hitro upadanje pretoka in daljše obdobje srednjih in nizkih vod (Sl. 35). Tudi prikaz v regresijskem diagramu potrjuje določeno povezavo, hkrati pa odstopanje od regresijske premice kaže na pomembno vlogo nekih dodatnih procesov, ki nanjo vplivajo (Sl. 36). Nekatere od njih sem podrobno obdelala že v poglavju o napajanju. Števini pa ostajajo skriti neposredni analizi, zato sem za njihovo ovrednotenje uporabila metodo črne skrinjice, pri kateri lahko na osnovi primerjave med vhodno in izhodno funkcijo sklepamo o značilnostih procesov znotraj kraškega sistema. Procesi med napajanjem in praznjenjem so izraženi matematično, brez natančnega poznavanja fizikalnega ozadja. Vsi parametri sistema, ki vplivajo na filtracijo vhodnega signala, so združeni v funkcijo transferja, odnos med vhodnim in izhodnim signalom pa je definiran s funkcijo, ki jo imenujemo konvolucija. Njene značilnosti so predstavljene v različnih hidroloških študijah, osnove pa so povzete po splošni matematični literaturi (enačba 11). Vsaka vrednost vhodne funkcije I(t) ima ustrezen odziv v izhodni funkciji O(t), povezava med njima pa je določena s funkcijo transferja Z(t), ki odraža delovanje kraškega sistema. Dekonvolucija je obraten postopek, pri katerem na osnovi primerjave med vhodno in izhodno funkcijo določimo funkcijo transferja. Za veljavnost postavljene enačbe morata biti izpolnjena pogoja o stacionarnosti in linearnosti sistema. V tem primeru lahko za enoten, časovno nespremenljiv linearni sistem odvisnost izrazimo v integralski obliki (enačba 12). Problem pa se pojavi pri njeni uporabi za analizo kraških sistemov, saj prej našteti pogoji za veljavnost enačbe niso izpolnjeni. Kljub temu se je metoda v številnih raziskavah kraških vodonosnikov pokazala kot primerna ob predpostavki, da nelinearnost ni prevelika. Za dve ločeni, končni seriji, ki jih običajno primerjamo, lahko konvolucijski integral zapišemo v diskretizirani obliki (enačba 13). V tem primeru je v funkcijo vključena tudi neka napaka kot posledica predpostavk modela, ki ne ustrezajo povsem realnim razmeram. Lahko pa so razlog zanjo tudi napake v vhodni in izhodni funkciji sistema.

Tudi ocena značilnosti odnosa med napajanjem in praznjenjem vodonosnika v zaledju izvirov Vipave temelji na predstavljeni osnovni enačbi, zaradi specifičnih značilnosti kraških sistemov in glede na razpoložljivost podatkov pa sem jo nekoliko prilagodila. Izhajala sem iz predpostavke, da je hidrološka kompleksnost kraških vodonosnikov predvsem posledica zelo spremenljivih pogojev napajanja in heterogenih lastnosti podzemnega toka. Procese, ki te pogoje in lastnosti opredeljujejo, sem povezala v konceptualni model, v katerem je kraški sistem obravnavan kot več povezanih podsistemov. Da bi lahko primerjala vplive posameznih podsistemov, sem predpostavila 3 različne modele napajanje - praznjenje in se s spreminjanjem vhodnega signala skušala čim bolj približati realnim razmeram. V prvem sem primerjala kar merjene padavine in pretoke izvirov, kraški vodonosni sistem med njima pa obravnavala kot celoto. Delovanje znotraj sistema sem izrazila s funkcijo transferja, ki transformira vhodni signal v izhodnega.

V drugem modelu je bil posebej izpostavljen podsistem efektivne infiltracije. Njegovo delovanje sem opisala z modelom bilance vode v tleh, v katerem so bili vključeni procesi prestrezanja padavin na vegetacijskem pokrovu, snežnih padavin in taljenja snega, evapotranspiracije, uskladiščenja vode v tleh in sekundarne infiltracije. Na ta način so bili že pri določitvi vhodne komponente upoštevani omenjeni procesi v zraku, vegetaciji in tleh, ki značilno vplivajo na dejansko količino in časovno razporeditev infiltracije padavin. Odziv kraških izvirov nanjo pa opisuje funkcija transferja.

Tretji model je upošteval še značilnosti podsistema nezasičene cone. Oblika vhodne funkcije temelji na ugotovitvah o hidrodinamični vlogi epikraške cone kot kontrolnega faktorja, ki določa časovno distribucijo napajanja. Številne študije so namreč pokazale, da se ob visokih vodah del infiltrirane padavinske vode hitro prenese v mrežo kanalov, ostanek pa se uskladišči v bazi epikrasa in nato počasi napaja slabše prepustne cone vodonosnika. Te značilnosti sem skušala izraziti z ločevanjem hitrega in počasnega napajanja. Na osnovi primerjave med dnevnimi vrednostmi efektivne infiltracije ter deleži direktnega in baznega odtoka skozi kraške izvire Vipave znotraj posameznih padavinskih intervalov sem po metodi hidrološke bilance za vsak pripadajoči padavinski dogodek ocenila razmerje med hitrim in počasnim napajanjem. Vsaki od obeh komponent sem nato priredila ustrezno funkcijo transferja.

Za vsakega izmed treh opisanih modelov sem z izbrano enačbo vsako dnevno vrednost praznjenja v obdobju dveh hidroloških let 1993-1995 izrazila kot funkcijo merjenih padavin ali ocenjene efektivne infiltracije ali komponent počasnega in hitrega napajanja ter ustreznih funkcij transferja. Na ta način sem dobila sistem linearnih enačb, v katerem so neznanke komponente funkcij transferja. Za poenostavitev izračuna sem na osnovi predpostavljenega trajanja teh funkcij določila število členov v enačbi. Ocena njihovega trajanja je temeljila na rezultatih primerjave vhodnih in izhodnih funkcij z metodo križne korelacije. Izbran je bil časovni interval, v katerem imajo padavine še statistično značilen vpliv na pretoke, zaradi primerjave dobljenih rezultatov pa sem za prva dva modela privzela po dve različni dolžini funkcij transferja (Petrič 2000b, Martin *et al.* 1997). Na ta način sem dobila skupno 5 različic osnovnega modela napajanje - praznjenje. Za reševanje postavljenih sistemov linearnih enačb sem uporabila metodo najmanjših kvadratov in za vsak model določila ustrezne funkcije transferja, pri katerih je doseženo najboljše ujemanje med vhodnim in izhodnim signalom in je rezidualna napaka najmanjša.

Tako dobljene funkcije transferja (Sl. 37, 40 in 43) sem nato skupaj z izmerjenimi dnevnimi vrednostmi padavin in meteoroloških parametrov uporabila v enačbah 15, 19 in 20 ter za vsak model izračunala dnevne vrednosti praznjenja v kalibracijskem obdobju 1993-1995.

Za testiranje postavljenih hipotez sem primerjala ustreznost posameznih modelov. Ocenila sem točnost simulacije, ki se nanaša na sposobnost funkcije transferja, da reproducira pretoke, na osnovi katerih je bila določena. Z različnimi statističnimi metodami sem torej primerjala izmerjene in izračunane vrednosti praznjenja (Sl. 38, 39, 41, 42 in 44). Najprej sem določila karakteristične pretoke, nato pa uporabila še regresijske diagrame, objektivne funkcije, koeficiente določenosti in učinkovitosti ter kumulativne krivulje ostankov. Za osnovno oceno značilnosti izvirov sem izračunala karakteristične pretoke in sicer minimalne (najmanjše izmerjene), srednje (povprečno vrednost pretokov) in maksimalne (največje izmerjene) pretoke (Tab. 2).

Z regresijskimi diagrami in izračunom koeficientov korelacije sem ocenila stopnjo ujemanja med merjenimi in izračunanimi vrednostmi. Po pričakovanju je ujemanje najmanjše pri modelu, kjer so bile kot vhodna funkcija privzete kar merjene padavine. Pri tem so rezultati nekoliko slabši pri predpostavljeni krajši funkciji transferja. Koeficienta korelacije sta 0,89 oz. 0,88 (Sl. 47). Opazno je izboljšanje v primeru, ko je bila kot vhodni signal privzeta funkcija efektivne infiltracije in je bil izračunan koeficient korelacije 0,94 oz. 0,95 (Sl. 48). Še boljše je s koeficientom korelacije 0,97 ujemanje ob upoštevanju razdelitve napajanja na počasno in hitro komponento (Sl. 49).

Za dnevne in mesečne vrednosti sem po enačbah 21 in 22 izračunala še objektivni funkciji. V tabeli 3 so prikazane vrednosti parametrov OBJ1 in OBJ2 v razmerju glede na najnižjo vrednost, ki je bila dobljena pri modelu počasno in hitro napajanje - praznjenje. Rezultati so pokazali, da pomeni bistveno izboljšavo uvedba funkcije efektivne infiltracije namesto merjenih padavin. Tudi predpostavljeno daljše trajanje funkcije transferja ima pozitiven vpliv na rezultate. Še posebej je to očitno pri primerjavi dnevnih vrednosti na funkciji OBJ2, ki odraža razmere pri nizkih vodostajih. Sposobnost postavljenega modela za oceno praznjenja se v splošnem poveča z razdelitvijo napajanja na počasno in hitro komponento, nekoliko slabši rezultati so le pri simulaciji dnevnih vrednosti ob nizkih vodah.

Koeficient določenosti D (enačba 23) meri stopnjo ujemanja med merjenimi in izračunanimi vrednostmi, koeficient učinkovitosti E (enačba 24) pa sposobnost modela, da reproducira merjene vrednosti. S koeficientom učinkovitosti je možna tudi ocena usmerjenosti. Če je korelacija med merjenimi in izračunanimi vrednostmi velika, korelacijska premica pa odstopa od premice y=x, je koeficient učinkovitosti manjši od koeficienta določenosti. V tabeli 4 so predstavljene vrednosti koeficienta določenosti D in koeficienta učinkovitosti E za vse obdelane primere. Na osnovi relativno visokih vrednosti prvega parametra bi lahko sklepali na dobro ujemanje med izračunanim in izmerjenim praznjenjem, še posebej v primerih, ko je vhodna funkcija v sistem definirana kot efektivna infiltracija in je predpostavljen daljši čas trajanja funkcije transferja. Nekoliko slabša pa je ocena ustreznosti postavljenih modelov glede na koeficient učinkovitosti. Manjše vrednosti kažejo na odstopanje od premice y=x, torej na napako zaradi usmerjenosti izračunanega praznjenja v smislu precenjenih ali podcenjenih vrednosti. Na osnovi obsežne študije primerjave simulacij mesečnih pretokov je Chiew s sodelavci (1993) zaključil, da lahko oceno pretoka ovrednotimo kot »povsem sprejemljivo«, če je koeficient učinkovitosti večji od 0,9 in srednji izračunani pretok znotraj 10 % srednjega merjenega pretoka. Rezultati pa so »sprejemljivi«, če je koeficient učinkovitosti večji od 0,6 in je srednji izračunani pretok znotraj 15 % srednjega merjenega pretoka. Ob privzetju teh standardov lahko zaključim, da je »povsem sprejemljiv« model, pri katerem je bila vhodna funkcija napajanja razdeljena na dve komponenti, »sprejemljivi« pa ostali primeri. Izjema je model, kjer so bile kot vhodna funkcija privzete padavine in predpostavljena dolžina funkcije transferja 7 dni.

Nekoliko drugačen pristop k oceni ujemanja merjenih in izračunanih vrednosti je uporabljen pri metodi kumulativne krivulje ostankov. Pomembna razlika je ta, da so zaradi kumulativnega načina izračuna upoštevani tudi predhodni dogodki in zato s to metodo lahko zaznamo sistematično napako. Najprej sem določila ostanke tako, da sem od posameznih mesečnih vrednosti odštela srednji mesečni pretok. Dobljene ostanke sem kumulativno seštela in zaporedje mesečnih ostankov prikazala s krivuljami na diagramu (Sl. 50). Uspešnost postavljenega modela se odraža z ujemanjem med kumulativno krivuljo ostankov za merjene in za izračunane vrednosti. Tudi pri tej primerjavi se pokaže, da so rezultati najboljši pri modelu z razdelitvijo napajanja na dve komponenti, čeprav tudi tu odstopanja kažejo na določeno napako. Za oceno napake lahko uporabimo koeficient kumulativne krivulje ostankov R (enačba 25). Prednost ocenjevanja s tem parametrom v primerjavi s koeficientom določenosti in učinkovitosti je v tem, da meri povezavo med zaporedjem pretokov in ne samo med posameznimi dogodki. Za večino obdelanih primerov je bila vrednost koeficienta kumulativne krivulje ostankov manjša od prej omenjenih koeficientov, izjema je le model s počasno in hitro komponento napajanja, kjer njegova večja vrednost le še potrjuje prednosti tega modela pred ostalimi (Tab. 4).

Zanimiva je tudi primerjava funkcije transferja za model efektivna infiltracija - praznjenje in obeh funkcij transferja za model počasno in hitro napajanje - praznjenje. Vse tri so prikazane na sliki 51, posebej pa je kot vsota funkcij transferja za počasno in hitro napajanje ob upoštevanju povprečnega deleža hitrega (62 %) in počasnega napajanja (38 %) v celotnem obdobju dveh hidroloških let 1993-1995 prikazana še skupna funkcija transferja. Ta se zelo dobro ujema z vrednostmi, ki so bile dobljene pri osnovni primerjavi efektivne infiltracije in praznjenja. Glede na ugotovljene lastnosti lahko sklepam, da so izračunane skupne vrednosti pretoka v celotnem obdobju pri obeh modelih zelo podobne, razlike pa se pojavljajo pri primerjavi dnevnih vrednosti in so značilno odvisne od spreminjanja razmerja med počasnim in hitrim napajanjem v posameznih padavinskih intervalih. To pomeni, da postopek razdelitve in ocenjeni deleži obeh komponent napajanja pomembno vplivajo na končni rezultat primerjave med napajanjem in praznjenjem.

Model počasno in hitro napajanje - praznjenje se je torej pokazal kot najbolj primeren za opis razmer v kraškem vodonosniku v zaledju izvirov Vipave za obravnavano obdobje dveh hidroloških let 1993-1995. Za potrditev njegove ustreznosti pa sem v nadaljevanju izvedla še postopek validacije. To je proces ocenjevanja učinkovitosti modela na osnovi primerjave izmerjenih in izračunanih vrednosti za interval vhodnih podatkov, ki niso bili vključeni v postavitev in kalibracijo modela. V ta namen sem uporabila podatke za obdobje osmih hidroloških let od 1.10.1985 do 24.8.1993. Za primerjavo sem validacijo izdelala še za model efektivna infiltracija - praznjenje. Ker v obdobju 1985-1993 nekateri parametri niso bili merjeni, sem morala nekoliko prirediti model ocene efektivne infiltracije. Težave so se pojavile pri določitvi sekundarne infiltracije, saj merilne postaje na ponikalnicah z nekraškega obrobja v letih od 1985 do 1993 še niso delovale. Glede na majhen delež te komponente v skupni vrednosti sem izračun poenostavila tako, da sem model ocene efektivne infiltracije privzela za celotno kraško in nekraško zaledje v obsegu 149 km^2. Napako, ki se pri tem pojavi, sem ocenila na osnovi primerjave obeh načinov izračuna za obdobje 1993-1995 ter dobljene vrednosti ustrezno popravila (Sl. 52). Poenostavila sem tudi določitev funkcije praznjenja, saj za obravnavano obdobje 8 hidroloških let nisem razpolagala s podatki o pretokih Bele. Kot izhodno komponento sem privzela kar izmerjene pretoke izvirov Vipave, saj je primerjava korigiranih vrednosti praznjenja in merjenih pretokov v obdobju 1993-1995 pokazala le majhna odstopanja (Sl. 53). Vse opisane postopke ocene funkcije efektivne infiltracije in komponent počasnega in hitrega napajanja ter izračunane funkcije transferja sem vključila v dokument PREPAD v programu Microsoft Excel. V njem so z ustreznimi formulami in podprogrami združeni model ocene efektivne infiltracije in izbrana modela napajanje - praznjenje (model efektivna infiltracija - praznjenje ter model počasno in hitro napajanje - praznjenje), ki na osnovi potrebnih vhodnih podatkov o padavinah in meteoroloških parametrih omogočajo izračun dnevnih pretokov izvirov Vipave. Uporabila sem ga za simulacijo pretokov v intervalu 8 hidroloških let 1985-1993, ki sem jih nato v postopku validacije primerjala z izmerjenimi vrednostmi (Sl. 54). Ustreznost modelov sem spet ocenila s pomočjo že prej opisanih statističnih metod: karakterističnih pretokov (Tab. 5), regresijskih diagramov (Sl. 55), kumulativnih krivulj ostankov (Sl. 56), objektivnih funkcij, koeficientov določenosti in učinkovitosti ter koeficientov kumulativne krivulje ostankov (Tab. 6). V primerjavi z rezultati kalibracije modelov v obdobju 1993-1995 so po pričakovanju statistični parametri nekoliko slabši, najboljši pa je tudi za obdobje validacije 1985-1993 model z razdelitvijo napajanja na počasno in hitro komponento. Glede na koeficient učinkovitosti E bi lahko tudi model efektivna infiltracija - praznjenje ocenili kot »sprejemljiv«, večje odstopanje koeficienta kumulativne krivulje ostankov R pa kaže na obstoj neke sistematske napake. Validacija modela počasno in hitro napajanje - praznjenje je torej potrdila, da je z njim možno dovolj dobro simulirati odnos med napajanjem in praznjenjem kraškega vodonosnika v zaledju izvirov Vipave in na osnovi ugotovljenih povezav sklepati na značilnosti delovanja obravnavanega kraškega vodonosnega sistema. Zaradi razdelitve napajanja po metodi hidrološke bilance, ki temelji na primerjavi napajanja in praznjenja za celotne padavinske intervale, pa modela ni mogoče uporabljati za napovedovanje pretokov samo na osnovi podatkov o padavinah, debelini snežne odeje in meteoroloških parametrih. To možnost daje model efektivna infiltracija - praznjenje, vendar je bila pri njem ugotovljena značilno manjša točnost napovedovanja in nakazan obstoj neke sistematske napake.

Eden od možnih vzrokov za slabše rezultate v procesu validacije je lahko tudi neustrezna izbira intervala kalibracije modela. Za obdobje dveh hidroloških let 1993-1995 sem se odločila zaradi najbolj obsežne baze podatkov. Vendar pa ta interval po hidroloških razmerah najbolj odstopa od dolgoletnega povprečja, saj gre za izrazito namočeno obdobje. Zato se zdi smiselna ocena vpliva izbire kalibracijskega intervala na ustreznost postavljenih modelov. V primeru vodonosnika v zaledju izvirov Vipave sem zato funkcije transferja določila še za kalibracijske intervale hidroloških let 1988-1990, 1990-1992 in 1989-1994, pri validaciji pa sem v vseh treh primerih privzela preostala hidrološka leta iz celotnega obdobja 1985-1995. Izračunane funkcije transferja za izbrane intervale hidroloških let (Sl. 57) sem uporabila še za simulacijo pretokov v daljšem časovnem obdobju. Določila sem koeficient določenosti D, koeficient učinkovitosti E in koeficient kumulativne krivulje ostankov R (Tab. 7). V tabeli izstopata predvsem z višjim koeficientom kumulativne krivulje ostankov intervala 1990-1992 in 1989-1994.

Da pa bi lahko bolj natančno ovrednotila dobljene rezultate statistične analize, sem primerjala še hidrološke značilnosti izbranih intervalov. V diagramu sem srednje vrednosti pretokov, padavin in efektivne infiltracije za posamezna hidrološka leta izrazila v enakih enotah (Sl. 58). Že na prvi pogled je očitno, da so padavine značilno večje od pretokov. Razlika je predvsem odraz procesov v zraku, vegetaciji in tleh, ki sem jih upoštevala pri oceni efektivne infiltracije, zato je ujemanje povprečnih vrednosti efektivne infiltracije in pretokov že boljše. Seveda pa pri tej primerjavi ne smemo zanemariti dejstva, da sem model ocene efektivne infiltracije kalibrirala glede na skupni pretok izvirov Vipave v obdobju dveh hidroloških let 1993-1995. Zato je tudi ujemanje največje prav v kalibracijskem intervalu, v ostalih intervalih pa je efektivna infiltracija večja ali manjša od pretokov. Če izključimo možnost večjih napak v modelu ocene, lahko ta odstopanja interpretiramo kot rezultat različnih pogojev pretakanja in uskladiščenja znotraj kraškega vodonosnika. Tudi hidrološko leto namreč v smislu vodne bilance ni zaključena enota, saj se lahko vplivi različne namočenosti prenašajo tudi v precej daljšem časovnem obdobju v obliki nekega super-počasnega napajanja. Nekaj o osnovnih značilnostih delovanja kraških sistemov lahko torej sklepamo že iz razlik med srednjimi vrednostmi, za bolj natančno opredelitev procesov pa je potrebna bolj podrobna analiza, v katero je vključena obdelava in primerjava posameznih komponent. Razlika med srednjimi vrednostmi efektivne infiltracije in pretokov za izbrane intervale je največja za obdobje 1988-1990, manjša za 1990-1992, najmanjša in negativna pa za 1993-1995. Za čas med 1989 in 1994 veljajo podobne značilnosti kot za interval 1990-1992. Na osnovi te primerjave lahko zaključimo, da se ugotovljene razlike odražajo tudi na prej opisanih rezultatih statistične analize modelov z različnimi kalibracijskimi intervali. Večji presežki efektivne infiltracije se reflektirajo z ustrezno manjšimi vrednostmi funkcije transferja (Sl. 57). Pri simulaciji pretokov pa da najboljše rezultate model, ki je bil kalibriran glede na interval, v katerem se hidrološke značilnosti najbolj približajo povprečju. V obravnavanem primeru sta to bila intervala 1990-1992 in 1989-1994 (Tab. 7). Kljub ugotovljenim manjšim razlikam in povezavi ustreznosti modela s hidrološkimi razmerami v kalibracijskem intervalu lahko glede na rezultate opravljene ocene v splošnem zaključim, da je vpliv izbire tega intervala na značilnost modela majhen. Obstoječa baza podatkov je torej zadostna in dovolj homogena.

ZNAČILNOSTI ODNOSA MED NAPAJANJEM IN PRAZNJENJEM KRAŠKEGA VODONOSNIKA

Kljub nekaterim omejitvam opisane metode, ki poenostavlja dejanske razmere v kraških vodonosnikih, lahko ob zadovoljivem ujemanju med merjenimi in izračunanimi pretoki izvirov Vipave potegnemo tudi nekatere zaključke o značilnostih delovanja obravnavanega kraškega sistema. Z izboljšanjem rezultatov modela ob uvedbi funkcije efektivne infiltracije namesto padavin je bil izpostavljen pomemben vpliv, ki ga imajo vegetacija ter procesi v ozračju in tleh na količino in časovno razporeditev vode, ki dejansko vstopi v vodonosni sistem. Točnost simulacije se je še povečala ob razdelitvi napajanja na počasno in hitro komponento, kar govori v prid predpostavki o dvojnosti mehanizma delovanja sistema: o hitrem pretoku skozi kraško drenažno mrežo in daljšem zadrževanju vode v sistemu zaradi uskladiščenja v conah slabše prepustnosti.

Na značilnosti pretakanja in uskladiščenja znotraj kraškega sistema je možno sklepati tudi iz oblike funkcij transferja. Visoke vrednosti v prvem delu funkcije transferja za hitro napajanje kažejo, da se izviri odzovejo nanj s povečanjem pretoka že v prvih dneh po padavinskem dogodku. Po višku v času t=0 se vpliv hitrega napajanja najprej hitro, po treh dneh pa nekoliko bolj počasi postopno manjša. Počasno napajanje pa se razporedi na daljše časovno obdobje, ki je v obravnavanemu primeru omejeno tudi s predpostavljeno dolžino trajanja funkcije transferja. V začetnem delu se njene vrednosti gibljejo okrog 0. Take razmere se ujemajo z ugotovitvijo, da je zaradi povečanega potenciala v kraških kanalih, ki je posledica hitrega napajanja, iztok iz con slabše prepustnosti zanemarljiv. Pozitivne vrednosti v nadaljevanju pa odražajo postopno izcejanje vode, ki je bila v sistem infiltrirana kot počasno napajanje. Tako kot pri drugih funkcijah transferja z daljšim trajanjem se tudi v tem primeru pojavljajo oscilacije, ki kažejo na periodično večanje vpliva počasnega napajanja na pretok izvirov. Vsaj deloma so prav gotovo posledica napak pri oceni funkcij napajanja in praznjenja, pa tudi predpostavke o linearnosti sistema, ki ne ustreza povsem realnim razmeram.

Pomen natančne ocene efektivne infiltracije

Posebno pozornost sem posvetila podsistemu efektivne infiltracije, v katerega sem poleg padavin kot osnovnega vira vključila še vpliv prestrezanja padavin na vegetacijskem pokrovu, evapotranspiracije, snežnih padavin in taljenja snega, uskladiščenja vode v tleh ter sekundarne infiltracije ponikalnic, ki zbirajo površinsko vodo na flišnem obrobju. Ker so bili podatki o parametrih, ki vplivajo na te procese, pomanjkljivi, sem v postavitvi modela ocene uporabila nekatere predpostavke in kalibracijo glede na skupni pretok izvirov Vipave v obdobju dveh hidroloških let 1993-1995. Tak pristop sicer nekoliko zmanjšuje kakovost dobljenih rezultatov, vendar je vključitev efektivne infiltracije v model potrdila pomembno vlogo opisanih procesov pri proučevanju hidrodinamičnih značilnosti kraškega vodonosnika. Primerjava dobljenih vrednosti pokaže, da je pomemben predvsem vpliv na sezonsko razporeditev količine infiltracije. Razlika med merjenimi padavinami in efektivno infiltracijo je tako spomladi značilno večja kot jeseni, saj je večinoma odraz sprememb v klimatskih in vegetacijskih pogojih. Manjši delež efektivne infiltracije spomladi je predvsem posledica začetka bujne rasti vegetacije, ki se odraža z večanjem vpliva prestrezanja padavin na vegetacijskem pokrovu in deleža realne evapotranspiracije.

Ker imajo brez natančne ocene efektivne infiltracije že napake v vrednostih vhodne funkcije značilen negativen vpliv na rezultate nadaljnje analize delovanja kraških vodonosnih sistemov, je tej komponenti in njeni čim bolj natančni oceni potrebno posvetiti posebno pozornost.

Značilnosti sekundarnega napajanja iz površinskega toka na krasu

Zanimive rezultate je dala tudi bolj podrobna analiza medsebojnega vpliva površinske in podzemne vode potoka Bele in izvirov Vipave. S sledilnim poizkusom, primerjavo fizikalno-kemičnih značilnosti vode in merjenjem pretokov v številnih profilih vzdolž površinskega toka Bele so bile potrjene predpostavke o zatekanju vode iz Bele v izvire Vipave. Tok je v glavnem usmerjen proti izviru Vipava 7 (okrog 60 % povrnjenega sledila), glede na hidrološke razmere pa v različnih deležih tudi proti ostalim stalnim izvirom. Pokazalo se je, da se hidrološki odziv spreminja v odvisnosti od deleža napajanja iz kraškega ali flišnega zaledja. Visok vodostaj v neposrednem kraškem zaledju izvirov Vipave omejuje dotok iz smeri Bele, obratno pa se ob nizkem vodostaju poveča vpliv tega sekundarnega napajanja iz flišnega zaledja - ne le v izviru Vipava 7, ampak še bolj izrazito tudi v ostalih stalnih izvirih Vipave. Delež vode iz Bele v izviru Vipava 7 se giblje okrog 20 %, poveča pa se takrat, ko je intenzivnost in količina padavin v flišnem zaledju večja kot v kraškem.

Rezultati opravljenih raziskav povezave med potokom Belo in izviri Vipave so torej potrdili, da je obseg napajanja kraških izvirov iz površinskega toka na krasu značilno odvisen od hidroloških razmer.

Hidrodinamična funkcija epikraške cone

O značilnostih delovanja kraških vodonosnih sistemov lahko posredno sklepamo tudi na osnovi ugotovitve, da je najboljše rezultate dal model z razdelitvijo napajanja na počasno in hitro komponento. Ugotovljeno lastnost lahko povežemo z obstojem nekega mehanizma, ki omogoča hiter vstop infiltrirane padavinske vode v kraško drenažno mrežo in ima za posledico tipično reakcijo kraških izvirov s hitrim in izrazitim povečanjem pretoka. In ki na drugi strani omogoča, da se ob visokih vodah del infiltriranih padavin začasno uskladišči v bazi epikrasa in nato kot počasno napajanje še dalj časa v obdobju nizkih vod vzdržuje dotok vode do zasičene cone. Številne študije, ki jih zasledimo v literaturi, so tako vlogo pripisale epikraški coni, z nekoliko drugačnim pristopom k proučevanju delovanja kraških vodonosnih sistemov pa jih je potrdila tudi opravljena raziskava.

Možnost uporabe postavljenih modelov napajanje - praznjenje za simulacijo pretokov izvirov Vipave

Validacija modelov napajanje - praznjenje je nakazala tudi možnost njihove uporabe za napovedovanje pretokov izvirov Vipave na osnovi podatkov o padavinah in meteoroloških parametrih v zaledju. Čeprav je ob prvotni postavitvi najboljše rezultate dal model z upoštevanjem počasnega in hitrega napajanja, zaradi uporabljene metode razdelitve komponent napajanja ni primeren za simulacijo. Metoda hidrološke bilance namreč temelji na primerjavi efektivne infiltracije in praznjenja za celotne padavinske intervale. Da bi lahko model uporabljali za simulacijo, bi zato najprej morali pojasniti in kvantitativno opredeliti značilnosti razdelitve napajanja na osnovi primerjave vhodnih parametrov in ne na osnovi analize krivulj praznjenja, ki predstavljajo izhodno komponento modela.

Teh težav ni pri modelu efektivna infiltracija - praznjenje, saj je vanj že vključen kalibriran model ocene efektivne infiltracije. Potrebni vhodni podatki so tako merjene padavine, debelina snežne odeje ter temperatura in vlažnost zraka, hitrost vetra in osončenost. Problem pa ostaja manjša točnost simulacije, ki zmanjšuje uporabnost modela za napovedovanje pretokov v hidroloških analizah.

SKLEPI

Ugotovljene značilnosti odnosa med napajanjem in praznjenjem ter zaključki o vplivu posameznih komponent vhodne funkcije na delovanje kraškega vodonosnega sistema so predstavljeni v prejšnjem poglavju. Na tem mestu pa jih povzemam v odgovore na vprašanja, ki sem si jih zastavila v uvodu:

- Primernost modelov napajanje - praznjenje sem ocenila na osnovi statistične analize ujemanja izmerjenih in izračunanih pretokov izvirov Vipave. »Povsem sprejemljiv« je model počasno in hitro napajanje - praznjenje, »sprejemljivi« pa ostali modeli. Zaključim lahko, da nekoliko prirejena metoda črne skrinjice omogoča postavitev modelov, ki z zadovoljivo natančnostjo opisujejo odziv sistema na napajanje. Odstopanja med merjenimi in izračunanimi pretoki, ki se vseeno pojavljajo, pa so posledica napak pri oceni vhodnih in izhodnih parametrov ter uporabljenih predpostavk pri oblikovanju modela, ki ne ustrezajo povsem dejanskim razmeram v kraških vodonosnikih.
- Uporabljena metoda se je pokazala kot primerna tudi za oceno hidrodinamičnih značilnosti kraškega vodonosnika. Z izboljšanjem rezultatov modela ob uvedbi funkcije efektivne infiltracije namesto padavin je bil izpostavljen pomemben vpliv, ki ga imajo vegetacija ter procesi v zraku in tleh na količino in časovno razporeditev vode, ki dejansko vstopi v kraško kamnino. Točnost simulacije se je še povečala ob razdelitvi napajanja na počasno in hitro komponento. To govori v prid predpostavki o dvojnosti mehanizma delovanja sistema: o hitrem pretoku skozi kraško drenažno mrežo in daljšem zadrževanju vode v sistemu zaradi uskladiščenja v conah slabše prepustnosti ter o obstoju nekega mehanizma v epikraški coni, ki to časovno razporeditev napajanja omogoča.
- Ustreznost testiranih modelov potrjuje primernost postavljenega konceptualnega modela napajanja v kraških vodonosnih sistemih. Napajanje opisuje tok infiltrirane vode, ki doseže stalni nivo podzemne vode in ima za posledico povečanje količine uskladiščene vode. Osnovni vir so običajno padavine, na katere pa v zraku, vegetaciji

in tleh vplivajo številni procesi, ki značilno spremenijo količinsko in časovno razporeditev vnosa vode v epikraško cono. Ker imajo brez natančne ocene te efektivne infiltracije že napake v vrednostih vhodne funkcije značilen negativen vpliv na rezultate nadaljnje analize delovanja kraških vodonosnih sistemov, je tej komponenti in njeni čim bolj natančni oceni potrebno posvetiti posebno pozornost. Naslednja faza napajanja vključuje pretakanje vode skozi nezasičeno cono. Povečanje točnosti simulacije v zadnjem modelu je potrdilo predpostavko, da se zaradi značilne strukture epikraške cone napajanje razdeli v počasno in hitro komponento. Del infiltrirane vode se kot hitro napajanje skozi primarne kraške drenažne kanale hitro pretoči do nivoja podzemne vode, ostanek pa se začasno uskladišči v nezasičeni coni in potem vzdržuje počasno napajanje tudi v obdobju brez padavin.

IZVLEČEK

Kraški vodonosniki so nadpovprečno podvrženi onesnaževanju, hkrati pa predstavljajo pomemben rezervoar pitne vode. Raziskave dinamike pretakanja vode v njih so zelo pomembne za ustrezno načrtovanje gospodarjenja s kraškimi vodnimi viri. Zaradi heterogene zgradbe in zapletenega delovanja krasa naloga ni enostavna, lotevamo pa se je z različnimi raziskovalnimi metodami. V raziskavi kraškega vodonosnika v zaledju izvirov Vipave v jugozahodni Sloveniji sem z analizo značilnosti odnosa med napajanjem in praznjenjem, torej vhodne in izhodne funkcije kraškega sistema, sklepala o značilnostih njegovega hidrodinamičnega delovanja. Osnovno metodo črne skrinjice sem glede na zastavljene cilje in razpoložljive podatke nekoliko prilagodila. Izhajala sem iz predpostavke, da je hidrološka kompleksnost kraških vodonosnikov predvsem posledica zelo spremenljivih pogojev napajanja in heterogenih lastnosti podzemnega toka. Procese, ki te pogoje in lastnosti opredeljujejo, sem povezala v konceptualni model, v katerem je kraški sistem obravnavan kot več povezanih podsistemov. Da bi lahko primerjala vplive posameznih podsistemov, sem predpostavila 3 različne modele napajanje - praznjenje in se s spreminjanjem vhodnega signala skušala čim bolj približati realnim razmeram. V prvem sem primerjala kar merjene padavine in pretoke izvirov, kraški vodonosni sistem med vhodno in izhodno funkcijo pa obravnavala kot celoto. Delovanje znotraj sistema sem izrazila s funkcijo transferja, ki transformira vhodni signal v izhodnega.

V drugem modelu je bil posebej izpostavljen podsistem efektivne infiltracije. Njegovo delovanje sem opisala z modelom bilance vode v tleh, v katerem so bili vključeni procesi prestrezanja padavin na vegetacijskem pokrovu, snežnih padavin in taljenja snega, evapotranspiracije, uskladiščenja vode v tleh in sekundarne infiltracije. Na ta način so bili že pri določitvi vhodne komponente upoštevani omenjeni procesi v zraku, vegetaciji in tleh, ki značilno vplivajo na dejansko količino in časovno razporeditev infiltracije padavin. Odziv kraških izvirov nanjo pa opisuje funkcija transferja.

Tretji model je upošteval še značilnosti podsistema nezasičene cone. Oblika vhodne funkcije temelji na ugotovitvah o hidrodinamični vlogi epikraške cone kot kontrolnega faktorja, ki določa časovno distribucijo napajanja. Ob visokih vodah se tako del infiltrirane padavinske vode hitro prenese v mrežo kanalov, ostanek pa se uskladišči v bazi epikrasa in nato počasi napaja slabše prepustne cone vodonosnika. Te značilnosti sem skušala izraziti z ločevanjem hitrega in počasnega napajanja. Na osnovi primerjave med dnevnimi vrednostmi efektivne infiltracije ter deleži direktnega in baznega odtoka skozi kraške izvire Vipave znotraj posameznih padavinskih intervalov sem po metodi hidro-

loške bilance za vsak pripadajoči padavinski dogodek ocenila razmerje med hitrim in počasnim napajanjem. Vsaki od obeh komponent sem nato v sistemu napajanje – praznjenje priredila ustrezno funkcijo transferja.

Za testiranje postavljenih hipotez sem primerjala ustreznost posameznih modelov. Ocenila sem točnost simulacije, ki se nanaša na sposobnost funkcije transferja, da reproducira pretoke, na osnovi katerih je bila določena. Z različnimi statističnimi metodami sem torej primerjala izmerjene in izračunane vrednosti praznjenja. Glede na stopnjo ujemanja sem ocenila primernost postavljenih modelov, glede na njihovo zgradbo in lastnosti ter obliko in značilnosti funkcij transferja pa sklepala o vlogi obravnavanih podsistemov pri pretakanju in uskladiščenju vode v kraškem vodonosnem sistemu.

Kljub nekaterim omejitvam opisane metode, ki poenostavlja dejanske razmere v kraških vodonosnikih, lahko glede na zadovoljivo ujemanje med merjenimi in izračunanimi pretoki potegnemo tudi nekatere zaključke o značilnostih delovanja kraškega sistema. Z izboljšanjem rezultatov modela ob uvedbi funkcije efektivne infiltracije namesto padavin je bil izpostavljen pomemben vpliv, ki ga imajo vegetacija ter procesi v ozračju in tleh na količino in časovno razporeditev vode, ki dejansko vstopi v vodonosni sistem. Ker imajo brez natančne ocene efektivne infiltracije že napake v vrednostih vhodne funkcije značilen negativen vpliv na rezultate nadaljnje analize delovanja kraških vodonosnih sistemov, je tej komponenti in njeni čim bolj natančni oceni potrebno posvetiti posebno pozornost.

O značilnostih delovanja kraških vodonosnih sistemov lahko posredno sklepamo tudi na osnovi ugotovitve, da je najboljše rezultate dal model z razdelitvijo napajanja na počasno in hitro komponento. Ugotovljeno lastnost lahko povežemo z obstojem nekega mehanizma, ki omogoča hiter vstop infiltrirane padavinske vode v kraško drenažno mrežo in ima za posledico tipično reakcijo kraških izvirov s hitrim in izrazitim povečanjem pretoka. In ki na drugi strani omogoča, da se ob visokih vodah del infiltriranih padavin začasno uskladišči v bazi epikrasa in nato kot počasno napajanje še dalj časa v obdobju brez padavin vzdržuje počasno napajanje. Govorimo o specifični hidrodinamični funkciji epikraške cone, ki zaradi značilne strukture vpliva na časovno distribucijo napajanja.

Knjiga torej predstavlja več novosti v metodološkem pristopu k obravnavanju delovanja kraških vodonosnikov. Splošno priznana je teza, da je ob upoštevanju osnovnih značilnosti vodne bilance možno oceniti količino vode, ki se infiltrira v kraški sistem. V opravljeni raziskavi pa je bila razširjena v oceno, da je ob natančni analizi in parametrizaciji vseh dejavnikov možno pridobiti tudi relevantne vrednosti funkcije napajanja, ki so lahko osnova za analizo notranje dinamike sistema na dnevnem nivoju. Ta analiza temelji na načelu črne skrinjice, ki pa je nadgrajen z vključitvijo dodatnih, deterministično določenih parametrov in relacij. Preverjanje na vodonosniku v zaledju izvirov Vipave je dokazalo, da so bile postavljene hipoteze pravilne in potrdilo ustreznost razvitih metod za proučevanje hidrodinamičnih značilnosti kraških vodonosnih sistemov.

ABSTRACT

Karst aquifers are very exposed to pollution, and at the same time they represent important resources of drinking water. Researches of their hydrodynamic characteristics are essential for the sustainable management of groundwater in karstic environments. But due to their heterogeneous structure and complex functioning, identifying these characteristics is by no means an easy task. Therefore in a search for solutions, numerous research methods have been applied. In the research on the karst aquifer in the recharge area of Vipava springs in south-west Slovenia the analysis of relations between recharge and discharge, i.e. input and output functions of karst system was applied in order to define the characteristics of its functioning. With regard to the aspired aims and the available data, I slightly adapted the black-box method, following the assumption that the hydrological complexity of karst aquifers is primarily a consequence of very variable conditions of recharge and heterogeneous properties of the groundwater flow. Processes that determine these conditions and properties were combined into a conceptual model, wherein the karst system was dealt with as a group of several interconnected subsystems. To be able to compare influences of individual sub-systems three different recharge-discharge models were set up. By changing the input signal it was attempted to draw as near to the real conditions as possible. In the first one the measured precipitation and discharges of springs were compared, whereas the karst system between the input and the output was treated as a whole. The functioning within the system was expressed by the transfer function, which transforms the input signal into the output one.

In the second model I particularly exposed the sub-system of effective infiltration. I described its operation with the soil moisture balance model, wherein processes of interception on the vegetation cover, snowfall and snow melt, evapotranspiration, water storage in the soil and the secondary infiltration were included. In this manner, the just mentioned processes taking place in air, vegetation and in the soil, which significantly affect the actual quantity and temporal distribution of infiltration, were considered already in the determination of the input component. The response of karst springs to it, however, is described by the transfer function.

In the third model also characteristics of the sub-system of unsaturated zone were taken into account. The form of the input function is based upon findings about the hydrodynamic role of the epikarst zone and about its functioning as the controlling factor, that determines the temporal distribution of the recharge. Part of the infiltrated

water during high waters is rapidly transferred into the network of channels, whereas the remainder is stored in the epikarst base and subsequently recharges less permeable zones of aquifer. I tried to define these characteristics by the division into fast and slow recharge. On the basis of comparison between daily values of the effective infiltration and shares of direct and base flow through karst springs of Vipava within individual precipitation intervals I evaluated, by applying the hydrological balance method, for each corresponding precipitation event, the ratio between fast and slow recharge. For each one of the components I subsequently adapted the corresponding transfer functions in the recharge-discharge system.

In testing the set up hypothesis the adequacy of individual models was compared. I evaluated the accuracy of the simulation, which is related to the transfer function's ability to reproduce discharges, on the basis of which the transfer function was determined. By application of various statistical methods I thus compared the measured and calculated discharge values. With respect to the closeness of matching, I assessed the appropriateness of the set up models, whereas with regard to their structure and properties and with respect to the form and characteristics of transfer functions, I conjectured about the role of the considered sub-systems in the flow and storage of water within the karst system.

Despite certain limitations of the described method, which simplifies the actual conditions in the karst aquifer, we may nevertheless, with regard to the satisfactory correspondence of the measured and calculated discharges of Vipava springs, draw certain conclusions about the main characteristics of the functioning of the studied karst system. The improvement in the model's results, brought about by the introduction of the effective infiltration function instead of the precipitation, highlighted the significant influence exerted by the vegetation and processes in air and in the soil on the quantity and the temporal distribution of water, which actually enters into the aquifer. Due to the fact that errors in the input function values without the accurate estimation of effective infiltration already exert characteristic negative effect on results of the further analysis of the functioning of karst systems, it is obligatory to dedicate special attention to this component and to its most accurate evaluation.

The characteristics of the functioning of karst systems may be indirectly conjectured also from the conclusion that the best results were yielded by the model with the division into the slow and fast recharge component. We could relate this ascertained feature to the existence of the certain mechanism that enables rapid entrance of the infiltrated precipitation water into karst drainage network and brings about as its consequence a typical reaction of karst springs, i.e. their rapid and intensively increased discharge. On the other hand, such mechanism enables a part of infiltrated precipitation to be temporarily stored during high waters and subsequently sustains the slower emptying of the aquifer also in period of low waters. We talk about specific hydrodynamic function of epikarst which, due to its typical structure, influences the temporal distribution of recharge.

In the book some novelties in the methodological approach to the study of functioning of karst aquifers are presented. It is generally recognised that bearing in mind the basic characteristics of the water balance it is possible to estimate the amount of water that infiltrates into the karst system. And in the presented research this statement was broadened in the estimation that by using a precise analysis of all relevant factors and accurate evaluation of parameters it is possible to get relevant values of the recharge function, which can be then used as a basis for the further analysis of the inner dynamics of the system. In the analysis the basic principles of the black-box method were accepted, but some deterministically defined parameters and relations were included additionally. Correctness of the set up hypothesis and adequacy of the developed method for the study of hydrodynamic characteristics of karst systems were proved by testing on the karst aquifer in the recharge area of Vipava springs.

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