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ORIGINAL ARTICLE

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Water supply potential and optimal exploitation capacity of karst aquifer systems

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Abstract The management of groundwater flow systems in karst regions appears, at present, to be the most important procedure for solving water deficiency problems during periods of low rainfall. Faced with a lack of data for characterizing the water supply potential of karst aquifers, analyses of spring hydrographs may provide valuable indirect information regarding the structure of karst hydrogeological systems. To estimate the optimal exploitation capacities of karstic sources, a stochastic-conceptual approach was applied in case studies from the Serbian karst. Water supply potentials were initially evaluated on the basis of groundwater budgets. Further steps towards defining optimal "exploitable" regimes included analyses of storage changes in karst water reservoirs under natural conditions and calculation of the potential expansion of currently tapped sources. The results obtained through these analyses are a significant contribution to feasibility studies and aid in the avoidance of problems of overexploitation.

Keywords Karst aquifer system · Time series analysis · Aquifer storage · Exploitation capacity · Serbia

Introduction

The Carpatho-Balkan karst aquifer systems, typical of the geosynclinal type, represent the main sources for regional water supply in eastern Serbia. These large karst reservoirs, rich in groundwater resources, offer sufficient future water supplies under conditions of sustainable groundwater management. However, the main problem is a deficiency of water during recessional periods, which results from fast discharge of karstic groundwater through springs; a frequent problem in karst aquifers tapped for water supply.

Generally, there are several principles for karst groundwater management, including a "loan" of water from storage in karst reservoirs. The main reason for application of this concept is the relatively fast replenishing of water during high-water period, commonly accomplished during one hydrological cycle. Such a method is recommended for several sources in the region and is usually implemented by construction of deeper tapping structures. The main reasons for the use of this method are based on prompt compensation of water during high-water periods and also economical factors. Major concern for tapping karst groundwater in this way is the possibility of overexploitation which can cause multiple problems. Therefore, it is very important to establish the principles for karst aquifer characterization and to properly assess potential and available resources for groundwater tapping.

Studied area

Three characteristic karst springs were considered to establish basic principles of their groundwater potential. Selected karstic sources presented are typical of the

Carpatho-Balkanides with regard to their replenishing, circulation and discharge.

All three springs originate from a karst aquifer developed in Mesozoic (mostly Jurassic and Cretaceous) limestones. The climate of the study area is moderately continental, grading gently to mountainous. The average yearly precipitation measured at St. Petka is about 700 mm, while the average air temperature is about 7°C. The average annual infiltration values range from 60 to 30% for the Carpatho-Balkanic karst in Serbia (Stevanović and Filipović 1994).

Nemanja source is at the northern part of the study area (Fig. 1) and has a surface of karst area of about 30 km^2 compared to 50 km^2 of the total catchment area. Over 70% of the karst area is covered by a thin layer of Miocene sediments, as well as surface vegetation. Additionally, this source has a diffusive type of discharge, a very important characteristic. The main drainage points are five karst springs with relatively stable flow regimes, except the uppermost spring which has a ratio of Qmax:Qmin of 200:1. Furthermore, subsurface outflow to alluvial and Miocene aquifers is a very significant mode of drainage. The aquifer is recharged dominantly from percolating precipitation. Infiltration from surface streams flowing over karst terrains is also a source of recharge. Groundwater is also recharged from a part of the drainage area made up of low permeable Permian sandstones where surface streams flow to the lower limestone terrain.

St. Petka source is located on limestone and less porous Neogene sediments. The catchment area covers less than 30 km^2 and is characterized by well-developed karst surface and subsurface features. Average annual discharge is about 400 l s^{-1}, while values of outflow modules are 15 l s^{-1} km^{-2}. In contrast to the Nemanja, this source has concentrated discharge outlets by ascending springs, with discharge rates from about 100 l s^{-1} to over 3 m^3 s^{-1}. Replenishing of this source is accomplished exclusively through infiltration of precipitation, particularly through sinkholes in denuded areas.

Grza source is located on karstified limestone and Permian low permeable sandstone. During high-water period, the exsurgence zone is elevated over 5 m from contact. According to dye tests, the catchment area of Grza karst spring varies from approximately 30 km^2 to 50 km^2, depending on recharge conditions. Minimal discharge rate is about 20 l s^{-1} while maximum exceeds over 9 m^3 s^{-1}. This spring is fed by a relatively horizontal cave system with over 100 m of channels.

General characterization of karst aquifer

Karst aquifers are characterized by high heterogeneity, discontinuity and spatial variability of hydrogeological parameters. There is a "duality" of karst (Kiraly et al. 1995), in particular a duality of groundwater flow (White 1969; Atkinson 1977). The first part of this duality is represented by channel networks of great transmissivity, while the second one consists of voluminous media with poor permeability in matrix blocks. The presence of this duality causes a widely known phenomenon, "inversion of hydraulic gradient" (Drogue 1980). Establishing the relationship between those two types of interconnected flows provides valuable information about the storage capacity of the aquifer, an essential parameter for effective groundwater management. Determination of this parameter is not an easy

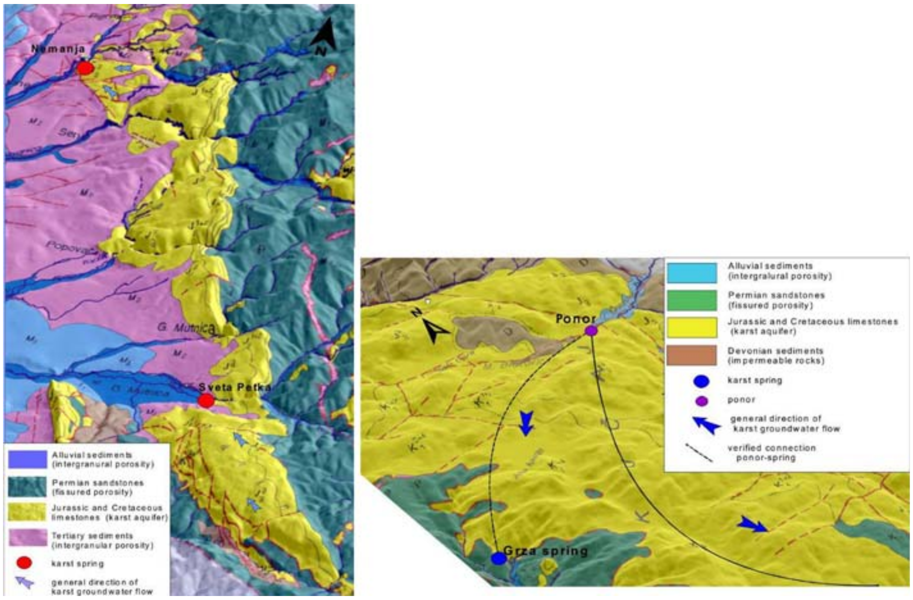


Fig. 1 Schematic hydrogeological maps of selected karst sources

task, although analysis of spring hydrographs may provide valuable indirect information on the structure of the karst hydrogeological system (Larocque et al. 1998; Bonacci 1993; Kresic 1997). For this purpose, the method of implementing systematic (time series) analyses was developed (Mangin 1984).

The systematic approach mainly refers to input–output relationship (without artificially changing system condition). As an initial step for characterization of a karst aquifer, the results of autocorrelation, spectral density and cross-correlation were considered for the characteristic examples of Serbian karst springs (Figs. 2, 3, 4).

For the St. Petka spring, the auto-correlogram exceeds the confidence limits for approximately 85 days. Results for Nemanja springs exceed the limits for 100 days. This implies that aquifer storage is significant and that water releases gradually. By contrast, Grza spring, with dominant large channels and relatively poorly developed matrix porosity, has a fast response on input and a consequently small storage capacity.

The spectral density function of the source discharges generally show high peaks at a low frequency of 0.0055 (182 days), which confirms the presence of a seasonal cycle for all springs. Considerable peaks at the middle frequencies (about 20–40 days) for Nemanja and St Petka show relatively low densities, again in contrast to Grza spring, which has a high density. At the high frequencies, low densities with random behaviour are exhibited only by the Grza spring. This analysis confirms the existence of quick flow for Grza spring, while St Petka and Nemanja springs are characterized by more seasonal recharge and discharge cyclicity.

Cross-correlograms for spring flow and precipitation are statistically insignificant for the Nemanja spring (Fig. 4). For the St. Petka spring, cross-correlation shows a very minor level of significance from 3 to 13 days, but after that changes are insignificant. Low cross-correlation values for both of these springs show that the influence of infiltration is significantly attenuated by the karst hydrogeological system. On the other hand, the cross-correlogram of Grza spring shows a relatively high and direct correlation between the discharge rate of the spring and precipitation in the first few steps (10 days), in direct response of large transmitters in the aquifer to significant rainfall events.

Altogether, the analysis presented shows large storage capacities for St. Petka and Nemanja springs, but not for Grza spring. Water is stored in these karst hydrogeological systems during the recharge period and is later released during the dry season. Dynamic resources are the consequence of a significant role of matrix porosity (slow subsequent water release following desaturation of larger fractures). Additionally, the presence of storage in the epikarstic zone certainly has a great influence on karst hydrogeological system behaviour, reflected in the long delay between inputs and outputs. This is obvious with Nemanja spring, where the dominant role of small fissures and presence of storage in the epikarst zone together provide slow and subsequent water release. On the contrary, Grza spring shows a dominant role of large channels and relatively

Fig. 2 Auto-correlograms of daily discharge of characteristic springs

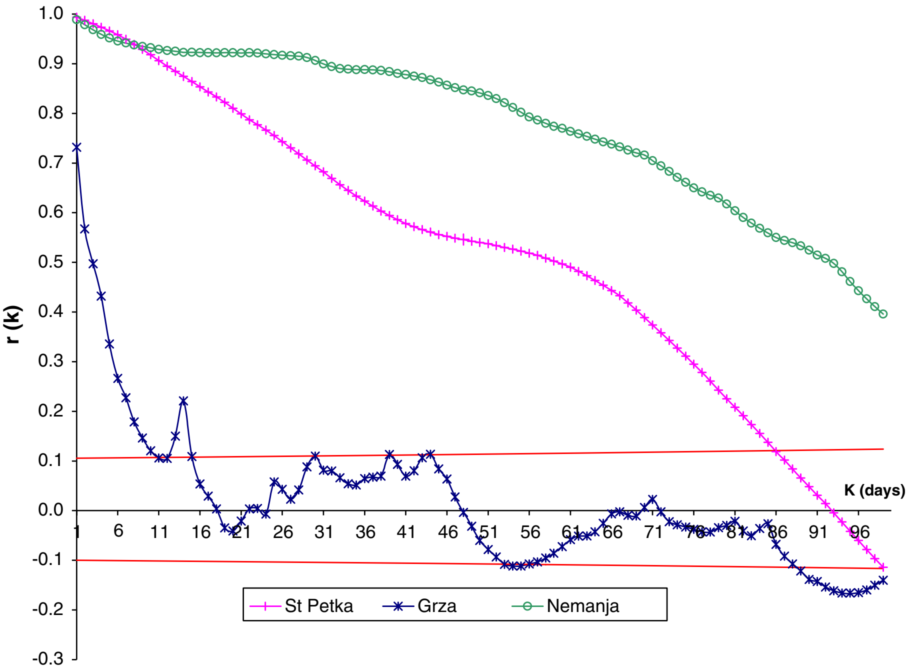


Fig. 3 Spectral density functions of daily discharge

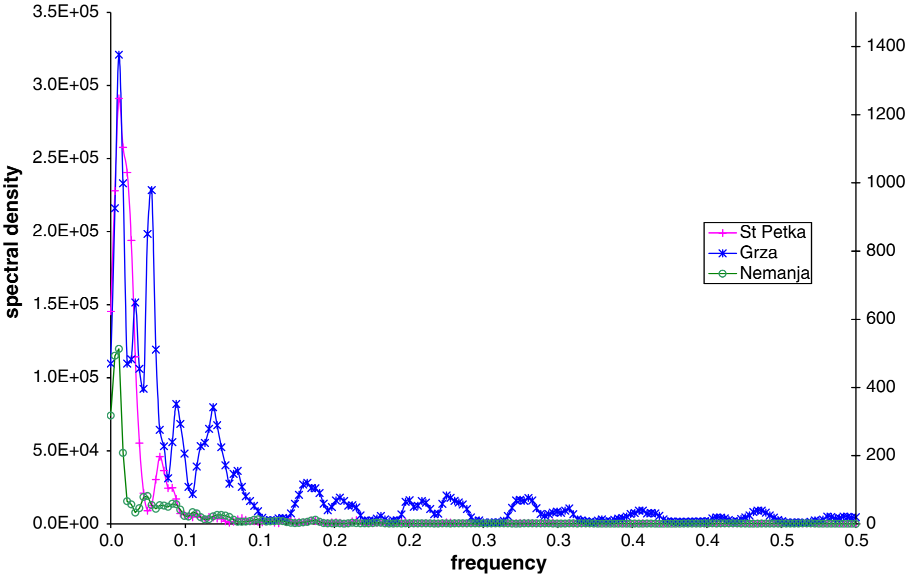
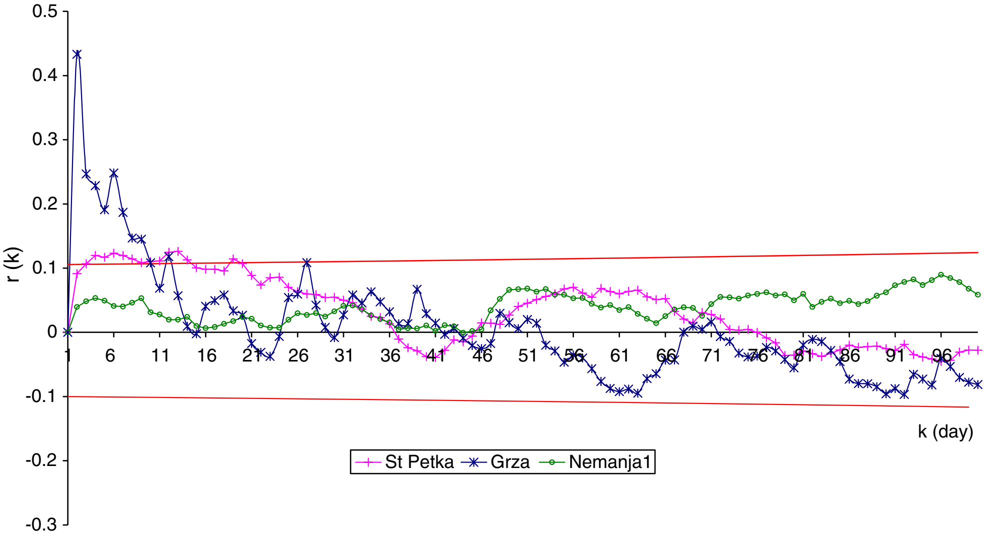


Fig. 4 Cross-correlograms of daily discharge and precipitation of characteristic springs



poorly developed matrix porosity, which causes the fast response on input and is responsible for the small storage capacity.

Regarding the potential for groundwater tapping based on ‘‘loan’’ of deeper stored water, the optimal source is St. Petka. The reasons for this are the well-developed matrix porosity and karst channels which provide, respectively, the amount of water to be loaned from storage during the recession period, and relatively fast water compensation during the recharge period. On the contrary, Grza spring is not suitable for application of such measures. As for Nemanja spring, there is a possibility for applying such measures, but defining the optimal exploitation capacity must be done with great attention due to the probability of overexploitation. This was proven during further hydrogeological exploration using mapping, geophysical methods, borehole drilling, etc.

In addition to the analysis presented, hydrograph separation to assess base flow was also undertaken. Considering that base flow represents drainage of previously accumulated water, the remainder must be newly infiltrated water (Kresic 1997). This graphical procedure does not estimate real values of base flow (reflected by appearance of negative values during recharge periods, Raudkivi 1979), thus showing only the ratio between two separated components of hydrograph.

To generally characterize the karst aquifer by hydrograph separation, the method of linear interpolation (including corrections in accordance with the recession coefficients) was adopted (Fig. 5). The main indicator of this analysis is the base flow index (BFI), which is the ratio between base flow and total flow. According to this parameter, information concerning storage capacity could be easily obtained.

To obtain structural and hydrodynamic characteristics of karst hydrogeological systems, some authors (Eisenlohr et al. 1997) suggest using numerical modelling.

Karst groundwater budget

As a first step towards rational management and use of karstic water resources, it is necessary to estimate the total (overall) water potential based on groundwater budget. The calculation of groundwater budget of a karst aquifer is based on the continuity equation in the natural state of the karst reservoir. The lack of available data is often conditioned by the determination of effective infiltration using the stochastic-conceptual model (Zhang et al. 1996; Jemcov et al. 1998). In practice, the system is often simulated as a Lumped-parameter model, as a special case of an ARCR (auto regressive–cross regressive) model (Kresic 1997). Since the relationship between input (precipitation, infiltration) and output (spring discharge, outflow and evapotranspiration) is non-linear, usage of a multiple non-linear regression (MNC) model could provide a better simulation.

$$\begin{aligned}Q_t = {} & \alpha_1 Q_{t-1} + \alpha_2 Q_{t-2} + \cdots + \alpha_{nq} Q_{t-nq} \\ & + \beta_1 f_1[R_{t-1}] + \beta_2 f_2[R_{t-2}] + \cdots \\ & + \beta_{np} f_{np}[R_{t-np}] + \cdots \gamma_{nt} g_{nt}[T_{t-nt}]\end{aligned}$$

Q_t daily mean discharge rate of the t-day from the spring

R_t daily values of recharge of the t-day

f_{np}, g_{nt} present non-linear function of influence daily recharge, on the flow rate Q.

In a karstic environment, assessing the effective infiltration rate (R) is closely related to the evaluation of potential and real evapotranspiration. Because of their simplicity, the Thornthwaite method for estimating potential evaporation was used (Thornthwaite 1948). The infiltration values (R) are obtained by calculating the rates between rainfall and evapotranspiration values by means of a daily budget. The computed values were also calibrated (slightly changing ratio between infiltration and evapotranspiration) to obtain a better fit between recorded and simulated values (Jemcov et. al 1998, 2001). From this calculation the annual infiltration values range from 27 to 35% for the Nemanja source, and 39 to 57% for the St. Petka source, depending on the water season.

On the basis of the inflow and outflow relationship, the values for changes in storage (ΔV_i) in the studied karst reservoirs were obtained by adding and varying the continuous cumulative values to the initial storage (Fig. 6). Thus, the state of water storage (karst accumulation) in the natural conditions is obtained through relationship $V_i = \Delta V_i + V_{i-1}$. The most sensitive part of this analysis is the estimation of initial storage. Knowledge of this particular parameter is strictly connected to the level of hydrogeological exploration, which should not be neglected, and could lead to underestimation or overestimation of possible exploitation capacity.

Fig. 5 Hydrograph separation of Grza spring

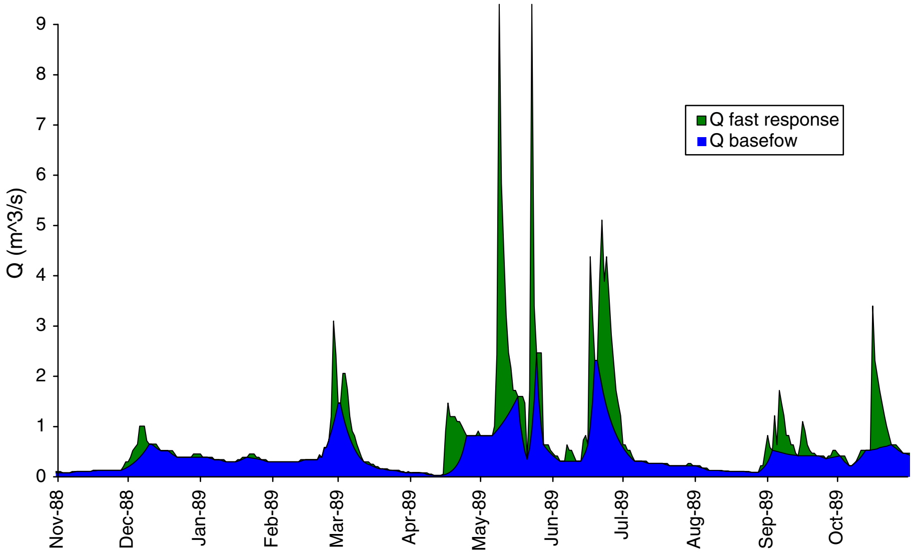


Fig. 6 Estimated volumes of water stored into karstic reservoir for Nemanja source

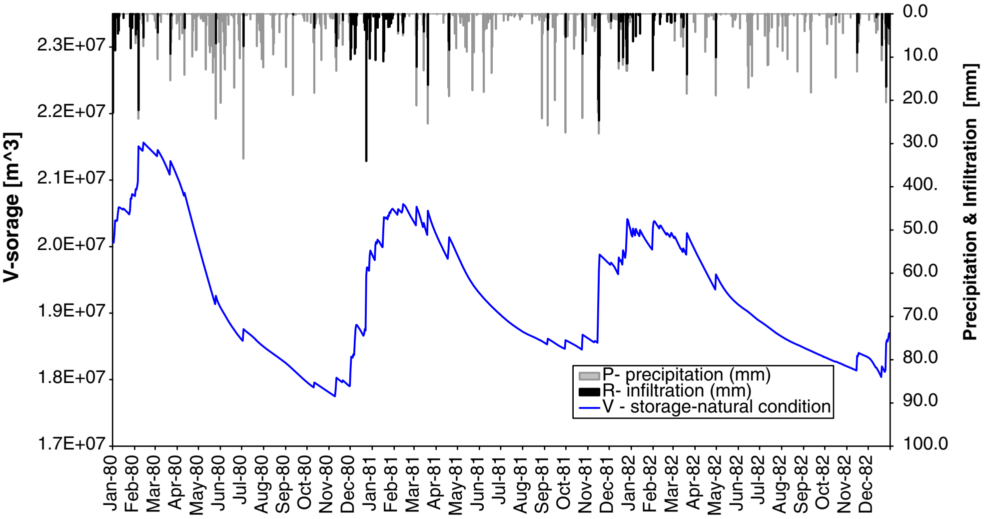
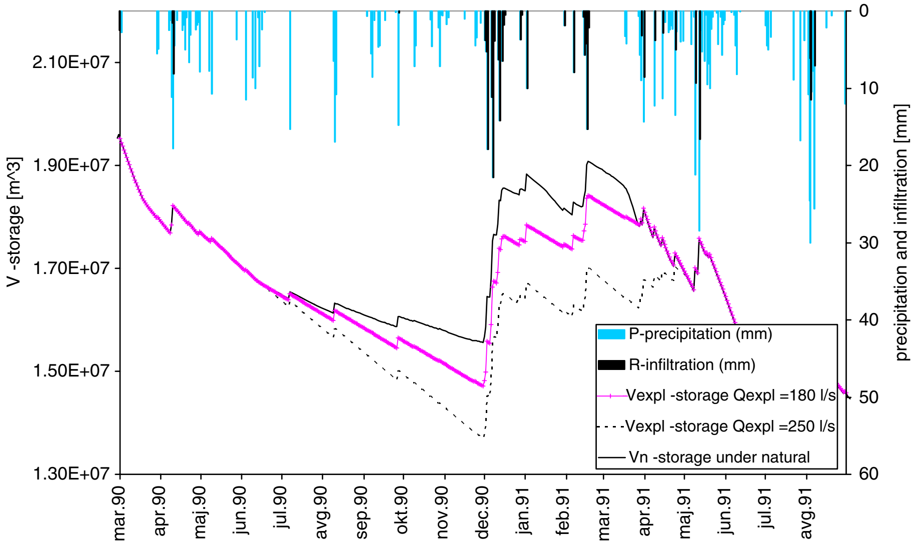


Fig. 7 Simulated exploitation rates of St. Petka spring



Establishing an optimal capacity

Using the estimated water resources stored in the karst aquifer under natural conditions as a baseline point, further analyses were conducted to assess the variations in storage under artificial conditions (exploitation potential, limits and optimal values) (Fig. 7). Considering that the concept of water tapping was based on a 'loan' from karstic reservoir storage, various exploitation scenarios were applied and tested. The optimal capacity does not mean avoiding overexploitation of karstic sources; thus, the rational exploitation demands respecting certain limitations, such as ecological limitations (i.e. the necessary minimal and sustained flows downstream of the tapped source, or 'Qecol') and a replenishment factor.

The results obtained through this analysis include a general characterization of, and proposed future withdrawal schemes from, explored karst sources. This is a significant contribution towards both feasibility studies and the definition of research programs to introduce sustainable management of karst aquifers.

Conclusions

It is demonstrated from several case studies that time series analysis is a very useful tool for the general characterization of karst aquifer systems, as well as for the assessment of effective infiltration rates and variations in accumulated resources under natural and artificial conditions. The applied concepts based on a karst groundwater budget provide valuable information about storage changes in karst reservoirs and further enable the prediction of optimal exploitation rates and facilitate karst water management.

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