Simulation of Karst Springs Discharge in Case of Incomplete Time Series

K. Katsanou · A. Maramathas · N. Lambrakis

Abstract The difficulty in measuring spring discharge in mountainous regions often leads to incomplete time series, which are of low importance. Instead, the complete time series enable to draw secure conclusions from the study of hydrographs. This article presents an innovative version of Modkarst model, which was originally developed to simulate the function of brackish coastal karst springs. Its originality is also related to its ability to complete time series and to give estimates with respect to important parameters of the karst aquifers, such as the storage coefficient and the extent of a spring's recharge area. The new model, based on the fast and slow flow concept, uses two tanks instead of three and an appropriate modified system of equations from the initial one. Its inputs are time series of daily rainfall, while the model fitting requires discharge values. Its application area, Louros River basin, is a mountainous area consisting of 10 significant springs with yields varying between 0.07 and 3.4 m^3/s, each of which discharges a hydrogeological karst unit. The validation of the model was accomplished by testing the accuracy of its results against a complete time series. Additional outputs, such as the estimated physical parameters, coincide with the outcomes from the hydrogeological investigation, thus confirming indirectly the code's accuracy.

Keywords Hydrological models · Spring hydrographs · Greece · Louros

1 Introduction

In recent decades the rapid evolution of computers prompted research in numerical methods for the modelling of natural phenomena. A large number of models can be now used to simulate groundwater flow and transport in order to solve problems related to groundwater movement and aquifers' contamination. Because of high karst heterogeneity no model is yet capable of simulating the whole aquifer, unless by making drastic simplifying assumptions (Groves et al. 1999). Thus, the karst system may be represented by either an equivalent porous

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medium or a fracture network or a network of conduits or by a combination of them (Dassargues and Brouyère 1997; Király 1998; Halihan et al. 2000; Worthington et al. 2000; Ghasemizadeh et al. 2012).

Karst flow models may simulate hydraulic heads, groundwater fluxes and springs' discharge, while transport models simulate the transport and distribution of substances (Scanlon et al. 2003). These models belong to two categories: i) physical or mathematical models and ii) lumped or global models (Kovács and Sauter 2007). The mathematical models that are also called distributive models are identical to both porous or continuous and discontinuous (fractured) media. They are now able to represent the flow conditions in a conduit-and-fracture network through a porous matrix, but they require a large amount of input data including much of a system's internal information. Hence, these models have been mostly applied in small catchments, which have been extensively studied. Gallegos et al. (2013) successfully applied, instead of MODFLOW model that simulates laminar flow, its new version (MODFLOW-CFP) which was transformed properly by USGS (Shoemaker-Barclay et al. 2007) to simulate laminar and non laminar flow in karst aquifers. In comparison, the global models that exploit discharge values are applicable at every scale though their predictive capability for time series is quite small. "Grey box" approaches belong to the global models. They consist of a series of reservoirs, aiming to represent the real processes and the storage that take place within a karst system. They are an alternative way to incorporate specific karst processes instead of using a distributive model that demands a large number of data.

Following Teutsch and Sauter (1991; 1998), the distributive models can be divided into five different approaches according to the geometric nature of the conductive features that they represent: the Equivalent Porous Medium Approach, the Double Continuum Approach, the Discrete Fracture Network Approach, the Discrete Channel Network Approach and the Combined Discrete-Continuum (Hybrid) Approach.

The global models use the springs' discharges that are related to the precipitation. The transformation of a precipitation event to karst spring's discharge depends on the morphological and geological features of the whole catchment area. Hence, the springs' hydrographs incorporate the properties of the surface catchment, the unsaturated zone and saturated zone of the aquifers. The necessity of the discharge data treatment led to the development of the global or lumped models, namely the black and grey box models. The reference of the colour represents the level of differentiation within the model. They do not use a spatial discretisation of the aquifer into meshes, but interconnected box reservoirs to represent the routing and storage of water. Therefore, the relationship between an input and an output signal of the system is expressed by these relationships without explaining the physical processes (Bezes 1976; Barrett and Charbeneau 1997; Long and Derickson 1999; Perrin et al. 2003). The lumped parameters are usually included in a mathematical analysis related to the temporal variations of springs' discharge (hydrographs) or chemical composition (chemographs). Some of these techniques combined with other exploitation methods may be used to: a) estimate the hydraulic parameters and conduit spacing, b) give information required for distributive flow models, c) give an understanding of the overall water budget in the karst system and d) interpret the groundwater chemistry (Kovács 2003). These models are distinguished into single event and time series analysis models (Kovács and Sauter 2007).

The single event models refer to and are based on the analysis of hydrographs. On the other hand time series analyses investigate the evolution of data through time, as well as the relationships among them. The univariate or bivariate methods were used for the characterization of the karst springs' reservoirs (Pulido-Bosch et al. 1995). However, the use of time series analysis is much wider, as shown by Alexakis and Tsakiris (2010), who evaluate the drought impact on annual water potential of Almyros karst spring. They studied both water

quantity and quality variations, using a gross annual water balance model. Drought years were represented by the use of the Reconnaissance drought index (RDI) (Tsakiris et al. 2007).

The predictive capability of the rainfall – runoff models is not obvious. According to Teutsch and Sauter (1998), the application of distributive models involves high prediction uncertainty in case of point observations treatment. In order to represent correctly a karst system, its discretisation into homogeneous subunits, each of which has its own hydraulic parameters, is required. The determination of these hydraulic characteristics is a costly and time consuming procedure. On the other hand, predictions treating integral observations, such as spring responses to rainfall, involve lower prediction uncertainty, mainly in the case that input is integral (e.g., rainfall in small spring catchments). Kovács and Sauter (2007) suggest that the predictive capability of global models is limited if they do not account for the laws of physics and the spatial structure of the catchment. Time series models are not directly related to physical parameters and fail to incorporate the temporal and spatial distributions of rainfall that may affect the statistical parameters. Therefore, the use of the appropriate model depends on the objective of the research, the availability of the data and the structure of the karst system (Teutsch and Sauter 1998).

The aforementioned global models require complete times series of input data that are rare for most of the areas worldwide. The lack of such data in ungauged areas was overcome during the early ages by their calculation. For the completion of missing data, Cai et al. (2014) proposed a distributed hydrological model driven by multi-source spatial data to estimate precipitation, potential evapotranspiration, air temperature, vegetation and soil parameters to reduce dependence on conventional observations. Pérez-Martín et al. (2014) presented a conceptual distributed water balance model that calculates runoff for medium to large river basins based on monthly precipitation and temperature time series. It uses basin properties as land-use, terrain slope, etc., while the parameters of the model are derived from a calibration of the basin's characteristics within each cell. Durga-Rao et al. (2014), aiming to calculate the runoff of the Godavari basin in India, transformed the simple and well known Thornthwaite Mather model by coupling the potential evapotranspiration and the land use within a GIS framework. Diodato et al. (2014) proposed a statistical model to assess monthly historical discharge, even when hydrological data were discontinuously available.

The objective of the present study was the development of a model able to complete successfully and exploit karst springs' sporadic discharge measurements in Louros karst system. For this purpose, Modkarst model (Maramathas et al. 2003) was chosen and properly revised.

2 Selection Criteria and Description of the Model

The main criteria of the model selection are its simplicity to be used and properly transformed in order to aid the completion of the discharge time series consisting of sporadic data. Additionally, it is based on a simple conceptual model of a double porosity continuum medium, one of relatively small hydraulic conductivity but of high storativity (e.g., fissures) and one of high hydraulic conductivity but small storativity (e.g. interconnected conduits). The model incorporates the features of global models, while, at the same time, it is not a "Black box" one (Maramathas et al. 2003). It is a deterministic model as each of its parameters has an exact geometric or physical meaning and was initially developed to simulate brackish or periodical brackish karst springs. In this study an innovative revision of this model, which successfully simulates inland karst springs, is presented. The tank of the sea that was used in the previous version was omitted and the two remaining, connected to appropriate pipes, lead

to the spring's outlet (Fig. 1). The equations related to this tank of infinite size were excluded as well as all the related parameters, i.e. the springs' elevation, the depth of the intersection between the sea and the fresh water tubes, the sea and the fresh water density, etc. The model does not require much fieldwork data, while all its parameters can obtain an average value from the fitting process. The input data of the model is precipitation, which is transformed to effective by the use of an infiltration coefficient. This coefficient can be taken as constant or even calculated from the determination of the effective precipitation, which can be derived from the difference between precipitation and the total deficits, i.e. retention water, real evapotranspiration and run-off. These deficits are calculated from precipitation by the use of coefficients that result from the fitting of the model. The code can relate them to basin and precipitation characteristics, i.e. the elevation, the slope, the intensity of the precipitation and the season, as in other models (Pérez-Martín et al. 2014).

Table 1 is a brief presentation of the used equations. Their identical application to both tanks leads to a system of non-linear differential equations. The code solves this system and calculates the tanks' discharge.

The first tank corresponds to a medium of high hydraulic conductivity but small storativity (e.g. interconnected conduits), while the second to relatively small hydraulic conductivity but high storativity (e.g., fissures). Therefore, the first tank (karst 1, Fig. 1) simulates the function of the system's macro conduits and is discharged directly to the spring's outlet. After a certain rainfall event the level rises quickly, reaching a maximum that depends on the amount of rainfall and the reservoir characteristics, and drops relatively quickly as the tank is empting. The tank stops its function when the water level reaches the spring's outlet level. The flow is considered non steady and turbulent. Particularly, this tank serves the simulation of the hydrograph peaks. It mainly simulates the upper part of the concentration curve and most of the depletion curve of the hydrograph. The second tank (karst 2) simulates the micro conduits and corresponds to the part of the system, which is discharged slowly. The flow in this tank is considered as non steady, and, if not turbulent, is probably out of Darcy's Law validity range. This tank contributes mainly to the simulation of the recession curve. Thus, the overall spring's discharge is the sum of the two tanks.

The model does not match any of the aforementioned categories. It uses the general macroscopic mass and energy balance equations of fluid mechanics in order to describe flow in conduits and fissures in a Double Continuum (DC) approach medium.

The first numerical solution using the DC approach was provided by Teutsch (1989). In such a model the interconnected conduit network and the fissured or medium matrix are both represented by continuum formulations. The exchange of water and solutes between two interacting continua is calculated, based on their difference in hydraulic head, using a linear exchange term. The DC Concept is able to describe adequately the dual behaviour of the karst
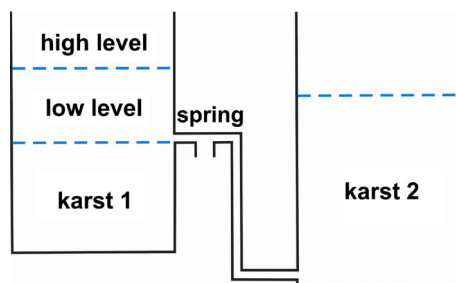
Fig. 1 Hydrodynamic model of the karst springs

Table 1 System equations

Karstic subsystems equations	Variables
$sS_1\frac{dH}{dt} + Q - \gamma PS_1 = 0$	Q: Karst system discharge (L^3/T)
	H: Effective water table elevation of the spring's reservoir (L)
	Parameters
$sS_1 H\frac{dH}{dt} + \frac{Q^3}{2gS_2^2} - H\gamma PS_1 + L\left[\frac{Q}{sS_1}\right]^2 Q = 0$	P: Rainfall (L/T)
	s: Storage coefficient
	S$_1$: Recharge area (L^2)
	γ: Infiltration coefficient
	g: Gravity (L/T^2)
	S$_2$: Karst system outflow tube cross-section (L^2)
	L: Energy loss coefficient (L^{-1} T^{-2})

aquifers. It simply has to be kept in mind that the distributions of the hydraulic parameters are the average of the real parameters that are normally provided by calibration.

The model adds understanding of the karst function and structure by estimating the variation of the mean effective water level, the extent of the recharge area, the storage coefficient and the completed discharge time series (Table 2). It deepens further than those governed by energy loss laws, like Darcy's law, so it can take into account linear or non-linear losses. Therefore, its performance is adequate in all flows, laminar to turbulent, regardless of the Reynolds number. This is very important since the flow in karst formations is mostly out of the range of Darcy's law. All the parameters of the model are lumped. Within a largely heterogeneous medium this implies that the estimated parameters are not spatially differentiated, thus summarising information for the whole karst aquifer system. This is advantageous provided that the interest of the simulation, and thereafter the exploitation, focuses on the springs' outlet that is related to the whole karst system.

Model calibration is performed by the application of the least squares combined with the Newton-Raphson optimisation method by the following equation:

where:

$$\sum_{t=1}^{D}\left[\left(Q_{Mt_t} - Q_{F_t}\right)^2\right] \tag{1}$$

Q_{Mt_t} the estimated discharge values

Q_{F_t} the measured discharge values for a period of time (D). The calibration modules estimate the values of the parameters so that the Eq. (1) gets the minimum value.

## 3 The Hydrogeological Setting of the Study Area

The Louros mountainous basin is formed by 10 karst individual subsystems, which are discharged through 10 major springs (Table 2, springs 1–10) and covers an area of 400 km^2 (Katsanou 2012). Geologically, the study area is hosted in the formations of the Ionian geotectonic zone (Katsikatsos 1992) (Fig. 2).

Its limits are defined by the flysch outcrops at the western and the Ziros-Zalongo fault zone at the southern margin (Fig. 2). The southern, eastern and northern limits were determined by stable isotope analyses and hydraulic load distribution maps (Leontiadis and Smyrniotis 1986; Katsanou 2012). The Pantokrator and Upper Senonian limestones are considered to be

Table 2 Results of the MODKARST application in the springs' discharge data

Parameter		Melligoi	Viros	Mousiotitsa	Sykies	Kerasovo	Vathi	Omorfada	Ag. Georgios	Ziros	Kouklesi	Skala*
Effective water table elevation of the spring's aquifer (m)	Min	0	0	0.3			11.2	158.9	0.5	0	0	0.07
	Max	51	14	16.5			85.4	394.7	26.8	21.71	21.71	16.25
	Mean	9.8	4.97	6.23			46.3	279.8	12.6	7.33	7.33	65.16
Area (km^2)		7.7	38.5	18.1	6.26	22.9	79.19	31.4	151.1	35.0	4.81	151.1
Storage coefficient		6.28E-03 3.57E-07	4.00E-02 1.84E-07	5.0E-02	2.04E-05	1.4E-04	6E-03	2.5E-03	3.4E-04 2.4E-06	2.4E-02	1.64E-02	5.2E-03 3.6E-06
$\overline{Q}_{(1980)}$ (m^3/s)										0.08	0.11	
$\overline{Q}_{(1981)}$ (m^3/s)										0.09	0.11	
$\overline{Q}_{(1982)}$ (m^3/s)						0.54	1.77			0.07	0.09	3.20
$\overline{Q}_{(1983)}$ (m^3/s)						0.55	1.71	0.69				3.02
$\overline{Q}_{(1984)}$ (m^3/s)		0.14	0.90	0.46		0.41	2.07	0.77				3.40
$\overline{Q}_{(1985)}$ (m^3/s)		0.15	0.71	0.33	0.16			0.59	2.86			3.07
$\overline{Q}_{(1986)}$ (m^3/s)		0.15			0.17				3.07			
$\overline{Q}_{(1987)}$ (m^3/s)				0.12					2.69			
$\overline{P}_{(1980-1987)}$ (m)**		1.45	1.40	1.49	1.77	1.46	1.67	1.39	1.49	1.92	1.44	1.45
$\overline{I}_{(1980-1987)}$ (%)***		0.41	0.47	0.46	0.43	0.47	0.44	0.49	0.40	0.38	0.42	0.46
$\overline{Q}_{(2008)}$ (m^3/s)		0.12	0.67	0.40	0.12	0.42	1.42	0.71	2.51	0.06	0.07	4.3
$\overline{Q}_{(2009)}$ (m^3/s)		0.33	1.84	0.55	0.20	0.69	2.16	0.80	4.04	0.11	0.12	
$\overline{Q}_{(2010)}$ (m^3/s)		0.32	1.69	0.71	0.20	0.71	2.36	0.84	4.31	0.12	0.13	

*Springs located outside the mountainous basin of Louros River. **: Mean Annual Precipitation, ***: Mean Infiltration
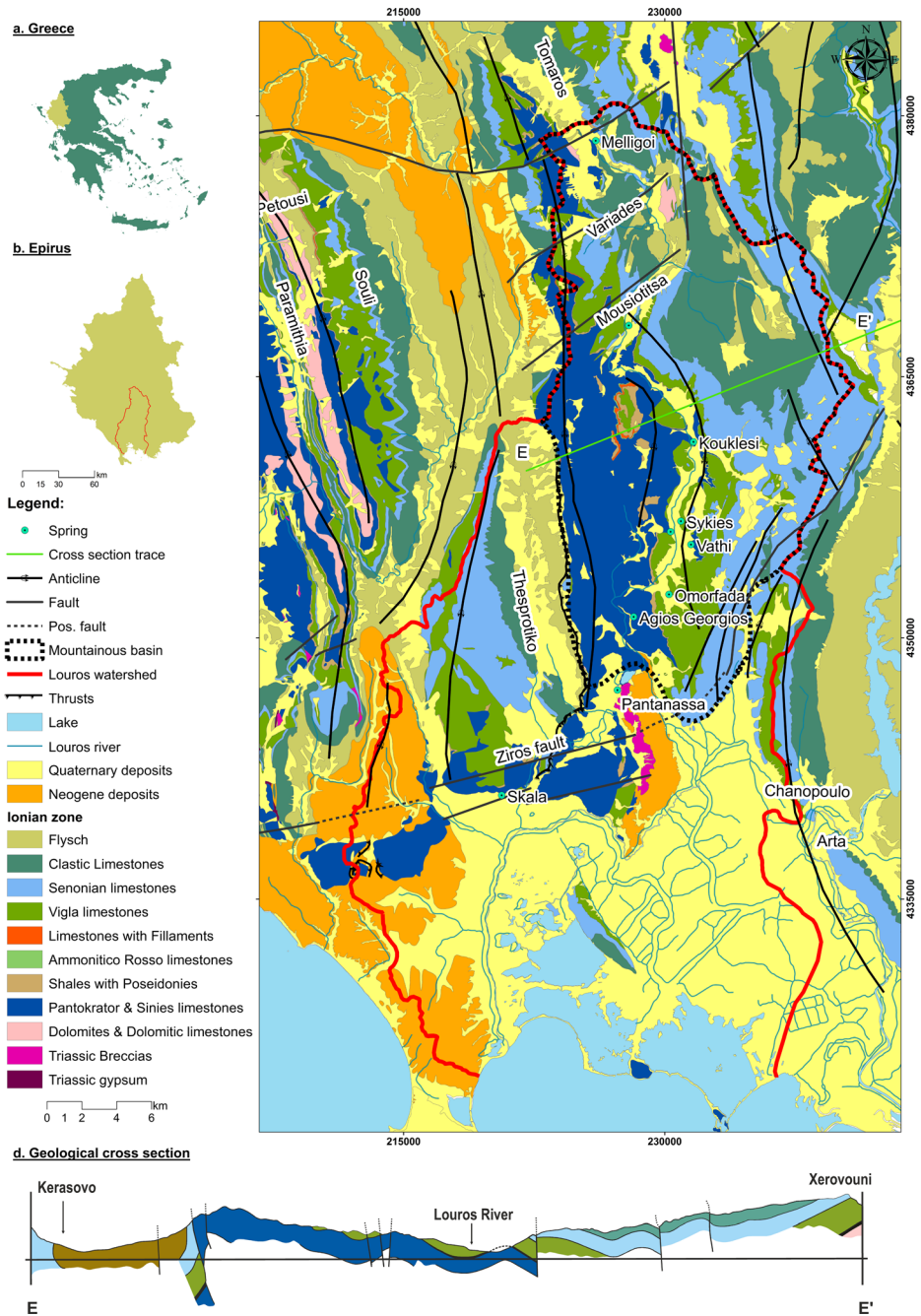
Fig. 2 The geological map of the study area

permeable. Eocene and Vigla limestones are considered of low permeability. In the case where Vigla limestones underlie limestones of high permeability, such as the Senonian ones, they act as an impermeable layer (Smyrniotis 1991). The springs that discharge in the middle part, at

similar elevations along Louros bank, contribute to the formation of the most important aquifer of the area. It is developed in the granular sediments and their surrounding carbonate rocks. A detailed study of the hydrogeological balance (2008–2010) carried out by Katsanou (2012) led to the estimation of the real evapotranspiration (33 %) and the karst formations' properties, such as the storage capacity, which exceeds 1 % and is considered as high.

4 Results and Discussion

In the broader area 11 major karst springs were monitored during the past years (Table 2). For these springs, sporadic daily measurements within a month and for several years (1982–1987) were available. Ten of them (Table 2, springs 1–10) belong to the mountainous area, while the last one (Table 2, spring 11) is located in the lowlands, at the margins of the basin, and is subjected to similar hydrogeological conditions as the previous one. This spring is accessible and gauged, and, therefore, is characterised by high quality data and extensive recordings. Apart from the initially available time series, at this spring daily discharge measurements were also carried out during 2008–2009. Therefore, it was used to assess the overall performance of the model. For all the other springs the calibration was based on the available period of records. The main advantage of calibrating over the available period is that the most optimum calibration for this data can be achieved. The problem that derives from this procedure is that there is no indication of the performance of the model outside the range of the calibration period, i.e. how robust is the model. For this reason, it is not the recommended approach for calibrating a model. However, under certain circumstances, where there is only a small amount of data, there might be no other option than to use the entire period. In this case the robustness of the model should be checked by other criteria, for example, how close the parameters' values are to the physical ones. This method was applied to the 10 springs for which the short period of existing measurements restricted a secure validation.

The application of the model, after optimum fitting using the equation (1), led to the calculation of the modeled hydrograph. In Fig. 3, an example of the performance of the model is given. As can be seen, the real and the modelled hydrographs are similar, indicating that the model is performing well.

The effectiveness of the model, and especially its prediction capability, was tested against measured values. In Fig. 4 similarities between the predicted and the measured values are obvious.
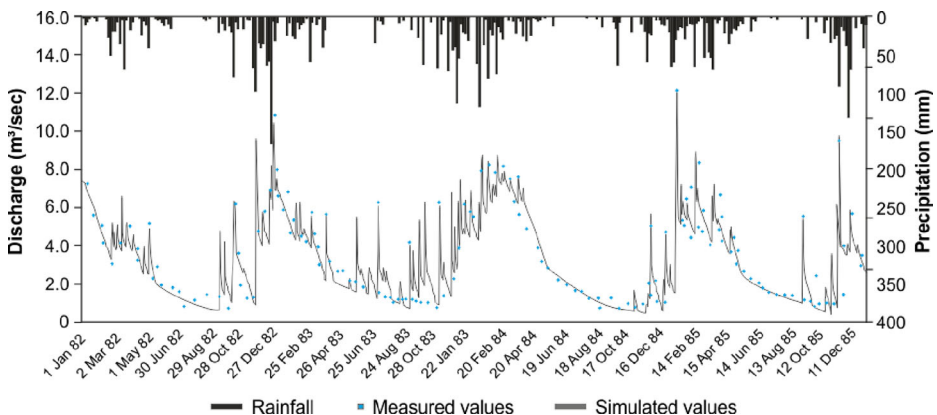

Fig. 3 The hydrograph of Skala
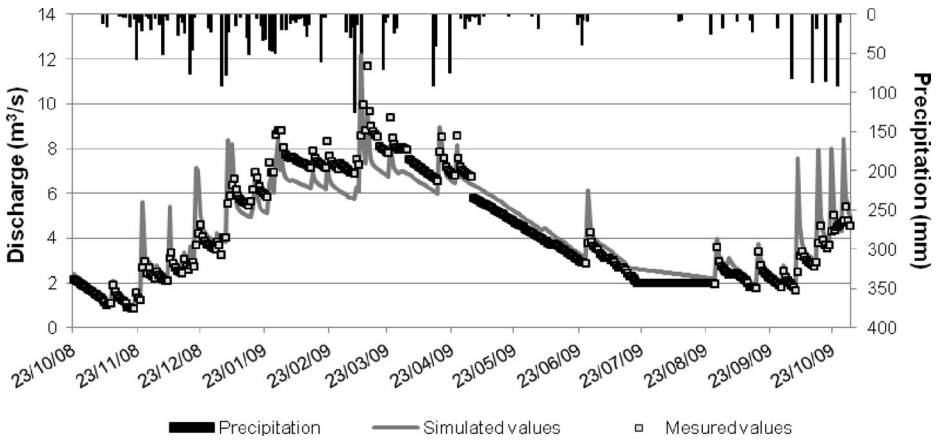
Fig. 4 Measured against simulated values of Skala spring

The validation of the model could also result from indirect methods. The simulation results after calibration are shown in Table 2, which presents the estimated values for the effective water elevation (m), the catchment area (km^2) and the storage coefficient (%). All estimated parameters lie within acceptable ranges (Table 2). It is worth mentioning that the extent of the mountainous area derived from the model, as a sum of the subcatchments, coincides with the one derived from the hydrogeological survey (400 km^2). This also confirms the good performance of the model, which was mainly used for the completion of missing values of the spring's discharge.

The methodology of the flow duration curves in studying the hydrological features of a catchment can be applied to many different situations; e.g., in order to identify the best water management practice, to evaluate flow data quality control, to design hydropower plants, etc. (Liucci et al. 2014). In the present study, they were used to check the performance of the model for both the measured and simulated data, i.e. average and extreme values. The data were distinguished into 10 classes of magnitude. As can be seen in Fig. 5, there is a good fit between
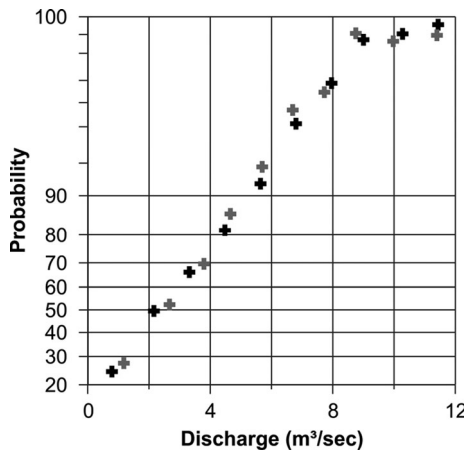
Fig. 5 Duration curves of the modelled (*black* symbols) and the observed (*grey* symbols) of the Skala discharge values for the period 1/1/1982-11/12/1985

the duration curves of the measured and simulated data verifying that the results were satisfactory for all discharge classes.

The sensitive analysis tests proved that there is no strong correlation among the parameters. The most sensitive is the storage coefficient which is considered to be precise, while others lie within the acceptable range.

5 Conclusions

The present study proposes a simple and effective model to complete the missing discharge time series data of inland karst springs. Its performance is based on the representation of the highly heterogeneous karst aquifers using two tanks of fast and slow flow connected to appropriate pipes that lead to the spring's outlet. The model is advantageous over others as it provides simplicity, demanding only precipitation and discharge data, while all its variables and parameters result from the fit of the model. It performs satisfactorily for all classes of data, indicating that the springs' discharge could be properly simulated by applying the mass balance and energy balance equations. The model innovates against others in the estimation of the lumped parameters of the karst aquifers. Therefore, this new approach is important in achieving a better flow prediction and gaining insight into the flow transfer mechanism, which is essential for the management of such aquifers.

The model was applied for a large number of springs of Louros uniform karst system, which is dominated by carbonate rocks of different properties. The results of the application showed that the model can be successfully used in other karst terrains for providing simulation of springs' missing data. Its function is satisfactory even with limited data, though the occupancy of data increases the efficiency of the model.

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