Groundwater balance estimation in karst by using simple conceptual rainfall-runoff model

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1) Research motivation

- Investigation of groundwater regime at Opačac karst spring (Figure 1.) and overcoming problems of limited amount and type of data
- How to use known verified methods for parameterization of proposed conceptual model
- Karst spring hydrograph can reflect the groundwater regime and consequently the analysis is based on them

Figure 1. Opačac spring

2) Study objectives

- Soil-moisture and groundwater balance method simulating discharge flow of karst spring
- Minimizing the fitting parameters by preliminary hydrograph analysis: base flow index (BFI), recession curve coefficient and effective rainfall (Palmer's method)
- Sizing a karst's spring recharge area
- Evaluating simulation results with time series analysis

3) Data sets

- Inputs – measured discharge from spring Opačac and two nearby water gauges (WG) - Kamen most and Šumet (see Fig. 2)
- DHMZ (Meteorological and Hydrological Service of Croatia) provided data for station Imotski

Table 1. Main characteristics of analysed station and gauges

Name	Observation	Analysed period	Daily values MIN	Daily values AVR	Daily values MAX
Imotski	precipitation (mm)	1995 - 2010	0	3.5	163
	temperature (°C)	1995 - 2010	-5.9	14.1	32.4
	humidity (%)	1995 - 2010	26	69.7	99
Opačac	discharge (m^3/s)	1995 - 2010	0.7	6.82	49.9
Kamen most	discharge (m^3/s)	1995 - 2010	0.45	7.84	61.5
Šumet	discharge (m^3/s)	1995 - 2010	Dry	0.6	11.6

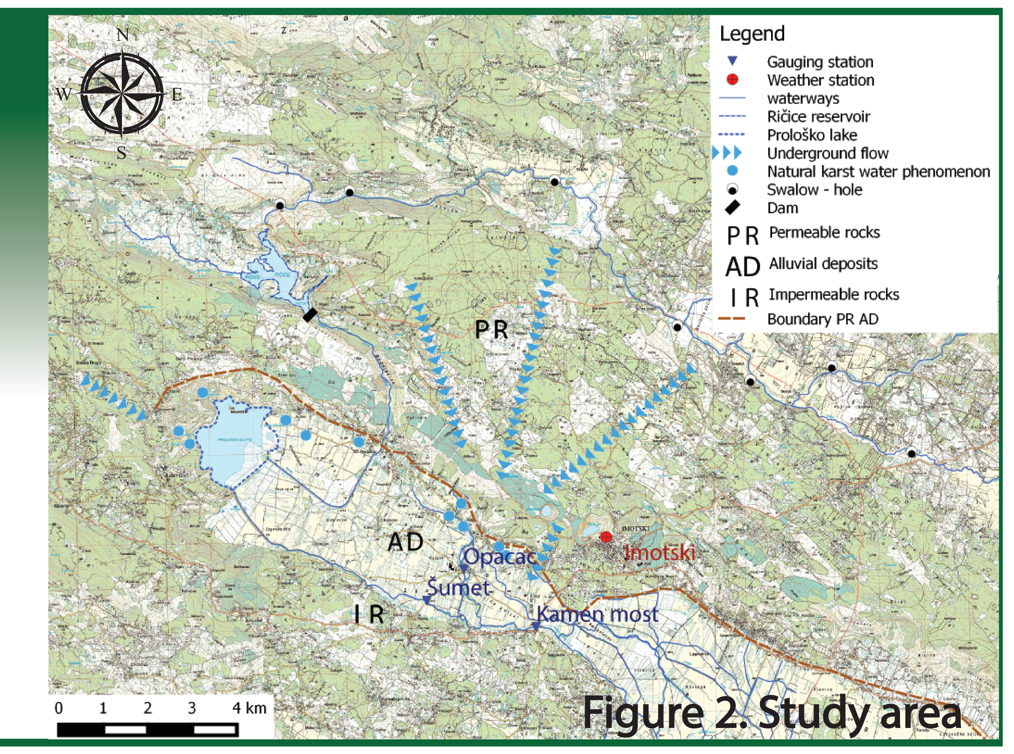

Figure 2. Study area

4) Conceptual model

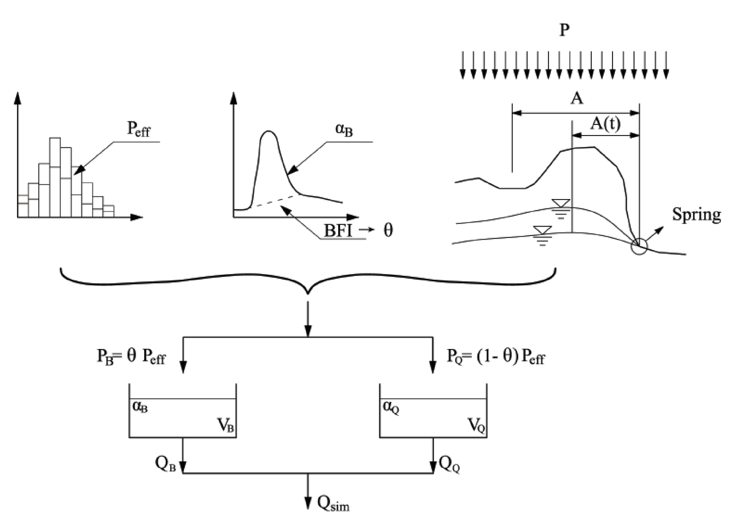

Figure 3. Conceptual model

- Lumped grey model (Fig. 3) – part of behaviour is understood
- Parameter estimation procedure merges soil-moisture balance and groundwater balance approaches to obtain complete groundwater budget
- Parameters used in lumped models are not directly measurable – calibration is required
- Parameters are therefore chosen by their ability to describe hydrological processes as realistical as possible

$$Q_{sim,b}(t) = Q_{sim,b}(t-1) \times e^{-\alpha_b} + \theta \times R(t) \times (1 - e^{-\alpha_b}) \quad \text{(Eqn. 1)}$$

$$Q_{sim,q}(t) = Q_{sim,q}(t-1) \times e^{-\alpha_q} + (1-\theta) \times R(t) \times (1 - e^{-\alpha_q}) \quad \text{(Eqn. 2)}$$

$$Q_{sim}(t) = Q_{sim,b}(t) + Q_{sim,q}(t); \;\; R(t) = P_{eff}(t) \times A(t) \quad \text{(Eqn. 3 and 4)}$$

where:

$Q_{sim,b}(t)$ - base flow
$Q_{sim,q}(t)$ - quick flow
R(t) - recharge
$P_{eff}(t)$ – effective rain (Palmer's method)
A(t) – recharge area as time depended variable (monthly variation)
α_b – recession coefficient for base flow (obtained from hydrograph analysis)
α_q – recession coefficient for quick flow (simulated)
θ – base/quick flow ratio - presumed to be equal to BFI

- Simulated discharge is expressed by two-part equation representing reservoirs for base flow (Eqn. 1) and quick flow (Eqn. 2)
- Linear reservoir method enables transformation of effective rainfall into runoff hydrograph
- The method is based upon hypothesis of aquifer reservoir behaviour – volume of groundwater recharge is linear to runoff

5) Simulation and calibration

- Calibration process is done manually (defining varibale range) and automatically by computer software (finding maximum coefficient of efficiency)
- After flow simulation (Fig. 4) for various range of unknown or uncertain variable, Nash-Sutcliffe coefficient (CE) is used to estimate success of simulation (Table 2.)
- $S1_{max}$ and $S2_{max}$ in Table 1. are values for maximum capacity of surface (S1) and subsurface (S2) vegetation layer

Table 2. Results of calibration

	$S1_{max}$	$S2_{max}$	α_q	θ	CE
α_q [0.1,0.5]; θ [0,1]	0	10	0.1	0.66	0.6379
	0	120	0.1	0.66	0.8243
	10	10	0.1	0.66	0.7549
	10	120	0.1	0.66	0.8151
	20	10	0.1	0.66	0.7724
	20	120	0.1	0.66	0.7964
α_q [0.1,0.2]; θ [0.6,0.7]	0	10	0.13	0.62	0.6444
	0	120	0.1	0.65	0.8248
	10	10	0.12	0.63	0.7575
	10	120	0.1	0.66	0.8171
	20	10	0.11	0.64	0.7727
	20	120	0.1	0.66	0.7997
α_b = 0.006	0	120	0.1	0.65	0.8210
α_b = 0.008	0	120	0.1	0.65	0.8251

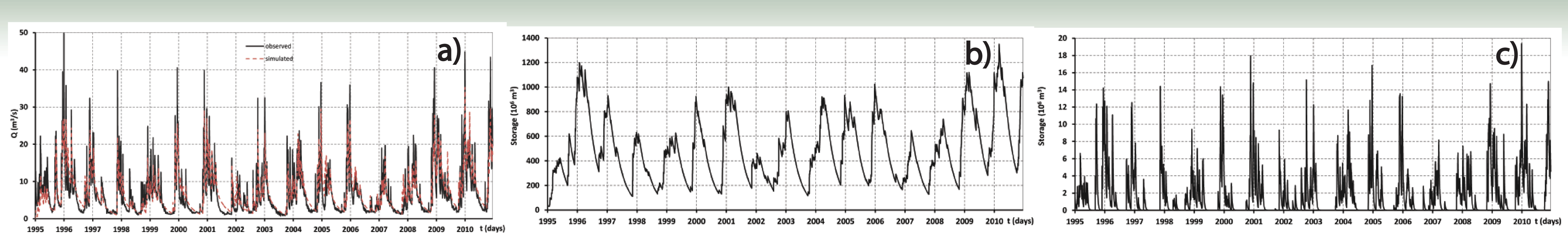

Figure 4. Model results: a) discharge simulation; b) groundwater storage from base flow; c) groundwater storage from quick flow

6) Time series analysis

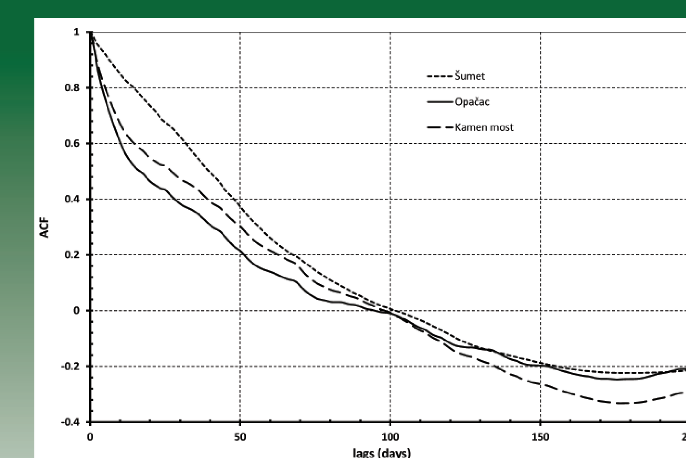

Figure 5. Autocorrelation function

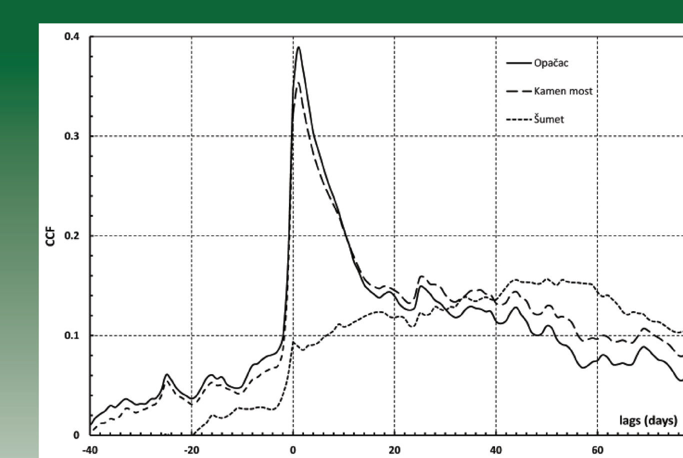

Figure 6. Cross-correlation function (CCF)

- Identifcation of periods is a key issue in hydrologic time series analysis
- Annual periodicity is visible and system memory is very long (100 days) but no distinguish lump to determine quick flow in autocorrelation function (Fig. 5): can be an indicator of prominent base fow determined with model
- Cross-correlation function (CCF, Fig. 6) shows weak output response with value of 0.35 for spring Opačac and slightly below (0.32) for gauge Kamen most. Stream Sija (WG Šumet) has slow and low (0.09) response and its homogeneity is indication of absent quick flow. Low CCF values assume main contributor of the flow to be further north (across country border)

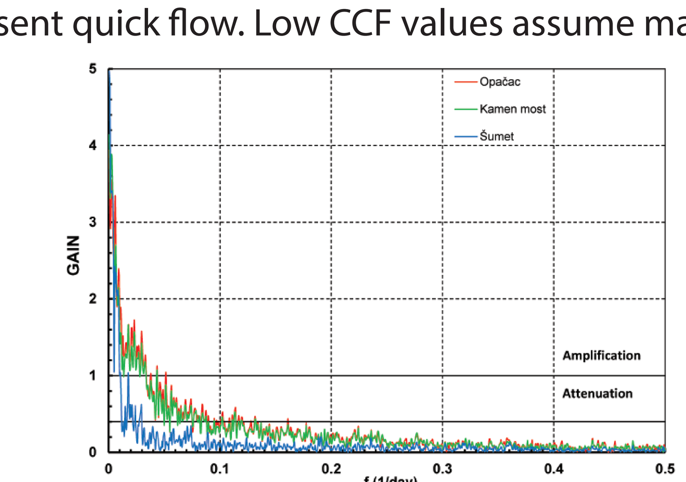

Figure 7. Gain function shows strong fltering and attenuation

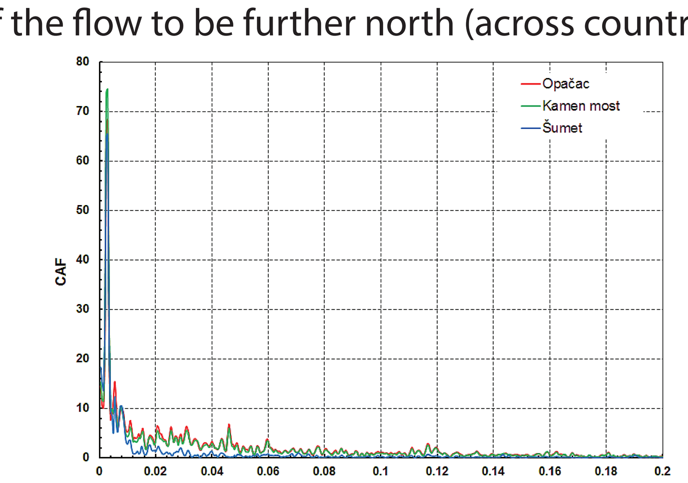

Figure 8. Cross-amplitude function (CAF) suggest infuence of quick flow is very small

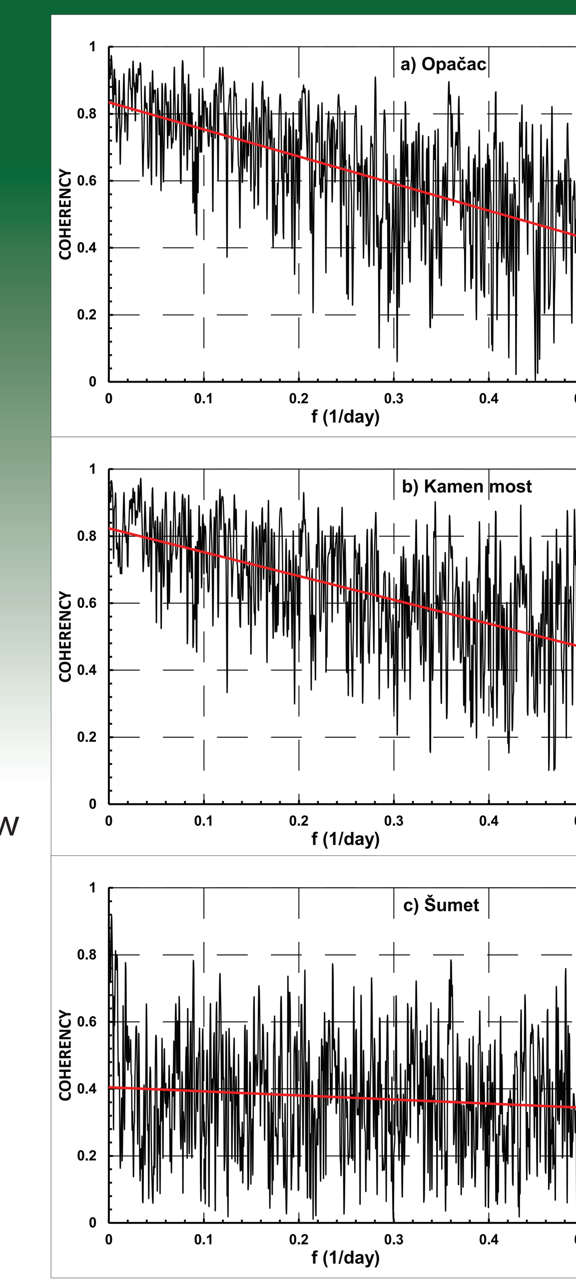

Figure 9. Coherency function for WG (average value in brackets): a) Opačac (0.63), b) Kamen most (0.65) and c) Šumet (0.37)

7) References

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8) Conclusions

- Conceptual models are good starting point for uninvestigated area
- Nash–Sutcliffe model efficiency coefficient shows sufficient predictive power of proposed model
- Model calculated signifcant amount of base flow
- Variety of numerical techniques have been applied (correlation, spectral analyses) to determine the relationship between the rainfall and response of the karst system - these systems can contribute to understanding behaviour of similar systems
- Interpretation of correlation and cross-spectral analyses may be used to identifcate the quick fow from the base flow
- The results of time series analysis showed that the aquifers of Opačac and Kamen most are highly karstifed and their flows are generated from the same recharge area
- The Sija aquifer (WG Šumet) is a case of a slightly karstified system, with a poorly developed karst network – it is assumed that most of effecitve rainfall recharges the main contributor of the river Vrljika, while river Sija has no evident underground connection