Journal of Hydrology (2008) **348**, 412–424

available at www.sciencedirect.com

ScienceDirect

journal homepage: www.elsevier.com/locate/jhydrol

A multi-model approach to the simulation of large scale karst flows

C. Makropoulos [a,*], D. Koutsoyiannis [b], M. Stanić [c], S. Djordjević [a], D. Prodanović [c], T. Dašić [c], S. Prohaska [d], Č. Maksimović [e], H. Wheater [e]

[a] *Centre for Water Systems, School of Engineering, Computer Science and Mathematics, University of Exeter, EX4 4QF, UK*
[b] *Department of Civil Engineering, National Technical University of Athens, Greece*
[c] *Faculty of Civil Engineering, University of Belgrade, Serbia*
[d] *Jaroslav Černi Institute, Belgrade, Serbia*
[e] *Department of Civil and Environmental Engineering, Imperial College London, UK*

Received 20 February 2007; received in revised form 25 September 2007; accepted 8 October 2007

KEYWORDS
Black-box models;
Conceptual models;
Impact assessment;
Karstic hydrology;
Multi-modelling;
Physically based models

Summary The possible effects of water transfer through a tunnel from Fatničko Polje to Bileća Reservoir on the hydrologic regime of the Bregava River located in Eastern Herzegovina, in an area characterised by a predominantly karstic terrain, are studied. Three different simulation models of the area were developed and their predictions compared under a range of current and future hydrological and operational management conditions. These are based on a range of modelling approaches from a simplified conceptual approach to a quasi-physically based one. Despite the large complexity of the natural system, the models gave good fits to existing flow data with the most simplified model providing the closest agreement to historical flows. Calibrated models were used to study the possible effects of the intervention under a range of operational scenarios and identify the sources of the associated uncertainties. The results of the work suggest that the system of tunnels in question has a favourable effect in reducing flood hazard in the area, thus liberating scarce land resources for agriculture, and in reducing flows in the Bregava River (especially high flows). It is also suggested that a significant reduction in the uncertainty of modelling the karstic environment can be achieved by an appropriate, complementary combination of modelling approaches viewed as a multi-model ensemble.

* Corresponding author. Tel.: +44 1392 264049.
E-mail address: c.makropoulos@exeter.ac.uk (C. Makropoulos).

0022-1694/$ - see front matter
doi:10.1016/j.jhydrol.2007.10.011

Introduction

General

This study investigates the possible effects of a water transfer scheme on the hydrologic regime of the Bregava River in Eastern Herzegovina, in an area characterised by a predominantly karstic terrain (complete details, including an extensive presentation of data, models and results is included in ICCI (2004), available online). The system is complex, and data are limited, hence the study uses different modelling approaches to assess the robustness of management decisions in the face of system uncertainty. Since the primary objective was to assess the impact of the water transfer scheme on the hydrologic regime, given limited system information, the intercomparison of methods, focussed on criteria for the overall behaviour of the models, rather than on their performance with respect to the detail of the system representation.

Flow in the karstic zone represents one of the most complex hydrologic phenomena. The area studied is characterised by *karstic depressions* or valleys (poljes) connected by a system of karstic conduits. Poljes are flat and fertile, usually a few hundred meters wide and one or two kilometers long or more. Water enters the poljes through *karstic springs* and leaves them through *swallow holes* (ponors) which represent the exit and entrance of karstic conduits, respectively. The function of karstic conduits (including quantity and direction of flow) is complex and subject to extreme seasonal variations, including flow reversals (for example Albéric, 2004). The relevant literature, on both conceptualising karstic conduits, particularly when aquifer hydraulic parameters are limited, as well as comparing numerical versus statistical approaches in modelling their responses is growing (see for example Eisenlohr et al., 1997a,b) and recent work has concentrated, *inter alia*, on the possibility of extracting quantitative information about the geometric and hydraulic aquifer parameters in karstic systems from spring hydrograph analysis (Kovacs et al., 2005). In any case, it is suggested that the complexity and uncertainty inherent in the representation of the karstic environment, particularly where data are scarce and may be unreliable, have significant implications in managing karstic aquifers and their water resources, particularly in terms of their vulnerability (Andreo et al., 2006; Vias et al., 2006).

Background to the study

The case study area is characterised by the existence of surface and underground karst phenomena, with little arable land. This study focused on two major catchments of the area, which are hydraulically connected through karstic conduits (Fig. 1): (a) the Trebišnjica River which is the biggest sinking river in Europe and regularly floods its poljes, rendering some of them unsuitable for human settlements and limiting possible agricultural exploitation and (b) the Bregava River, which in addition to its direct (topographic) catchment, is mainly fed through springs which originate from a karstic field (the Dabarsko polje — DP). Although the Fatničko polje (FP) belongs to the Trebišnjica catchment, seasonal water transfers take place between the FP and the Bregava catchment, regulated by a ''bottleneck'' in the karst downstream of the Dabarsko polje which limits the peak flows to the capacity of an underground system of fissures and larger karstic conduits (Fig. 1). The study dealt with the upstream part of the Bregava catchment (near the hydrometric station Do, near Stolac, see Fig. 1). Downstream of Do, the river flows mostly underground in periods of low discharge.

In the late 1950s a water management plan for the area was conceived, with the original objectives of hydropower generation and flood alleviation. This has evolved in a number of stages, involving the construction of tunnels, dams, and the installation of turbines. While part of the system downstream of the Bileća Reservoir (BR) is currently in an advanced stage of development, in the upstream region, a tunnel DP—FP has been constructed while a tunnel FP—BR is about to be constructed.

The two tunnels, at different development stages, form the hydrosystem, the impacts of which this paper attempts to study. Some basic characteristics of those two tunnels are:

- Tunnel Dabarsko Polje to Fatničko Polje (DP—FP): The tunnel is approximately 3.2 km long and was constructed in 1986. The flow is regulated at the downstream end of the tunnel by a vertical sluice gate, which is operational. At present (2004 — before the construction of the tunnel between Fatničko Polje and Bileća Reservoir) the operational rule requires that the gate should be closed only when the water level in Fatničko Polje is higher than in Dabarsko Polje.
- Tunnel Fatničko Polje to Beleća Reservoir (FP—BR): The tunnel is much longer than DP—FP (approximately 15 km) and also has a flow regulation gate at its downstream end. Under the present operational management framework it is to be kept open at all times.

The problem

Due to the existence of karstic conduits, linking DP and FP with both catchments, the operation of the two tunnels effectively links the two catchments and thus an assessment of the impact of their operation was needed. In particular a concern was that the operation of the tunnels would have adverse effects on the Bregava River, by lowering the low flows, and thus contributing to increased water scarcity in the Bregava catchment.

The approach

Evaluating the system's response was a particularly challenging process, in terms of data availability, data and system uncertainty, understanding of system operation, system modelling, results comparison and interpretation. The overall system is highly complex and poorly understood. Interventions in one part can have hard-to-quantify and widely variable effects on remote locations linked through underground karstic conduits. Furthermore, data were scarce and to a large extent unreliable, particularly since the regular monitoring programme was disrupted by the 1991—1995 civil war. The approach adopted was to employ a range of models,