Integrating Groundwater Models within a Decision Support System

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Abstract. An attempt is made to integrate groundwater models within a decision support system (DSS) called HYDRONOMEAS which is designed to assist large multi-reservoir system (MRS) management. This will help managing conjunctive use schemes. The DSS is currently used for the water supply of Athens, Greece. The simulated system is the Boeoticos Kephisos River Basin and its underlying karst. The karst supplies irrigation water locally as well as drinking water to Athens. Furthermore, the basin's surface outflows account for most of the inflow into Lake Iliki, one of the three main reservoirs of the Athens MRS. Three models of different levels of complexity are tested. The first model is a multi-cell model that simulates surface flows within the basin coupled to subsurface flows. The second model is a conceptually-based lumped model while the third model is a pre-existing distributed groundwater model based on the MODFLOW package. Tests with various management scenarios allow to draw conclusions regarding model efficiency and suitability for use within a DSS.

Keywords: Groundwater, multi-cell models, MODFLOW

1. Introduction

Nowadays, decision support systems (DSSs) in water resources management (WRM) are widely recognised as the primary tools that assist decision makers in their judgement (Watkins and McKinney, 1995). Modern DSSs allow for efficient gathering, organising, storage and processing of data, and they communicate the resulting information effectively through proper visualisation, e.g. using geographical information systems (GIS). Historically, DSSs for WRM appeared as stand-alone simulation or optimisation routines. To simulate water flows, a hydrosystem was represented by storage and conveyance elements (e.g. reservoirs and water-ways) for which inflow time series, whether they originate from surface or ground waters, are pre-computed and entered externally. However, in many cases, this becomes impossible due to decision-related interactions between surface and groundwater flows. A typical case consists of ground water abstractions or diversions within a basin with a reservoir at its downstream end. Generally, all water management schemes with conjunctive use of surface and ground water suffer from this. The problem has been tackled through the use of special elements in the system representation based on some form of simplified lumped models, such as the "groundwater reservoir node" in the RIBASIM package (Waterloopkundig Laboratorium, 1991). However, these elements possess two drawbacks. First, they constitute very simplified models for ground water flow. Second, they contain parameters that normally need some calibration and validation effort. Thus, they do not take advantage of the advances in groundwater modelling. Attempts to bridge this gap are very few (Fredericks et al., 1998). The aim of this paper is to investigate the possibility of direct integration of known and well tested groundwater models into a DSS. Although karstic aquifers are considered only, models of general use were chosen without special features for karst. The criteria for suitability of a model will be its efficiency and adaptability to the DSS requirements.

Thus far, no fully adequate model for karstic aquifers has been developed. Three categories of models appeared in the literature. In the first category lie the so-called parsimonious models either lumped (one-cell) or semi-distributed (multi-cell) (Bear, 1979; Barret and Charbeneau, 1996; Todd et al., 1998). These are of great usefulness when adequate measurements are lacking but they give information on hydraulic heads only at very coarse scales. The second category concerns distributed models and comprises two subcategories: first, models based on the equivalent porous medium (EPM) approach (White, 1999) for aquifers with fractures that are sufficiently interconnected and closely spaced, and second, models with two distinct flow systems, i.e., a conduit system and a fracture system (Teutsch and Sauter, 1991; Mohrlok and Sauter, 1997; Eisenlohr et al., 1997). This category of models is very promising but requires good knowledge of the hydrogeological features of the aquifer studied. In a third model category we mention statistical methods, essentially of the black-box type, with the obvious advantage of simplicity and effectiveness.

In this work we opted for three models: a multi-cell model, the well-known MODFLOW model within the EPM approach and a lumped model. All models are applied to data from the Boeoticos Kephisos River Basin in the Eastern Sterea Hellas Region, Greece. The DSS chosen for testing is HYDRONOMEAS which is currently used for managing water resources for the water supply of Athens, Greece.

The paper is organized in five sections. In Section 2, a brief description of the models is given by omitting MODFLOW which was ready-made for the study basin (Perleros, 2000) and adapted for operational use (Nalbantis and Rozos, 2000). In Section 3 features related to model calibration are presented while in Section 4 problems regarding model integration within the DSS are discussed. Some concluding remarks are depicted in Section 5.

2. Model description

2.1. The multi-cell semi-distributed model

The model consists of N interconnected cells. Each one of these is further subdivided into one surface water sub-cell (SWSC) and a ground water sub-cell (GWSC). SWSC operates as a modified Thornthwaite model with precipitation and potential evapotranspiration as inputs and surface runoff, actual evapotranspiration and percolation to the underlying aquifer as outputs. Surface runoff is formed by a fraction SSO of the water content above a threshold THRES and the spill over the sub-cell storage capacity CAP. SWSC feeds GWSC through a fraction (PERC) of its storage content percolated per time step. GWSC functions according to Darcy's law. It accepts percolation and lateral inflow as inputs and yields lateral outflow to adjacent cells or the sea, spring runoff as well as water abstractions for irrigation and water supply as outputs. The model has eight parameters for each cell, i.e., four for SWSC, the transmissivity T and the specific storage S of GWSC, and two conductance parameters CSP and CSEA that regulate outflows from GWSC to springs and the sea respectively.

2.2. The lumped model

The whole basin is represented by a single cell (Nalbantis, 1998). A fraction α of monthly areal precipitation P_t (for month t) runs-off as overland flow, while a fraction β of it percolates to the aquifer. Two fractions of the monthly average water content (denoted as S_t for the end of month t) appear as spring runoff: γ for the content above a threshold ξ and δ for the whole content. Water demand is satisfied through withdrawals from surface water $W_t^{(s)}$ and groundwater $W_t^{(g)}$. The water balance equation for the surface water and the aquifer take the form

$$Q_t = ((\gamma + \delta)(S_{t-1} + S_t)/2) - \gamma\xi + \alpha P_t - W_t^{(s)} \quad (1)$$

$$S_t = [(1 - (\gamma + \delta)/2)S_{t-1} + \gamma\xi + \beta P_t - W_t^{(g)}]/(1 + (\gamma + \delta)/2)$$

where Q_t is surface water discharge at the outlet and α, β, γ, δ and ξ are parameters.

3. Model calibration

All investigations are carried out on the Boeoticos Kephisos karstic system. The river drains an area of approximately 2000 km^2 within the region of East Sterea Hellas north of Attica. The watershed is formed on limestone which is heavily karstified thus forming a significant aquifer system. This is fed by infiltrating water but, also, by the river itself which is leaking in its middle course. The main discharge points are large karstic springs in the lower part of the basin. The most important springs are the Melas and Mavroneri springs with an average discharge of 300000 and 150000 m^3/day respectively. Water is pumped from the aquifer for irrigation purposes. Also, boreholes that can supply water to Athens have been drilled in 1993 at the region Vassilika-Parori following the severe drought of the years 1988-94.

The outflows from the Boeoticos Kephisos Basin flow into the Lake Iliki which is formed within a closed basin with a karstic background. The lake receives surface waters from its own basin also (400 km^2). Until 1980, it has been the main water resource that supplied water to Athens by pumping. Thereafter, two major dams at the Mornos and Evinos river basins had been constructed in the West Sterea Hellas Region. These supply water by gravity. Lake Iliki suffers from considerable leakages to the surrounding karst. For high water elevations in the lake, leakages may reduce the water potential to half of it. The Boeoticos Kephisos Basin and the Lake Iliki are shown in figure 1 together with the main groups of karstic springs and irrigation areas.

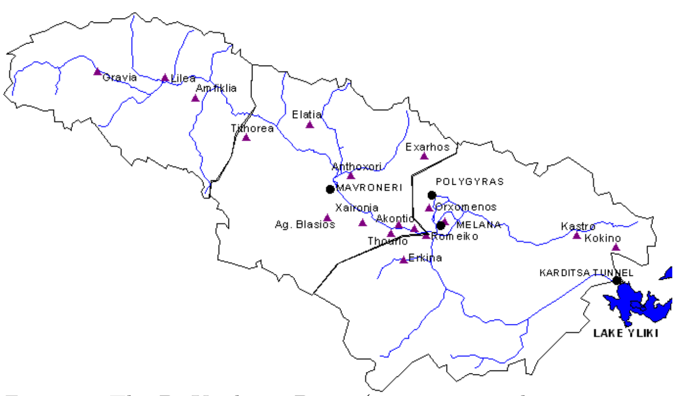

Figure 1. The B. Kephisos Basin (springs in circles, irrigation areas in triangles).

All models were calibrated based on monthly data of a common five-year period (1984–85 to 1988–89) and were validated on a five-year period (1989–90 to 1993–94). Three cells were used in the multi-cell model (sub-basins upstream Mavroneri Springs, between Mavroneri and Melas Springs and downstream). Only the two most upstream cells include

Table I. Parameter values of the multi-cell model for each cell $i = 1, 2, 3$.

Cell	CAP (mm)	THRES (mm)	SSO	PERC	T (m^2/s)	S	CSP (m^2/s)	CSEA (10^{-3}) (m^2/s)
1	500	145	0.19	0.20	0.13	0.06	90.2	0.00
2	500[1]	145[1]	0.19[1]	0.20[1]	0.13[1]	0.06[1]	41.4	0.17
3	500	0	0.11	0.11	NA	NA	NA	NA

NA = not applicable
[1] = Forced to be equal to value of cell 1

groundwater sub-cells since the porous aquifer below cell 3 is insignificant. For each sub-basin monthly areal rainfall depths were estimated. For the multi-cell and the lumped model the shuffled complex evolution (SCE) method (Duan et al., 1992) was used for parameter optimisation, using a multi-variate objective function. The multiple variates were the surface water discharge at the outlet of the whole basin and the total discharge of the Mavroneri and the Melas Springs with weights 0.50, 0.25 and 0.25 respectively. Water abstractions for irrigation were estimated based on irrigated areas for each crop separately and the related evapotranspiration estimates per crop. The calibration of the MODEFLOW model is performed manually. For the surface outflow, the coefficient of determination (also known in hydrological applications as the Nash's efficiency criterion EFF) in calibration took comparable values for the multi-cell and the lumped model, i.e., 0.87 and 0.91 respectively. For the Mavroneri Springs the multi-cell model gave 0.77 and MODFLOW 0.73. For the Melas Springs low EFF values were obtained. In validation, EFF for the surface outflow dropped to 0.60 and 0.75 for the multi-cell and the lumped model respectively. For Mavroneri Springs, the multi-cell model and MODFLOW gave 0.66 and 0.52 respectively. Parameter values of the multi-cell model are depicted in table I while parameters of model 1 are $\alpha = 0.074$, $\beta = 0.215$, $\gamma = 0.326$, $\delta = 0.006$ and $\xi = 100$ mm.

4. Model use within HYDRONOMEAS

HYDRONOMEAS is a DSS originally developed for the management of the Athens water resource system. It makes use of the latest technologies which comprise of a relational database, networking, telemetric, GIS, and advanced algorithms that help seek the optimal management policy of the water resource system under study. Details are given

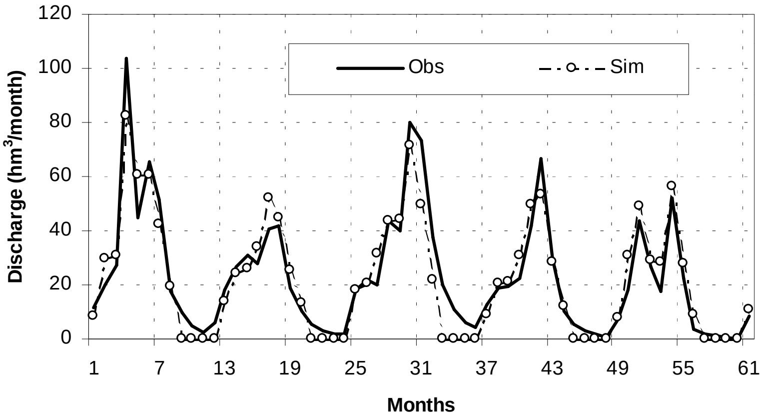

Figure 2. Simulated versus observed discharge at Karditsa Tunnel for the calibration period and the lumped model,

elsewhere (Koutsoyiannis et al., 2001; Nalbantis and Koutsoyiannis, 1997). The DSS incorporates stochastic simulation within an optimisation scheme which yields optimal parametric operating rules for the system studied. Although the DSS has been designed to be configurable for any water resource system, the Athens water supply system will be considered here to illustrate the problem of using ground water models within the DSS.

The problem is posed as follows. When simulation has reached time step t, inflow to Iliki Q_t is known from the stochastic generator CASTALIA (Koutsoyiannis, 2000) which reproduced the statistics of the historical data. Trying to satisfy many types of constraints, a first optimisation cycle based on network optimisation algorithm yields an optimal withdrawal from the Boeoticos Kephisos aquifer W_t as well as withdrawals from Lake Iliki and other reservoirs. Q_t is, however, erroneous since it reflects historical inflows corresponding to essentially different groundwater abstractions. To correct this, W_t is inserted to the Boeoticos Kephisos ground water model together with stochastically generated basin rainfalls and a new estimate of the inflow to Iliki $Q_t^{'}$ is obtained which allows for a second optimisation cycle. Our investigations showed that one iteration suffices. Figure 3 schematises the above algorithm.

5. Summary and concluding remarks

The ability of DSS to manage water resource was enhanced so as to handle complex decision-related surface water—ground water interactions. This was achieved through integrating groundwater models into

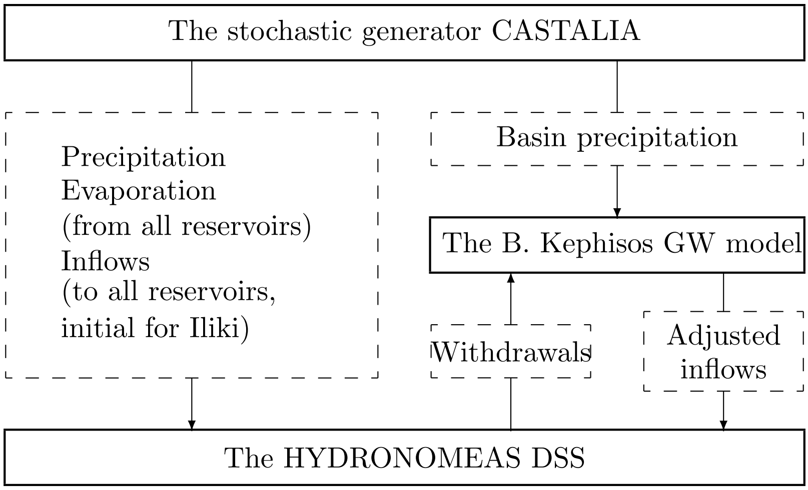

Figure 3. The link of HYDRONOMEAS to the groundwater (GW) model of Boeoticos Kephisos

it. Three alternative models were tested: a multi-cell model that simulates both surface flows and groundwater flow, a lumped model and a distributed model based on the MODFLOW package. Investigations were carried out on the Boeoticos Kephisos River Basin. It appeared that: (a) regarding prediction accuracy, all models performed almost similarly in calibration as well as in validation, (b) one monthly five-year simulation lasts for 1.5×10^{-6} s, 2.0×10^{-2} s and 5 min for the lumped, the multi-cell and the MODFLOW model respectively (for PC Pentium III at 600 MHz); given that optimisation comprises thousands of simulation cycles, this precludes the use of MODFLOW within the DSS but, also, adds a high computational burden when the multi-cell model is used also, (c) in the optimisation phase HYDROMEAS can afford only the lumped model, while for a single simulation cycle the multi-cell model is proposed since it yields more information, (d) distributed models, although useful for better spatial information treatment, remain ineffective as to their ability to run in stochastic simulation mode within a DSS.

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