Journal of Hydrology 509 (2014) 193–206

Contents lists available at ScienceDirect

Journal of Hydrology

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

Multi-response calibration of a conceptual hydrological model in the semiarid catchment of Wadi al Arab, Jordan

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ARTICLE INFO

Article history:
Received 29 April 2013
Received in revised form 23 October 2013
Accepted 16 November 2013
Available online 1 December 2013
This manuscript was handled by Konstantine P. Georgakakos, Editor-in-Chief, with the assistance of Marco Borga, Associate Editor

Keywords:
Groundwater recharge
Hydrological modelling
Multi-response calibration
J2000g
Semiarid
Jordan

SUMMARY

A key factor for sustainable management of groundwater systems is the accurate estimation of groundwater recharge. Hydrological models are common tools for such estimations and widely used. As such models need to be calibrated against measured values, the absence of adequate data can be problematic. We present a nested multi-response calibration approach for a semi-distributed hydrological model in the semi-arid catchment of Wadi al Arab in Jordan, with sparsely available runoff data. The basic idea of the calibration approach is to use diverse observations in a nested strategy, in which sub-parts of the model are calibrated to various observation data types in a consecutive manner. First, the available different data sources have to be screened for information content of processes, e.g. if data sources contain information on mean values, spatial or temporal variability etc. for the entire catchment or only subcatchments. In a second step, the information content has to be mapped to relevant model components, which represent these processes. Then the data source is used to calibrate the respective subset of model parameters, while the remaining model parameters remain unchanged. This mapping is repeated for other available data sources. In that study the gauged spring discharge (GSD) method, flash flood observations and data from the chloride mass balance (CMB) are used to derive plausible parameter ranges for the conceptual hydrological model J2000g. The water table fluctuation (WTF) method is used to validate the model. Results from modelling using a priori parameter values from literature as a benchmark are compared. The estimated recharge rates of the calibrated model deviate less than ±10% from the estimates derived from WTF method. Larger differences are visible in the years with high uncertainties in rainfall input data. The performance of the calibrated model during validation produces better results than applying the model with only a priori parameter values. The model with a priori parameter values from literature tends to overestimate recharge rates with up to 30%, particular in the wet winter of 1991/1992. An overestimation of groundwater recharge and hence available water resources clearly endangers reliable water resource managing in water scarce region. The proposed nested multi-response approach may help to better predict water resources despite data scarcity.

1. Introduction

Groundwater resources in Jordan are strongly limited due to (semi-) arid climate conditions. Significant overuse by groundwater abstraction intensifies the situation, clearly documented by falling groundwater levels, the disappearance of springs and saltwater intrusions from deeper aquifers.

For sustainable future use of water resources reliable estimates of water balance components are necessary, particularly of groundwater recharge as the main source of replenishment of water resources. Linking between hydrological and groundwater flow models is an appealing way to estimate groundwater recharge rates in semi-arid regions. The spatio-temporal patterns of GW recharge as output of the hydrological models is thereby used as input in GW flow models for managing water resources (e.g. Al-Abed et al., 2005; Abdulla and Al-Assa'D, 2006; Wu et al., 2011; Gräbe et al., 2012). Hydrological models may be seen as a transformator of input, e.g. rainfall to output, e.g. runoff. This transformation follows (a) some general (physical or conceptual) principles, i.e. the model structure or model equations, and (b) some degree of freedom to adapt the general principles to the local conditions, the model parameters, which are calibrated. The hydrological model has to be complex enough to account for the dominant process, but simple enough not to be over-parameterized (Blöschl and Grayson, 2002).

However, complex highly non-linear processes and sparse data challenge hydrological modelling in semi-arid regions as Jordan.

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http://dx.doi.org/10.1016/j.jhydrol.2013.11.026

Model of intermediate complexity, such as J2000 g (Kralisch and Krause, 2006) has to be proven to be a good balance to account for the complex and the scarcity on data to reliably estimate model parameters. Similar to the choice of model structure, data scarcity also limits classical approaches to calibrate model parameters (e.g. Klemeš, 1986). One approach to overcome the limitation of sparse calibration data is to use additional data sources to calibrate or validate model parameter sets. These can be geo-chemical data (Mroczkowski et al., 1997), groundwater data (Madsen, 2003), soil moisture data (Western and Grayson, 2000) or regional relationship of model parameters (Parajka et al., 2007a,b). The general idea of these approaches is to constrict the model parameter space by establishing a multi-objective calibration, i.e. by trying to fit model state variables, such as soil moisture or groundwater recharge to observations, additional to the classical calibration towards runoff. For example Marce et al. (2008) successfully use a multi-objective function calibration strategy to solve the parameterization of a complex application of a hydrological model.

Such additional data may be available in various degrees of spatio-temporal information content, such as time series of hydrological variables at single locations within the catchment, e.g. times series of groundwater levels in a well, or as integral measures over time and space, such as groundwater recharge derived from chloride mass balance. This clearly affects the approach to calibrate model parameters. A common way is to calibrate all model parameter at once, using a multi-objective optimization function, to fit model parameters to the times series of observed runoff and e.g. soil moisture data. However, this requires spatio-temporal information content of the additional data source. If only integral information in space and time are available, different strategies are needed.

First, more than one additional source of data may be used. For example, Sharda et al. (2006) uses chloride mass balance (CMB) and water table fluctuation (WTF) in a multi-response approach for the quantification of the groundwater recharge. Sophocleous (1991) successfully combines a soil water model and the water table fluctuation method to quantify groundwater recharge. A second aspect concerns the calibration of model parameters to additional data. One promising strategy is to use a nested approach, in which some sub-parts of the model are calibrated to the data in a consecutive manner. Such sub-parts can be sequences of hydrological processes, e.g. parameters of the soil moisture routines are calibrated first to measured soil moisture data, then all remaining parameters are calibrated to runoff, while soil moisture parameters remain unchanged in the second step. The idea of this approach is to reduce the degree of freedom. If all parameters are changed at once, unrealistic values of one parameter can be compensated by other parameters and, hence, a large amount of different parameter sets give equally good performance. This effect of equifinality is widely shown in hydrological modelling (e.g. Beven and Binley, 1992). Independent calibration of some parameters in a consecutive manner may reduce compensation.

The objective of this study is to apply a nested multi-response calibration approach for the conceptual hydrological model J2000 g to estimated groundwater recharge in the semi-arid Wadi Al-Arab catchment (Jordan). Information on groundwater recharge based on the chloride mass balance (CMB), observed spring discharges and surface runoff observations are used for calibration. The calibrated model is then validated using the water table fluctuation method and compared to estimates given by the model, with a priori parameter values derived from literature values.

2. Study area of Wadi al Arab

Wadi al Arab is a semi-arid catchment in NW Jordan (Fig. 1) located between the Yarmouk River valley in the north, the Jordan River Valley in the west, the foothills of the Ajloun Dome in the south and the branch of the Azraq plain in the east. The altitude varies from −20 m mean sea level (msl) in the Jordan River Valley to more than 1100 m msl in the mountain range of the Ajloun. The surface catchment area covers about 200 km^2 (Fig. 1B), while the groundwater catchment contains an area of about 300 km^2 (Fig. 1A). Important perennial springs exist only in the north-western part of the study area (Fig. 1A and C). Wadi al Arab starts to incise south of Irbid, the second largest Jordan city and continues NW-wards. South of the perennial spring region, the Wadi abruptly changes its flow-direction to the SW (Fig. 1).

The annual precipitation varies between <350 mm and >550 mm (Ref. to Fig. 3A). Precipitation occurs generally in the wet season from October to April, while the largest quantities with up to 80% fall between December and February. Average daily temperature varies from about 12.5 °C during winter season (from November to April) to around 23 °C during summer season (from May to October).

Alternating sequences of Cretaceous to Cenozoic age and different hydraulic conductivities represent the geological setting of the catchment (Fig. 1). The fractured and karstified package from the Cretaceous Upper Ajloun Group (A7) to the Cenozoic Lower Belqa Group (B1 + B2) is the major aquifer for water supply in the study area. On its top, the A7/B2 aquifer is hydraulically separated from the locally productive B4 aquifer by the Muwaqqar aquitard (B3). Due to the NW-wards dip of the formations, the A7/B2-aquifer becomes confined in the NW part of the study area.

As a follow up of the geological and climatic conditions, the main soil types are Inceptisols (Terra Rossa and Dark Rendzina), Entisols and Vertisols (Grumusol) (USDA, 1975). The depth of the corresponding soil types shows a strong variation and depends strongly on the dominating vegetation cover. Predominant soil types feature A- and C-horizons with a mis-sing B-horizon. In areas with poor vegetation and steep slopes even the A-horizon is missing. During rain fall events the dry and immature soils possess only small capabilities to store an adequate amount of water. Thus, in combination with the steep morphology the precipitation excess accumulates quickly and flows downhill inducing flash floods.

According to Zohary (1973), Wadi al Arab belongs to the Mediterranean and the Irano-Turanian vegetation zones. The Mediterranean vegetation zones are characterized especially by *Pinus halepensis*, *Quercus coccifera*, *Quercus ithaburensis*, *Ceratonia siliqua*, *Olea europaea* and *Pistacia spp*. The Irano-Turanian zone consists of mostly shrubs and bushes, like *Retama raetam*, *Ziziphus lotus*, *Artemisia herba-alba*, *Noaea mucronata* and *Anabasis syriaca* (Al-Eisawi, 1996).

3. Methods

3.1. GSD – gauged spring discharge method

The springs of Ein Umm Qais (catchment 1.7 km^2) and Ein el Asal (catchment 1.1 km^2) drains the two corresponding headwater catchments. Spring discharges were manually measured from October 2007 to October 2008. Fig. 2 shows the discharge curves of both springs versus precipitation between October 2007 and October 2008. Both springs quickly react on the precipitation of the rainy season in Winter 2007/2008. However, Ein el Asal responses slightly earlier than Ein Umm Qais and shows a much longer lasting discharge peak up to the end of the wet season. The direct response of the spring discharges on the precipitation events and the continuing spring discharge in the dry summer season indicates that the discharging aquifer is characterised by a double porosity system that is dominated by matrix flow. The average spring discharges are in Ein Umm Qais 0.41 l/s and in Ein el