Journal of Hydrology 519 (2014) 3550–3556

Contents lists available at ScienceDirect

Journal of Hydrology

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

Estimation of watershed hydrologic processes in arid conditions with a modified watershed model

Jian Sha [a], Dennis P. Swaney [b], Bongghi Hong [b], Jinnan Wang [c], Yuqiu Wang [d,*], Zhong-Liang Wang [a,1]

[a] *Tianjin Key Laboratory of Water Resources and Environment, Tianjin Normal University, Tianjin 300387, China*
[b] *Dept. of Ecology & Evolutionary Biology, Corson Hall, Cornell University, Tower Road, Ithaca, NY 14853, USA*
[c] *Chinese Academy For Environmental Planning, Beijing 100012, China*
[d] *MOE Key Laboratory of Pollution Processes and Environmental Criteria, College of Environmental Science and Engineering, Nankai University, Tianjin 300071, China*

ARTICLE INFO

Article history:
Received 11 August 2014
Received in revised form 27 October 2014
Accepted 30 October 2014
Available online 6 November 2014
This manuscript was handled by Peter K. Kitanidis, Editor-in-Chief, with the assistance of Christophe Darnault, Associate Editor

Keywords:
GWLF
ReNuMa
Low-flow estimation
Algorithmic revision
GLUE

SUMMARY

Watershed models play an important role in modern water resource management, increasingly demanding a robust hydrologic data framework to estimate watershed hydrochemical processes. The Generalized Watershed Loading Function (GWLF), a typical watershed model with modest data requirements, has been applied to watershed-scale hydrochemical estimation worldwide. However, while it generally successfully estimates flows in humid regions, the model suffers from a weakness in hydrologic estimation during low-flow periods, which are projected to continue increasing with global climate change in many places. To address this issue, three algorithms describing functional responses of flows to saturated water storage, the segment function approach, linear function approach, and exponential function approach, have been proposed in this paper, integrated with a previous leakage mechanism for unsaturated water storage used in two earlier GWLF versions, and applied to a case study of Shuai Shui River watershed in China. Comparisons of this version, including new algorithms or algorithm linkages, with the earlier GWLF versions, show that all the new algorithms improve model accuracy in low-flow months; the linear function approach linking the leakage process has the best effect. This work refines the framework of GWLF model to address both humid and arid conditions that can be used as alternatives for future applications. These new functional dynamic responses should also have potential application in other similar watershed models.

1. Introduction

Watershed models have become fundamental tools for modern water resource management (Chen et al., 2014; Wu et al., 2012). They can be used to simulate watershed hydrochemical processes and estimate pollution loads and source apportionment, providing critical information for decision making support (Pokhrel et al., 2012; Singh et al., 2011). To adequately describe the environmental behavior of pollution in a watershed, models should have a proper hydrologic framework to accurately characterize the transport of components (Fu et al., 2014; Xu et al., 2007). Many well-established hydrologic functions (e.g. the Soil Conservation Service Curve Number (SCS-CN) method) have been widely integrated into watershed models (Haith and Shoenaker, 1987; Tolson and Shoemaker, 2007). An accurate hydrologic model is the precondition for a successful watershed model application (Golden et al., 2014; Narula and Gosain, 2013) and research that has improved the hydrologic structure of watershed models over their historical development (Dechmi et al., 2012; Wang and Brubaker, 2014) has resulted in more sensible management measures as the model structures have improved (Fu et al., 2014; Strauch et al., 2013).

The Generalized Watershed Loading Function (GWLF) model, with a good record of estimating watershed hydrochemical processes with modest data requirements, has been an effective modeling tool for water resource management support (Du et al., 2014; Jennings et al., 2009; Schneiderman et al., 2013). The model was initially proposed (GWLF V1) in 1987 (Haith and Shoenaker, 1987), followed by an enhanced version considering unsaturated zone water capacity and evaporation limit (GWLF V2) in 1992 (Haith et al., 1992). More detailed discussions about variants of the GWLF model are provided in Supplementary Material. The framework of GWLF model is robust and flexible and has worldwide applications (Hong et al., 2012; Li et al., 2010; Schneiderman et al., 2007).

---

[*] Corresponding author. Tel./fax: +86 22 23502448.
E-mail addresses: yqwang@nankai.edu.cn (Y. Wang), wangzhongliang@vip.skleg.cn (Z.-L. Wang).
[1] Co-corresponding author. Tel.: +86 22 23766256; fax: +86 22 23766557.

http://dx.doi.org/10.1016/j.jhydrol.2014.10.063

While used to characterize watershed-scale water resources particularly in humid regions like the Eastern US, the original GWLF application showed a weakness in estimating low monthly groundwater volumes in dry seasons (Lee et al., 2000; Schneiderman et al., 2002). As the dominant component of streamflow in low-flow months, the groundwater contributions to streamflow during these periods are commonly underestimated, creating potentially significant biases in pollution load estimates. Although such biases have little impact on annual load estimates (the contribution of loads during low-flow periods to cumulative loads is minimal) they can affect the validity of estimates of both pollution loads and outflow concentrations in low-flow months. Both are critical indicators for water resource management, especially under arid conditions projected to be more extreme under future climate change scenarios (Narsimlu et al., 2013; Parry, 2007).

Although previous research has addressed this issue by adding a leakage mechanism for saturated zone recharge (Schneiderman et al., 2002), we believe that additional improvements are possible with relatively simple modifications of the model. In this study, we propose three new algorithms to refine the framework of the groundwater transfer mechanism of GWLF to improve streamflow predictions without additional data requirements, and apply the modifications to estimate watershed hydrologic processes in arid conditions. The ReNuMa modeling platform (Hong and Swaney, 2008), which uses the same hydrologic model components as the original GWLF V1 or V2, was used here because of its flexible code and data handling, and powerful capability in Bayesian parameter estimation. We generalized the new algorithms for the saturated zone based on GWLF V2 and integrated them with a previously-developed unsaturated zone leakage algorithm approach (Schneiderman et al., 2002). We then compared the modeling results from different resulting GWLF versions with hydrological observations in a watershed of China, which has an uneven precipitation distribution with dry periods occurring in the spring and autumn months of most years. The goal of our research is to develop refinements in the groundwater framework of the GWLF model to better estimate hydrology in dry seasons or arid areas that are of particular concern to management under climate change. These new algorithms also offer an approach which may be useful for other similar watershed models with steady groundwater transfer mechanisms (Allred and Haan, 1996; Frankenberger et al., 1999).

2. Materials and methods

2.1. Model modifications

Three new algorithmic modifications have been made to estimate fluxes of water to streamflow and deep seepage from groundwater storage in GWLF V2. The three algorithms, describing functional relationships between the fluxes and storage, are respectively called the segment function approach, linear function approach, and exponential function approach in this paper. The modifications are designed to refine streamflow estimates during low-flow periods by replacing fixed "transfer coefficients" with functional relationships.

The transfer of groundwater to streamflow and deeper layers in the original model is calculated simply as the product of fixed coefficients, the recession coefficient and seepage coefficient, and daily water storage in the saturated zone, which can be formulated as:

$$\text{recession yield} = \text{recession coefficient} \times \text{saturated zone storage} \tag{1}$$

$$\text{seepage yield} = \text{seepage coefficient} \times \text{saturated zone storage} \tag{2}$$

Here, the saturated zone of the watershed is considered to be a linear reservoir. The recession yield indicates a water transfer from the saturated zone to streamflow; this can be conceptualized as a "horizontal flow" from the saturated zone to streamflow. The seepage yield indicates the corresponding "vertical water transfer" lost from the saturated zone to deeper layers. These two transfer approaches comprise the main mechanisms for groundwater simulation in the GWLF model based on two simple "lumped" parameters, the recession coefficient and seepage coefficient, which approximate the average, depth-integrated behavior resulting from a more detailed characterization, such as a hydraulic conductivity tensor or transmissivity profile. Recession coefficient and seepage coefficient can be calibrated to reflect the local aquifer properties of the simulated region; for a low permeability aquifer region, such as silty-sand sediments, the seepage coefficient could be very low (or even set to zero to represent an impervious layer); for gravel aquifer with high permeability, the seepage rate could be set at a higher value (to a maximum of 1). However, although such mechanisms are clear and require little data, the approach disregards a key point regarding the relationship between water transfer rates and saturated zone storage: that water storage in the saturated zone is the source of energy for groundwater transfers, so that the recession coefficient and seepage coefficient should be variable functions of water storage rather than fixed coefficients. The smaller the water storage, the smaller the hydraulic head of groundwater, associated with both lateral and vertical flows, having less energy for groundwater transfer. In the original algorithm with invariable coefficients, the recession coefficient and seepage coefficient would likely be overestimated during the low-flow period with little infiltration water recharging the saturated zone storage, leading to an overdraft of water storage from the saturated zone, as a result of which the groundwater flow would likely be underestimated relative to the real flow in the later low-flow period (Eq. (1)). The proposed solution is to construct a positive functional relationship between water transfer rates and saturated zone storage to better reflect its physical behavior; as described below, we have developed three alternate algorithms to address this issue (Fig. 1).

2.1.1. Segment function approach

The first approach, a "segment function", was introduced to characterize daily recession and seepage. The groundwater transfer coefficients here were divided into quick and slow recession and seepage coefficients depending upon whether the saturated zone water storage was above or below a threshold value, which can be formulated as:

$$\text{Daily recession coefficient} = \begin{cases} \text{recession coefficient}_{\text{quick}}(\text{saturated zone storage} \geqslant \text{threshold}_{\text{recession}}) \\ \text{recession coefficient}_{\text{slow}}(\text{saturated zone storage} < \text{threshold}_{\text{recession}}) \end{cases} \tag{3}$$

$$\text{Daily seepage coefficient} = \begin{cases} \text{seepage coefficient}_{\text{quick}}(\text{saturated zone storage} \geqslant \text{threshold}_{\text{seepage}}) \\ \text{seepage coefficient}_{\text{slow}}(\text{saturated zone storage} < \text{threshold}_{\text{seepage}}) \end{cases} \tag{4}$$

In this algorithm, two groups of groundwater transfer coefficient were used in the model. When the saturated zone water storage is smaller than a threshold value (a low-flow situation), the slow transfer coefficients would be applied to calculate the slow transfer process on that day. Otherwise, the quick flow coefficients would be used to represent the normal groundwater process. The critical threshold parameter for saturated zone storage is obtained by calibration.

2.1.2. Linear function approach

As the second alternative, a linear relationship is assumed between the saturated zone water storage and groundwater