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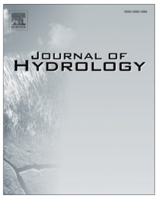

A simple iterative method for estimating evapotranspiration with integrated surface/subsurface flow models

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SUMMARY

This work presents an iterative, water balance based approach to estimate actual evapotranspiration (ET) with integrated surface/subsurface flow models. Traditionally, groundwater level fluctuation methods have been widely accepted and used for estimating ET and net groundwater recharge; however, in watersheds where interactions between surface and subsurface flow regimes are highly dynamic, the traditional method may be overly simplistic. Here, an innovative methodology is derived and demonstrated for using the water balance equation in conjunction with a fully-integrated surface and subsurface hydrologic model (HydroGeoSphere) in order to estimate ET at watershed and sub-watershed scales. The method invokes a simple and robust iterative numerical solution. For the proof of concept demonstrations, the method is used to estimate ET for a simple synthetic watershed and then for a real, highly-characterized 7000 km^2 watershed in Southern Ontario, Canada (Grand River Watershed). The results for the Grand River Watershed show that with three to five iterations, the solution converges to a result where there is less than 1% relative error in stream flow calibration at 16 stream gauging stations. The spatially-averaged ET estimated using the iterative method shows a high level of agreement ($R^2 = 0.99$) with that from a benchmark case simulated with an ET model embedded directly in HydroGeoSphere. The new approach presented here is applicable to any watershed that is suited for integrated surface water/groundwater flow modelling and where spatially-averaged ET estimates are useful for calibrating modelled stream discharge.

1. Introduction

The dynamics of water movement and distribution within the hydrologic cycle involves physical processes in the atmosphere, land surface and subsurface and their interactions (VanderKwaak and Loague, 2001; Panday and Huyakorn, 2004; Kollet and Maxwell, 2006; Kundzewicz et al., 2007; Maxwell et al., 2007; Aquanty Inc., 2015; Delfs et al., 2013; Niu et al., 2014). The processes controlling the movement of water from one reservoir to another include precipitation, evapotranspiration (ET), overland flow, infiltration, recharge/discharge, and groundwater flow. Within the water cycle, understanding the balance of available water between reservoirs is critical for analyzing the sustainability of the surface and subsurface water resources (Partington et al., 2011; Rassam et al., 2013; Li et al., 2015).

The concept of a watershed provides a convenient logical unit for hydrologic analyses, as it serves as semi-closed system for water. In an ideal watershed, precipitation is the only source of water; and thus, it is balanced by all of the sinks in the system, such as stream flow at the watershed outlet, ET, and anthropogenic water consumption for urban and agricultural purposes (Li et al., 2008; Bolger et al., 2011; Pérez et al., 2011; Frey et al., 2013; Condon and Maxwell, 2014; De Schepper et al., 2015). When average precipitation and stream discharge at the outlet are known for a natural watershed, ET can be accurately estimated if the assumption is made that groundwater flow is limited between the watershed and its surroundings. At the sub-watershed scale, the use of more sophisticated tools such as numerical modelling and isotope tracers are often required for water balance analysis, as these areas are typically considered as open groundwater flow systems (Yi et al., 2010; Bearup et al., 2014; Ala-aho et al., 2015).

In analyzing the water balance for a hydrologic system, precipitation and stream flow are relatively easy to measure compared to groundwater flow, infiltration and exfiltration, and ET. Because changes in ET impact on the amount of soil water availability, ET is an important hydrologic component that controls water cycling in the eco-hydrosphere as well as the moisture distribution in the

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atmosphere (Sellers et al., 1996; Gowda et al., 2008; Hanson, 2009). Many variations of the water budget method have been used to estimate ET for watershed and river basin scale analyses (Quinn and Beven, 1993; Hornberger, 1998; Rodell and Famiglietti, 2002; Rodell et al., 2004; Buerge et al., 2009; Davis and Dukes, 2010; Van Stempvoort et al., 2011; Dastorani and Poormohammadi, 2012; Robertson et al., 2013; Xue et al., 2013; Hassan et al., 2014; Ala-aho et al., 2015).

Integrated surface and subsurface hydrological models are becoming increasingly popular tools to characterize major hydrological processes, as well as detailed surface water and groundwater interactions within watersheds. The physical processes considered and the degree of comprehensiveness reflected in the implementation of those processes can vary widely among the different models; Ebel and Loague (2006) indicate that physics-based integrated surface/subsurface simulations can increase both the model complexity and the uncertainty associated with the simulation results on account of the additional parameters and calibration data that are required. For this reason, many studies have combined integrated numerical models with neural network and inverse algorithms to analyze hydrological processes (Maneta et al., 2008; Goderniaux et al., 2009). In this study, the main objectives are (1) to suggest a simple Newton iterative approach that estimates actual ET from measured stream flow using the HydroGeoSphere (HGS) integrated surface/subsurface model (Aquanty Inc., 2015; Hwang et al., 2014); and (2) to validate the accuracy and applicability of the iterative model with a real-world watershed.

2. Theory

This study presents an iterative method to estimate ET using an integrated surface/subsurface model. The ET estimation is based on the water balance in a watershed system. Fig. 1 depicts the major processes controlling the water balance in an idealized watershed where two upstream and downstream sub-watersheds are assumed to interact with each other. The outflow of surface water ($\mathrm{surf_{out}}$) and groundwater ($\mathrm{GW_{out}}$) from the upstream sub-watershed are the inflow for surface water ($\mathrm{surf_{in}}$) and groundwater ($\mathrm{GW_{in}}$) for the downstream sub-watershed. For the entire watershed and each of the sub-watersheds, precipitation (P) acts as a source of water, evapotranspiration (ET) is a sink, and the surface and subsurface flow regimes interact through infiltration and exfiltration. Water balance at steady-state conditions in an integrated surface and subsurface flow system can be described by the following equation:

$$Q_p + Q^{in}_{surf} + Q^{in}_{GW} = Q_{ET} + Q^{out}_{surf} + Q^{out}_{GW} \tag{1}$$

where the left side of the equation represents the sources of water for the system in terms of the average rate of effective precipitation (Q_p) consisting of liquid precipitation and snowmelt, and surface water and groundwater flowing into the domain (Q^{in}_{surf} and Q^{in}_{GW}), and the right terms are the sinks and include ET (Q_{ET}) and surface water and groundwater flowing out of the system (Q^{out}_{surf} and Q^{out}_{GW}). In Eq. (1), no storage change is considered as the system is assumed to be at equilibrium.

Using an integrated surface/subsurface model with ET, the water balance can be presented in the model as

$$Q_p + \widehat{Q}^{in}_{surf}(Q_p) + \widehat{Q}^{in}_{GW}(Q_p) = \widehat{Q}_{ET}(Q_p) + \widehat{Q}^{out}_{surf}(Q_p) + \widehat{Q}^{out}_{GW}(Q_p) \tag{2}$$

where $\widehat{Q}$ represents the simulated Q using the numerical model. If the stream flow rates are measured at specific locations in the system, an inverse problem can be defined in order to find the optimal parameterization for flow and ET that minimizes the difference between measured and simulated flow rates. It is noted that among the hydrologic processes simulated by physics-based integrated numerical models, ET typically requires the largest number of parameters as it is a function of both surface and subsurface moisture conditions as well as climate conditions (potential ET); and thus, this inverse problem often becomes an ill-posed problem.

As this study is concerned with the average rate of ET, the use of net precipitation ($Q_p - Q_{ET}$) can significantly simplify the system. If the net precipitation ($Q_p - Q_{ET}$) is represented by αQ_p or $\alpha \equiv (Q_p - Q_{ET})/Q_p$, Eq. (2) can be re-arranged as:

$$\alpha Q_p + \widehat{Q}^{in}_{surf}(\alpha) + \widehat{Q}^{in}_{GW}(\alpha) = \widehat{Q}^{out}_{surf}(\alpha) + \widehat{Q}^{out}_{GW}(\alpha) \tag{3}$$

where α is the ratio of net precipitation to total precipitation. In Eq. (3), surface water and groundwater flow components are assumed to be driven by a given net precipitation in the model. Generally, stream flow at a measurement location can be considered within the context of the water balance for the catchment area of that specific location. Taking into account the water balance at the stream flow measurement location (i.e. $Q^{in}_{surf} = 0$ and

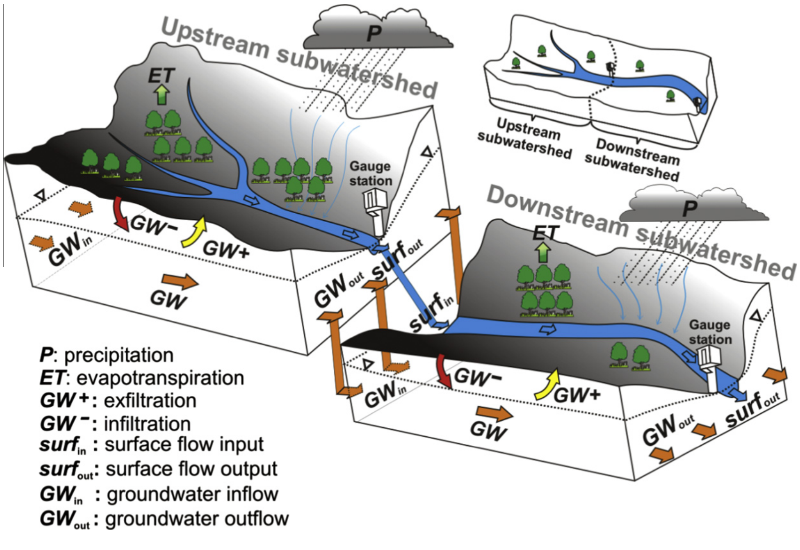

Fig. 1. Schematic of water balance in upstream and downstream watersheds.