Journal of Hydrology 528 (2015) 571–583

Contents lists available at ScienceDirect

Journal of Hydrology

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

A simple hydrologic model for rapid prediction of runoff from ungauged coastal catchments

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ARTICLE INFO

Article history:
Received 20 March 2015
Received in revised form 18 June 2015
Accepted 20 June 2015
Available online 28 June 2015

This manuscript was handled by Geoff Syme, Editor-in-Chief

Keywords:
Lumped rainfall–runoff model
Linear reservoir routing
Runoff prediction of ungauged basins
South Florida hydrology

SUMMARY

We developed a lumped conceptual rainfall–runoff model for rapid prediction of runoff generated in the unique hydrological setting with flat terrain, sandy soils, high groundwater table, and a dense drainage canal network in south Florida. The model is conceptualized as rainfall and evapotranspiration filling and emptying the root zone and excess rainfall recharging three storage zones. Outflows from these storage zones, routed with parallel arrangement of three linear reservoirs, represent different flow components of catchment runoff, i.e., slow drainage (shallow subsurface flow), medium drainage (interflow and saturation excess overland flow), and fast drainage (direct runoff from impervious urban areas or from water table management in agricultural land). The model is parsimonious with eight model parameters along with two optional water management parameters. A regionalization study was conducted through model parameterization to achieve target hydrological behavior of typical land uses, which are the most significant basin descriptor affecting catchment hydrology in south Florida. Cross validation with 16 gauged basins dominated by urban, agricultural, and natural lands, respectively, indicated that the model provides an effective tool for rapid prediction of runoff in ungauged basins using the regionalized model parameters. A case study is presented, involving application of the model to support real-time adaptive management to hydrological operations for protection of estuarine ecosystems.

1. Introduction

Rainfall–runoff dynamics are inherently complex, consisting of rainfall, evaporation, infiltration, and surface and subsurface flows, which all vary at different temporal and spatial scales. Depending on the degrees of mathematical and physical approximations of these processes and the spatial heterogeneity of the catchment (soil, vegetation, land use, and geomorphologic features), two lines of hydrological models can be distinguished – distributed physical models and lumped conceptual models. Distributed models, such as the SHE model (Abbott et al., 1986), precursor of the MIKE SHE model (Thompson et al., 2004), represent the spatially non-uniform processes in a watershed by discretizing the model domain into small grids or meshes concerning the spatial distribution of controlling variables or parameters. These models are physically-based, utilizing analytical or numerical solutions of partial differential equations governing the hydrodynamic and hydrological processes (e.g., the Richards equation and the St. Venant equation). Spatially explicit prediction of the hydrological impacts using distributed models is attained at the expense of increased computational and data demands along with the requirement of accurate measurements of the landscape properties (Huggins and Burney, 1982; Beven, 2001).

Lumped conceptual models, in contrast, aggregate the spatially varying, dynamic rainfall–runoff relationships conceptually into a few simple linear or non-linear equations relating a discharge hydrograph or runoff rate with catchment storage under specified climate inputs (Zhao, 2002; Kirchner, 2009). With no requirement of explicit representation of specific, hydrologic processes, lumped models contain fewer parameters than their distributed counterparts. Their simplicity and computational efficiency has allowed for many applications. Recent work is exemplified by Buytaert et al. (2004) using a linear reservoir model to quantify the land use change impact on catchment hydrology, Oudin et al. (2008) and Zhang and Chiew (2009) examining regionalization performance of lumped models for runoff prediction of ungauged basins based on 913 French catchments and 210 Australian catchments, respectively, and Seiller and Anctil (2014) comparing 20 lumped models to evaluate the uncertainty of climate change impacts on hydrologic regimes.

The concept of lumped models was proposed decades ago before distributed models became popular and their applications and updates have continued up to today (Huggins and Burney,

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http://dx.doi.org/10.1016/j.jhydrol.2015.06.047
0022-1694/

1982; Loague and Freeze, 1985; Michaud and Sorooshian, 1994; Yue and Hashino, 2000; Kirchner, 2009). The unit hydrograph method, as a typical example of the lumped models, was initially proposed by Sherman (1932) to estimate direct runoff from rainfall excess. The assumption is that the basin system transforming the rainfall excess to direct runoff follows a linear and time-invariant relationship with the magnitudes of runoff proportional to the depth of rainfall excess. Since then, it has been widely used with many updates and complexities added onto it. Advancement work along this line is exemplified by Nash (1957) on a cascade of n equal linear reservoirs as a storage–runoff model for the natural watershed and Dooge (1959) on using a cascade of linear channels and linear reservoirs in series to model the basin response. The work on the non-linearity of rainfall and runoff includes Young and Beven (1994) introducing the data-based mechanistic models through transfer functions for model structure identification and parameter estimation, and Kirchner (2009) reporting a simple rainfall runoff model that eliminates the need to estimate the absolute values of storage, yet through the observed flow data the model can be used to infer effective rainfall and evapotranspiration (ET) for "doing hydrology backwards".

Successful applications of the unit hydrograph theory (linearity of the hydrological system) in lumped rainfall runoff modeling takes two fundamental steps, which are (1) determining rainfall excess from climate inputs, and (2) runoff generation and routing through an explicit accounting of water storage. Through this approach, there have been dozens of lumped models reported in the literature, and some of the widely used ones include the Stanford Watershed Model, which later became HSPF (Donigian and Imhoff, 2002), IHACRES (Jakeman et al., 1990), HBV (Bergstrom, 1992), the Xinanjiang model (Zhao, 2002), SAC-SMA (Burnash, 1995), and SIMHYD (Chiew et al., 2002). These models resemble one another in that runoff generation and routing is mostly based on parallel or cascading arrangement of linear storage pools to account for different responses reflected in the hydrograph (Jakeman et al., 1990; Bergstrom, 1992; Zhao, 2002). However, they also differ in many ways such as the conceptualization of the hydrological system, the model structure, and the functions used to connect the storage elements. The difference among these models may lead to significantly different hydrological predictions even with the same climate inputs and calibration data set (Seiller and Anctil, 2014). While any model carries the subjectivity of the original developer, the fact that not all models work equally well in all environments reflects the need for practical consideration in selection of appropriate model structure to suit specific regional hydrological characteristics and climate/landscape controls on runoff generation (Parajka et al., 2013).

The South Florida hydrologic system managed by the South Florida Water Management District (SFWMD) and the U.S. Army Corps of Engineers (USACE) encompasses an area of approximately 49,000 km^2 dominated by the Kissimmee River, Lake Okeechobee, and Everglades watersheds (Fig. 1). The system is highly engineered and managed with about 7700 km of major canals, 1350 major water control structures, and 70 pumping stations (Obeysekera et al., 2011). The humid, subtropical setting in south Florida features distinct wet (May–October) and dry (November–April) seasons with average annual rainfall of about 1290 mm/y, close to average annual potential evapotranspiration (based on the Penman–Monteith formulation of Allen et al., 1998). As a result, the region is prone to both flooding and droughts. The topography is flat (<0.1% slope from Kissimmee to Everglades); thus subtle difference in water levels influences water movement, and in many occasions, pumping is needed to move water for flood control or water supply. Most soils in the northern region are sandy and highly permeable but poorly drained due to a high groundwater table (Telis, 2001). Soils in the southern region include peats in the Everglades Agricultural Area (EAA) and shallow calcareous marl soils further south (Fig. 1). The interaction between surface water and groundwater is complex due to the high groundwater table, with percolation into the deep, confined aquifer being negligible in and north of the EAA, and significant percolation of surface water into the highly permeable limestone aquifer south of the EAA. Agricultural and urban development is made possible with an intricate drainage and irrigation network consisting of primary, secondary, and tertiary canals and field ditches for intensive water management. Due to the high water table and flat terrain in the region, runoff is delivered from tertiary and secondary canals to the primary canals mostly through water control structures such as gated culverts or pumps. Under this environment, rainfall tends to infiltrate rapidly into soils, leading to an immediate water table response. Surface runoff only occurs when water table rises near ground surface or on impervious surface in urban area. Thus, runoff rate is highly dependent on land use and land cover. As such, runoff discharged from natural, poorly drained areas is relatively slow and dominated by subsurface flow (Knisel et al., 1978; Campbell et al., 1995). In contrast, rapid drainage is necessary for flood control in urban areas and highly managed agricultural lands where specific water levels are required for crop production.

Hydrological modeling of the south Florida system has been conventionally conducted with physically based, integrated surface water and groundwater hydrological models implemented at the regional scale (SFWMD, 2005a,b; Obeysekera et al., 2011). Attempts made to apply existing lumped models such as HSPF recognize the need for substantial code modification to suit the unique hydrological setting in south Florida (Wan et al., 2003). Major limitations in these models are exemplified by their inadequacies to account for the influence of high water table conditions and intensive water management on surface water hydrology. For example, Version 12 of HSPF is largely a result of code modifications involving the addition of a special irrigation routine and enhancement of the PWATER routine to represent the interaction between groundwater and the upper and lower storage zones. However, the increased complexity in HSPF undermines the essence of simplicity as a lumped model. The objective of this paper is to introduce a new lumped conceptual model for rapid prediction of runoff from ungauged catchments to address the unique hydrological behavior of the system in south Florida. The model is named "LinRes" to reflect the application of the linear reservoir theory in runoff routing. Section 2 of the paper documents how LinRes is conceptualized and formulated. Section 3 examines model regionalization performance with land use specific parameterization for runoff prediction in ungauged basins. Section 4 provides a special case of model application in two ungauged coastal catchments to support decision making in real-time hydrological operations.

2. Model development

2.1. Model structure

The conceptual model structure of LinRes is given in Fig. 2. Input data include rainfall (R) and potential ET (ET_p), which are spatially averaged across a catchment characterized by different land use and land cover (LULC). Rainfall is firstly used, along with total storage (S_{total}) of water in the watershed, to satisfy ET for the day, resulting in the actual ET (ET_a). The remainder of rainfall replenishes the root zone storage (S_{root}), which consists fundamentally of soil tension water, plus vegetation interception and surface storage, if any, that does not contribute directly to the generation of runoff. The root zone storage increases with increasing rainfall to