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ARTICLE IN PRESS
Water Science and Engineering 2017, x(x): 1–8

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Water Science and Engineering

journal homepage: http://www.waterjournal.cn

A distributed eco-hydrological model and its application

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Received 23 March 2017; accepted 19 September 2017
Available online ■ ■ ■

Abstract

Eco-hydrological processes in arid areas are the focus of many hydrological and water resources studies. However, the hydrological cycle and the ecological system have usually been considered separately in most previous studies, and the correlation between the two has not been fully understood. Interdisciplinary research on eco-hydrological processes using multidisciplinary knowledge has been insufficient. In order to quantitatively analyze and evaluate the interaction between the ecosystem and the hydrological cycle, a new kind of eco-hydrological model, the ecology module for a grid-based integrated surface and groundwater model (Eco-GISMOD), is proposed with a two-way coupling approach, which combines the ecological model (EPIC) and hydrological model (GISMOD) by considering water exchange in the soil layer. Water interaction between different soil layers is simply described through a generalized physical process in various situations. A special method was used to simulate the water exchange between plants and the soil layer, taking into account precipitation, evapotranspiration, infiltration, soil water replenishment, and root water uptake. In order to evaluate the system performance, the Heihe River Basin in northwestern China was selected for a case study. The results show that forests and crops were generally growing well with sufficient water supply, but water shortages, especially in the summer, inhibited the growth of grass and caused grass degradation. This demonstrates that water requirements and water consumption for different kinds of vegetation can be estimated by considering the water-supply rules of Eco-GISMOD, which will be helpful for the planning and management of water resources in the future.

Keywords: Ecological model; Distributed hydrological model; EPIC; GISMOD; Heihe river basin

1. Introduction

Eco-hydrology was described as an independent discipline for the first time at the International Conference on Water and the Environment in Dublin, Ireland, held from January 26 to 31, 1992. Studies on eco-hydrological processes in arid regions, whose spatial heterogeneity leads to complex and little described eco-hydrological processes, have received broad attention in the fields of hydrology and water resources recently (Vertessy et al., 1996; Moret et al., 2007). The ecological and hydrological characteristics of arid and semi-arid areas have changed due to fragile ecological environments, water resources shortages, and intense disturbance by human activities.

However, the interplay between vegetation and water is insufficient in hydrological models, and most previous studies have only emphasized the importance of hydrological processes or ecosystems independently, while the connection between ecological systems and hydrological processes has been neglected. In the traditional hydrological models, the effects of vegetation ecosystems on hydrological processes are usually generalized as an empirical parameter, the value of which is fixed at spatial and temporal scales. In the current ecological models, hydrological processes are mainly

This work was supported by the National Natural Science Foundation of China (Grant No. 91125015).
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Peer review under responsibility of Hohai University.

https://doi.org/10.1016/j.wse.2017.12.007
1674-2370/

Please cite this article in press as: Xu, Zong-xue, et al., A distributed eco-hydrological model and its application, Water Science and Engineering (2017), https://doi.org/10.1016/j.wse.2017.12.007

conceptualized in terms of vertical processes of the soil-vegetation-atmosphere continuum (SPAC) and water movement in the soil, and the water interaction between plant roots and soil zone interface cannot be described in detail (Xu and Zhao, 2016; Zhao et al., 2015). For soil water simulation, the unsaturated zone is generally conceptualized as a reservoir, and water is generally simulated according to the principle of the water balance. In fact, hydrological processes in nature are closely related to the ecological processes of the land, while most hydrological models or ecological models are used to simulate hydrological and ecological processes independently.

With the development of computer science, remote sensing, and geographic information systems, and especially the improvement of earth observation system technology and digital simulation technology, eco-hydrological models have received more attention recently. At present, eco-hydrological models can be divided into two categories: loosely coupled models with ecological and hydrological simulation results, and one-way coupling models of the hydrological or ecological system. In order to reflect the relationship between water and ecology as a whole, two-way coupling of the water cycle and plant growth was realized in this study using a distributed eco-hydrological model, the ecology module for a grid-based integrated surface and groundwater model (Eco-GISMOD), which was developed to simulate eco-hydrological processes by considering the interaction between vegetation and water in different soil layers. Ecological and hydrological processes are synchronized in Eco-GISMOD through a series of processes of exchanges of water and energy between vegetation and soil, providing a new method for investigating eco-hydrological processes at the river basin scale.

2. Model description

Based on Eco-GISMOD, a new distributed eco-hydrological simulation system with a three-soil layer structure was developed using modular technology and distributed data management. It includes five modules: preprocessing, interpolation, evapotranspiration estimation, runoff simulation, and eco-simulation (including natural plants and crops). The model can be executed independently without another platform. Basic data of runoff generation, such as flow direction, simulation sequence, and potential evapotranspiration, are identified in the preprocessing and interpolation modules first. Then, the water allocation and movement of each layer are estimated on the basis of plant transpiration, ground evaporation, and precipitation intercepted by plants. Correspondingly, the dynamic characteristics of leaf area index for different natural vegetation types are computed according to the water requirements and water consumption for each type of vegetation in Eco-GISMOD.

2.1. Preprocessing

The pre-processing module is used to delineate the river basin and to extract the drainage networks automatically from the digital elevation model (DEM) data (Li et al., 2013). This module has various functions, such as flow direction definition, flow accumulation calculation, and drainage network generation, and the order of runoff simulation can be analyzed conveniently using a special approach (Xu, 2009).

2.2. Interpolation

The Thiessen method, gradient plus inverse distance squared method (GIDS), and inverse distance squared method (IDS) were used in the model for spatial interpolation (Nalder and Wein, 1998; Teegavarapu and Chandramouli, 2005).

2.3. Evapotranspiration estimation

Eco-GISMOD integrates eight methods (Allen et al., 1998; Hargreaves and Samani, 1985; Priestley and Taylor, 1972; Turc, 1961) to estimate potential evapotranspiration (PET) and also to enable users to import their own PET data.

Actual evapotranspiration (AET) can be assumed to be present, depleting water in the root zone of the soil (Beven et al., 1995; Kennen et al., 2008), and is expressed as a simple function of PET and the water content of the surface layer.

2.4. Runoff simulation

There are two types of grids in the runoff simulation module: the ordinary grid, which is vertically discretized into three layers: the surface layer, soil layer, and groundwater layer; and the river grid, which looks like a single reservoir for channel routing. In an ordinary grid, each portion of the outflow pours into its corresponding parts when the downstream grid is also an ordinary grid. Otherwise, yielding water will come together as streamflow into the river grid, then move among these river grids and eventually drain out of the watershed (Fig. 1). In Fig. 1, R is the daily precipitation, E is evapotranspiration, Q_{r0} is the inflow from the upstream neighboring surface layer, Q_{r1} is the inflow from the soil layer, Q_{r2} is the inflow from the groundwater layer, Q_{r3} is the inflow of river grid, Q_{s1} is the saturation excess flow, Q_{s2} is the infiltration excess flow, Q_{b0} is the recharge flow from the soil layer, Q_{b1} is recharge flow from the groundwater layer, Q_{c0} is the lateral outflow of the surface layer, Q_{c1} is the lateral

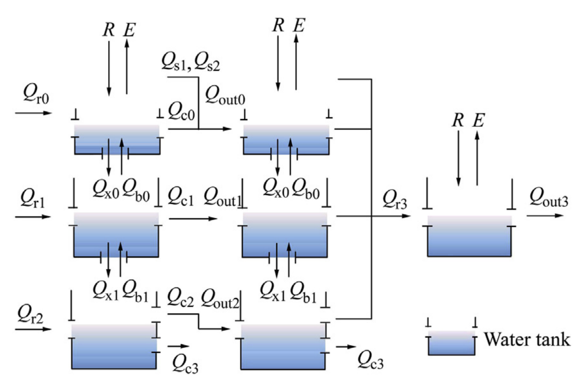

Fig. 1. Runoff generation structure.

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