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Development of a one-parameter variable source area runoff model for ungauged basins

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ABSTRACT

This research develops a one-parameter model of saturated source area dynamics and the spatial distribution of soil moisture. The single required parameter is the maximum soil moisture deficit within the catchment. The concept behind the development of the model comes from the fact that the complexity of topographically-driven runoff generation can be reduced through the use of geomorphological scaling relations. The scaling formulation allows the prediction of the dynamics of saturated source areas as a function of basin-wide soil moisture state. This model offers a number of potential advantages. Firstly, the model parameter is independent of topographic index distribution and its associated scale effects. Secondly, it may be possible to measure this single parameter using field measurements or perhaps remote sensing, which gives the model significant potential for application in ungauged basins. Finally, the fact that this parameter is a physical characteristic of the basin, estimation of this parameter avoids regionalization and parameter transferability problems. The model is tested using rainfall–runoff data from the 10.4 ha experimental catchment known as Tarrawara in Australia, the 37 km^2 Town Creek catchment in U.S.A., and the 620 km^2 Balaphi and the 850 km^2 Likhu sub-catchments of the Koshi river in Nepal. In sub-catchments of Koshi river, the simulation results compare favorably against the calibrated TOPMODEL both in terms of direct runoff and the spatial distribution of soil moisture state. In the Tarrawara and Town Brook catchments, simulation results compare favorably against observed storm runoff using all observed data, without calibration.

1. Introduction

Runoff is one of the most important hydrological variables in water resources studies. Reliable prediction of direct runoff is difficult in ungauged basins as adequate data do not exist to estimate the hydrological variable of interest with desired accuracy. Conventional models for predicting stream discharge require considerable quantities of hydrological and meteorological data. Predictions of daily streamflow at the catchment scale are a central component of many aspects of water resources and water quality management. The majority of river reaches in many catchments of the world are ungauged or poorly gauged, and in some countries existing measurement networks are declining [38]. There is a need for catchment-scale hydrological models that are capable of predicting the streamflow in ungauged basins [2].

A wide variety of models have been proposed for use in ungauged basins. While these models vary widely in underlying design philosophy, to date no model formulation has been developed that performs in a robust fashion without some degree of calibration to the response of the river basin. In basins with a sufficiently long record of observations, we can fall back on calibration to sufficiently constrain the model response [1,3]. Calibration enables somewhat reliable predictions of system response, although application of the model outside the bounds of calibration can be problematic, particularly for certain model formulations. Meeting the demand for spatially distributed model outputs such as soil moisture is a major challenge in distributed hydrological modeling, despite the ability of such models to explicitly describe spatially-varied hydrologic behavior and the impacts of natural and human activities on runoff [34]. While physics-based distributed-parameter hydrologic models surely have their place in water quality and land-use change studies, the ungauged basin problem has eluded solution using this approach, necessitating examination of simpler model formulations.

2. Problem identification, objectives and methodology and formulations

2.1. Problem identification

The variable source area concept is well established in hydrology [9,17,19]. A number of physically-based deterministic models of the

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variable contributing area concept of basin response are reported in the literature [4,6,11,12,18,20,29,30,41,44,49]. These models, of varying degrees of sophistication and methodological rigor have essentially been based on distributed moisture accounting for soil elements within segments of hillslope. However, the input and calibration requirements of these models often restrict their practical application in ungauged basins.

TOPMODEL [4] calibration parameters are relatively few in number and have obvious physical interpretations. TOPMODEL can be applied most accurately to catchments where the assumptions of the model are met, primarily wet catchments that have shallow, homogeneous soils and negligible deep groundwater fluxes. The effects of DEM resolution on the topographic index have been solved with the scaling relations developed by Pradhan et al. [8,31,32]. Although there are relatively few calibration parameters in the TOPMODEL, the TOPMODEL formulation does not allow the prediction of soil moisture distribution from an estimate of soil moisture at one point in the catchment. The TOPMODEL formulation entirely depends on its base-flow formulation to predict the distribution of soil moisture. Single parameter variable source area models such as those by Lyon et al. [23], Schneiderman et al. [36], Shaw and Walter [37], and Steenhuis [40] have been effectively used but the formulation of these models does not allow the prediction of distributed soil moisture based on an estimate of soil moisture at one point in the catchment. Knowledge of soil moisture state is the key for predicting direct runoff within the saturation excess runoff paradigm.

2.2. Objective

Recent work by Pradhan et al. [32] demonstrated that there exist certain scaling relations that can be used to account for DEM resolution effects in the topographic index distribution used in the TOPMODEL formulation. In the case of runoff generation that is dominated by the influence of topography, a natural extension of the scaling relations developed by Pradhan et al. [31,32] is the hypothesis that tightly-coupled scaling laws exist which reduce the complexity of the runoff prediction problem. This paper presents the development of a new one-parameter variable source area model, hereafter called "OPM", for "One-Parameter Model", to predict direct runoff. This model relies upon scaling relations to eliminate model parameters, resulting in a single parameter. This parameter represents the maximum soil moisture deficit within the catchment, which because of its physical basis, it may be directly estimable from field measurements or perhaps remote sensing. This single parameter model formulation, which is derived from appropriate scaling relations, allows prediction of saturated source areas dynamics as a function of basin-wide soil moisture state.

2.3. Development of a relation between the distribution of saturation deficit and threshold saturated area

2.3.1. Model conceptualization

Fig. 1 shows an up-valley cross-section of a saturation excess catchment. In this conceptualization, the catchment is represented horizontally by grids and Section A–A shows the vertical soil moisture profile. Along Section A–A location i_1 on the catchment divide has the highest soil moisture deficit. Furthermore, at location i_1 the upslope contributing area A is a single grid. Section A–A also shows that the soil moisture deficit decreases as the upslope catchment area increases towards the valley bottom. At location i_4 in Section A–A, the vertical soil moisture profile is completely saturated and is therefore a zero saturation deficit area grid. The upslope catchment area at location i_3, one grid upstream of location i_4 is called the threshold upslope contributing area A_t. The proportion of the catchment area with zero saturation deficit expands upstream with increasing soil moisture and contracts towards outlet with decreasing soil moisture.

2.3.2. Model formulation

From topographical considerations, the maximum saturation deficit in a catchment, SD_{max} [L] in Fig. 1, will likely occur at the catchment divide [33]. The minimum saturation deficit in a catchment, SD_{min} [L] in Fig. 1, occurs at a point just above a saturated grid from where the contributing area for storm runoff starts or from where surface streamflow starts in the basin.

Pradhan et al. [31] introduced an equation that defines the spatial distribution of the scaled upslope contributing area. This equation

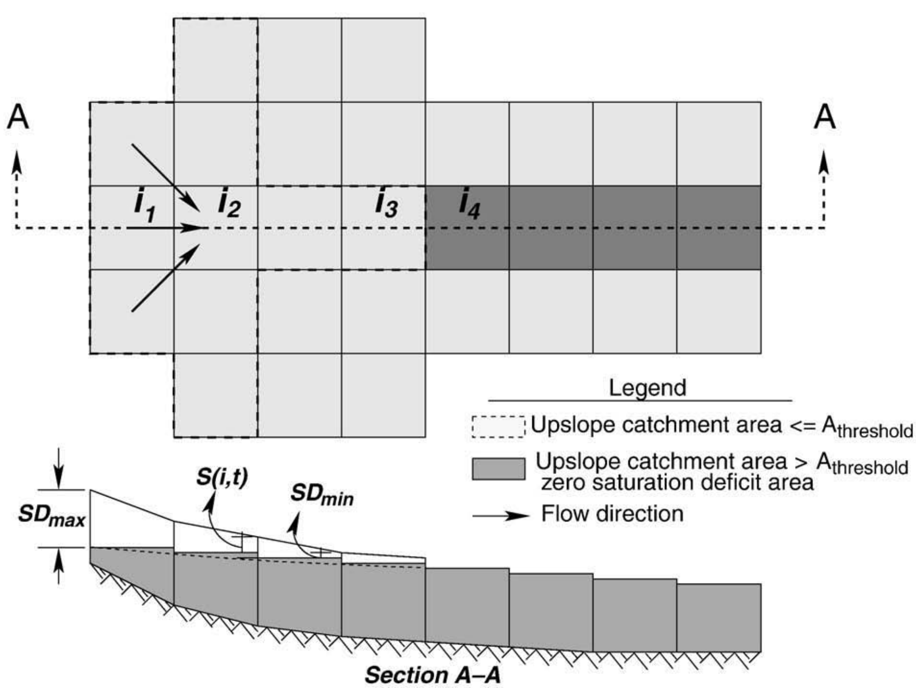

Fig. 1. Model conceptualization of saturation excess direct runoff flow from variable contributing area.