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A simple model to predict soil moisture: Bridging Event and Continuous Hydrological (BEACH) modelling

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A B S T R A C T

This paper introduces a simple two-layer soil water balance model developed to **B**ridge **E**vent **A**nd **C**ontinuous **H**ydrological (BEACH) modelling. BEACH is a spatially distributed daily basis hydrological model formulated to predict the initial condition of soil moisture for event-based soil erosion and rainfall–runoff models. The latter models usually require the spatially distributed values of antecedent soil moisture content and other input parameters at the onset of an event. BEACH uses daily meteorological records, soil physical properties, basic crop characteristics and topographical data. The basic processes incorporated in the model are precipitation, infiltration, transpiration, evaporation, lateral flow, vertical flow and plant growth. The principal advantage of this model lies in its ability to provide timely information on the spatially distributed soil moisture content over a given area without the need for repeated field visits. The application of this model to the CATSOP experimental catchment showed that it has the capability to estimate soil moisture content with acceptable accuracy. The root mean squared error of the predicted soil moisture content for 6 monitored locations within the catchment ranged from 0.011 to 0.065 $cm^3 cm^{-3}$. The predicted daily discharge at the outlet of the study area agreed well with the observed data. The coefficient of determination and Nash–Sutcliffe efficiency of the predicted discharge were 0.824 and 0.786, respectively. BEACH has been developed within freely available GIS and programming language, PCRaster. It is a useful teaching tool for learning about distributed water balance modelling and land use scenario analysis.

1. Introduction

The soil moisture content of the root zone is a key variable that controls nearly all the hydrological processes occurring at or near the land surface. It regulates the partitioning of precipitation into infiltration, runoff, storage in the root zone and percolation into deeper ground water storage. Soil moisture also influences evapotranspiration and water availability to plants and thus affects the success of agriculture. Therefore it is considered to be an important parameter in land surface hydrology models, climate models and general circulation models at a variety of scales. Despite this importance, due to its high spatial and temporal variability, soil moisture is not routinely monitored over the long term like precipitation and discharge (Georgakakkos, 1996; Yamaguchi and Shinoda, 2002). Generally speaking, soil moisture is measured at two extreme scales (Mohanty et al., 2000). It is either observed at a scale of square centimetres (point scale) with in situ measurement methods (e.g. gravimetric, TDR, etc.) or it is observed at a scale of several square metres (pixel size) with the use of remote-sensing techniques. Neither the in situ techniques nor the remote-sensing techniques provide observations at the appropriate resolution or sampling interval and are prone to large measurement errors (Walker, 1999; Evett et al., 2002; Casper et al., 2007). For these reasons, during the last 30 years there have been various studies that have attempted to develop a method to estimate the soil moisture content over a range of scales.

In general, the methods for estimation of spatially distributed moisture content are classified into three main groups: (i) extrapolation approaches; (ii) simulation models in open loops (without feedback mechanism); and (iii) data assimilation and integration of remote-sensing observations and computational modelling.

In the first group, area average of soil moisture is estimated by extrapolating point measurements across the landscape, either with geostatistical techniques (Western and Grayson, 1998; Wang et al., 2001;Western et al., 2004) or using wetness indices based on terrain information (e.g. Beven and Kirkby, 1979; O'Loughlin,

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1986; Svetlitchnyi et al., 2003; Teuling and Troch, 2005). In practice, both methods are difficult to apply. Due to the small correlation length of soil moisture variability, the application of geostatistical methods requires a large number of soil moisture observations for medium- to large-scale catchments which is unaffordable. The usefulness of the wetness indices is limited by the restrictive assumptions underlying their derivation (Grayson and Western, 1998). Moreover, the inclusion of these functions increases the complexity of the hydrological simulations (Engman and Rogowski, 1974), which may not be justifiable for a given marginal improvement in catchment prediction (Dunin and Aston, 1981).

Another method of estimating spatially distributed soil moisture that falls within the first group is the application of "time stability" (Vachaud et al., 1985). According to this concept, particular sites in the field always display the mean behaviour while others always represent extreme values (Teuling et al., 2006).

The second group includes Soil–Vegetation–Atmosphere Transfer (SVAT) models, Land Surface Model (LSM) and unsaturated zone models, which usually require the solution of a form of the Richards' equation (Hurley and Pantelis, 1985; Van Dam and Feddes, 2000; Downer and Ogden, 2004; Moran et al., 2004). Most of these models solve the Richards' equation in 1-D vertical direction and regionalisation is carried out based on land use, or soil, or topography, or two or three of these combined (Renschler et al., 2001). In a review study, Moran et al. (2004) reported that these simulation models, which are physically based, are generally of limited practical use because of the difficulties of specifying parameters and the initial and boundary conditions. Due to large uncertainties in the input parameters, the boundary conditions and the initial conditions, the physically based simulation models have a performance quality which is not much better than the results obtained with simpler conceptual models (Loague and Freeze, 1985; Chen et al., 1994; Hsu et al., 2002).

The third group, a fairly new method for estimating a spatially distributed soil moisture profile, comprises the integration of remote-sensing observations and hydrological modelling using data assimilation. For an excellent overview of this approach, see Heathman et al. (2003) and Moran et al. (2004). In this method, the profile soil moisture content is linked to the surface soil moisture content in order to combine the advantages of spatial predictability of the remote-sensing data with the continuous and depth-wise predictability of the in situ measurement tools and 1-D hydrological modelling (Kostov and Jackson, 1993; Entekhabi et al., 1994; Georgakakkos, 1996; Hymer et al., 2000; Heathman et al., 2003; Tischler et al., 2007). However, the remotely sensed soil moisture data is prone to errors introduced by soil type, landscape roughness and vegetation cover (Houser et al., 1998). Also, there is a mismatch in scale between the in situ measurements and the area estimates from remote sensing (Grayson and Western, 1998). Remote-sensing data yields the average value of the soil moisture content at the scale of a footprint that is larger than the scale of variability of soil moisture (Charpentier and Groffman, 1992; Western and Blöschl, 1999; Heathman et al., 2003; Western et al., 2004).

Despite the above-mentioned problems related to the measurement and prediction of the spatial and temporal distribution of soil moisture, the initial state of soil moisture is an important input parameter in modelling various hydrological processes like event-based surface runoff generation and soil erosion over a range of spatio-temporal scales. In addition, distributed physically based models such as ANSWERS, EUROSEM, KINEROS2 and LISEM have proven to be most sensitive to the initial soil moisture (De Roo, 1993; De Roo et al., 1996; Folly et al., 1999; Hantush and Kalin, 2005).

Therefore, correct representation of antecedent soil moisture condition over the catchment is of crucial importance for accurate simulation of runoff generation, soil erosion and non-point source pollution with such models (Aubert et al., 2003). In other words, the users of physically based, event-scale models are in need of a tool that provides detailed information on the spatial distribution of soil moisture at the onset of an event.

Reviewing the hydrologic literature and accounting advantages and disadvantages of the three groups of soil moisture estimation methods reveal that the simulation models (second group) have been the most frequently and readily used methods to generate soil moisture data and still remain as most appropriate tools.

One of the main goals of modellers in the area of environmental studies is to ever increase our understanding of complex natural systems and advance the development and application of models that simplify the representation of the real systems under study (Silberstein, 2006). In light of this, during the past few decades many experimental studies on infiltration and water movement in soil profiles have resulted in considerable progress in the conceptual understanding and mathematical description of soil water dynamics within the unsaturated zone. This progress has resulted in the development of various soil water dynamic models with different levels of complexity, process description, data requirement and scale of applicability. In general, existing models in hydrology are distinguished into three types, namely 1) empirical models (data-based models); 2) conceptual models; and 3) physically based models. Each type has its advantages and disadvantages. Since the level of complexity of the physically based models is generally agreed excessive for many practical problems (Marechal and Holman, 2005), in this study we develop a conceptual soil moisture model named BEACH (Bridging Event And Continuous Hydrological modelling) using simplified representations of the component processes.

In this paper, the steps involved in development, application, and evaluation of the BEACH model are demonstrated. BEACH is a spatially distributed computational model which would be a helpful tool for educators and students of environmental sciences. Model validation is assessed through a comparison of the model results with the soil moisture observation at six locations within the catchment, the discharge data at the catchment outlet as well as the inter-comparison of the model results with the BUDGET soil water balance model (Raes, 2002).

2. Model formulation

As mentioned in the introduction, in the hydrologic literature there are many simulation models of various complexities with the ability of continuously updating soil moisture content only on a 1-D soil profile. There are also some spatially semi-distributed or fully distributed physically based models. These models are complex, data-intensive, beyond the capability of the environmental scientists to adjust or modify for regional variations, and with limited exploitation of the advantages of GIS. Furthermore they have largely been developed with low level programming languages of thousands of lines of source code which make them non-tractable by the environmental scientists. GIS has already proven its ability as a tool for management, query, and visualisation of spatially distributed information and also as an environment to build simulation models and interpret the results in spatial context. For this, some environmental models have recently been loosely or tightly coupled with GIS (Pullar and Springer, 2000). However there are few models which have fully been integrated within GIS. One example of such models is the Soil Moisture Routing (SMR) model (Frankenberger et al., 1999). It has been fully integrated within the public domain GIS, GRASS. GRASS runs within the UNIX operating system. In this paper we developed the BEACH model which has been fully integrated within a public domain GIS and environmental programming language,