Journal of Hydrology (2006) **331**, 409–424

available at www.sciencedirect.com

ScienceDirect

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

Estimating the impact of rainfall seasonality on mean annual water balance using a top-down approach

Klaus Hickel *, Lu Zhang

CSIRO, Land and Water and Cooperative Research Centre for Catchment Hydrology, GPO Box 1666, Canberra ACT 2601, Australia

Received 2 May 2005; received in revised form 22 May 2006; accepted 23 May 2006

KEYWORDS
Water balance;
Seasonality;
Catchment Storage;
Top-down approach

Summary Seasonal variations of climate and catchment water storage affect the partitioning of rainfall into evapotranspiration and runoff. A new method was developed to estimate the seasonality effect on catchment-scale mean annual water balance using a top-down approach. The model is based on observed rainfall, potential evapotranspiration and streamflow data from 326 unregulated catchments in Australia. It assumes that catchment-scale annual evapotranspiration consists of two components: climate-controlled evapotranspiration and storage-controlled evapotranspiration. The distinction made here is to allow the effects of climate and catchment storage to be estimated separately. The climate-controlled evapotranspiration is affected by rainfall and potential evapotranspiration and can be accurately estimated by Budyko-type relationships using dryness index for different rainfall regimes. The storage-controlled evapotranspiration is influenced by seasonal catchment water storage. When rainfall and potential evapotranspiration are in phase, the effect of rainfall seasonality is to increase climate-controlled evapotranspiration. However, storage-controlled evapotranspiration tends to be smaller under this rainfall regime and exhibits the opposite behaviour of climate-controlled evapotranspiration. As a consequence, the seasonality effect on mean annual evapotranspiration cannot be adequately represented by phase difference between rainfall and potential evapotranspiration alone and the effect of water storage needs to be considered. Results show that inclusion of seasonal changes in catchment water storage significantly improves evapotranspiration predictions for catchments with winter-dominant rainfall.

* Corresponding author.
E-mail address: kjhickel@gmx.de (K. Hickel).

0022-1694/$ - see front matter
doi:10.1016/j.jhydrol.2006.05.028

Introduction

It has long been recognised that evapotranspiration is the result of complex interactions between the atmosphere, soil and vegetation (Brutsaert, 1982). Available energy and water are the primary factors that determine the rate of evapotranspiration (Budyko, 1958). On a mean annual basis, actual evapotranspiration will approach precipitation under very dry conditions, while under very wet conditions, actual evapotranspiration will asymptotically approach the potential evapotranspiration. Based on these considerations, Budyko (1974) proposed an empirical relationship for describing mean annual evapotranspiration. A number of similar relationships have been developed by Schreiber (1904), Pike (1964) and Fu (1981). Choudhury (1999) generalised these relationships by introducing an adjustable parameter. More recently, Zhang et al. (2001) developed a similar model with a parameter expected to be controlled by soil water storage.

These relationships for mean annual evapotranspiration only consider the first-order factors and yield good predictions for catchments where evapotranspiration is dominated by these factors. Budyko (1974) showed that his model was in excellent agreement with observed data for 29 large catchments (e.g. areas exceeding 10,000 km^2) in Europe and there was almost no scatter around the relationship. However, other studies showed that there can be large scatter around the relationship, especially in catchments where the dryness index, defined as potential evapotranspiration divided by rainfall, is close to unity (Milly, 1994; Zhang et al., 2001; Zhang et al., 2004). These studies suggest that there are other factors that affect the partitioning of mean annual water balance, and these include rainfall seasonality (e.g. non-seasonal rainfall, summer-dominant rainfall, and winter-dominant rainfall), seasonal water storage, and storm flow processes such as Hortonian overland flow.

The impact of rainfall seasonality and water storage on the mean annual water balance is important for better understanding the hydrology of catchments located in different climates. For example, two catchments with the same mean annual rainfall and potential evapotranspiration may have different runoff or evapotranspiration partitioning if rainfall distribution or water storage capacity are different. Understanding of the relationships between climate and catchment characteristics and their integrated effect on the water balance can help to improve predictions of mean annual water balance.

A number of studies have tackled the problem of seasonality and storage impact on mean annual evapotranspiration using process-based models (Schaake and Liu, 1989; Woods, 2003). Milly (1994) developed a theoretical framework for mean annual evapotranspiration using statistical-dynamical modelling. The model was based on the hypothesis that long-term evapotranspiration is determined by the local interaction of rainfall and potential evapotranspiration, mediated by soil water storage. With his theoretical framework, he identified several key variables, including seasonality, believed to be responsible for the partitioning of rainfall into evapotranspiration and runoff.

In this study we seek to develop a simple method to quantify the effect of seasonality on mean annual evapotranspiration based on observed climate and water balance data. The focus of the study is on representing the integrated effect of interactions between seasonal climate and catchment water storage on evapotranspiration, not on how to include highly individualised processes into a water balance model. The specific objectives of the study were twofold: (1) to investigate seasonal changes in storage in relation to climate and catchment characteristics; (2) to incorporate seasonal storage changes into a predictive mean annual water balance model to account for seasonality effects on mean annual evapotranspiration. Section 'Development of water balance model' presents the development of the water balance model by modifying the concept of water surplus and water deficiency developed by Thornthwaite (1948). It assumes that annual total evapotranspiration consists of two components: ''climate-controlled'' and ''storage-controlled'' evapotranspiration. Section 'Parameterisation of water balance model' shows that climate-controlled evapotranspiration is strongly linked with the dryness index, while storage-controlled evapotranspiration can be estimated from effective seasonal water storage. In section 'Model testing', the model is tested using observed rainfall, potential evapotranspiration, and streamflow.

Catchments and data

A collection of 326 Australian catchments from two datasets with an area between 50 and 2000 km^2 was available for this study. The location and climate regime of these catchments can be found in Fig. 1. The first dataset consists of monthly records of unimpaired streamflow, rainfall and potential evapotranspiration from 124 catchments as described by Peel et al. (2000). Unimpaired streamflow is defined as streamflow that is not subject to regulation or diversion. The second dataset contains 202 catchments with long-term average values of rainfall, streamflow and potential evapotranspiration. Vegetation cover information was obtained from Ritman (1995) and details can be found in Zhang et al. (1999). The second dataset was used for evaluation of the model.

Monthly rainfall for the first dataset was estimated from gridded daily rainfall (Peel et al., 2000). The spatial resolution of the gridded daily rainfall is 5 km by 5 km based on interpolation of over 6000 rainfall stations in Australia. The interpolation uses monthly rainfall data, ordinary Kriging with zero nugget and a variable range. Mean monthly potential evapotranspiration was calculated by use of the Priestley–Taylor equation (Priestley and Taylor, 1972). In this study, potential evapotranspiration is defined as the energy-limited evapotranspiration or the maximum attainable evapotranspiration in a wet environment, and was quantified using the Priestley–Taylor equation because it provides a physically robust energy-bounded upper limit for the evapotranspiration from terrestrial surfaces (Raupach, 2001). The input data (derived solar radiation, temperature) were produced by the Australian Commonwealth Bureau of Meteorology and were subsequently interpolated and gridded by the Queensland Department of Natural Resources and Mines. The spatial resolution of the data is 0.05°, and the data cover the period 1980–1999. Mean monthly values