Journal of Hydrology 371 (2009) 154–168

Contents lists available at ScienceDirect

Journal of Hydrology

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

Framework for exploration of climatic and landscape controls on catchment water balance, with emphasis on inter-annual variability

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ARTICLE INFO

Article history:
Received 12 March 2008
Received in revised form 27 February 2009
Accepted 25 March 2009

This manuscript was handled by K. Georgakakos, Editor-in-Chief, with the assistance of Andreas Bardossy, Associate Editor

Keywords:
Water balance
Rainfall–runoff models
Process controls
Hydrologic similarity
Hydrologic variability
Budyko curve

SUMMARY

This paper presents a systematic examination of the process controls on inter-annual variability of annual water balance. A simple, linear rainfall–runoff model is used for this purpose, in combination with idealised patterns of within-year variability of rainfall. The effects of these intra-annual patterns of variability of climate (e.g., storminess, seasonality) on annual water balance are examined through the simulation of annual runoff in three semi-arid catchments located in Queensland, South Australia and Western Australia, and one temperate catchment in New Zealand. A simple lumped model, that includes saturation excess overland flow and subsurface stormflow, is used, via sensitivity analyses with respect to different aspects of the intra-annual variability (i.e., seasonality and storminess). In the Queensland catchment storminess is found to be the dominant factor, whereas in Western Australia and South Australia seasonality is found to be the dominant climate control. In wetter catchments (e.g., New Zealand), the water balance is relatively insensitive to soil properties, whereas in dry places (e.g., Western Australia and South Australia) the water balance is highly sensitive to soil properties, such as the soil depth, confirming the results of previous modelling studies. The insights gained from this study can assist in the deciphering of the vast complexity of observed inter-annual variability of catchment responses in terms of their underlying process controls, which can be valuable towards the development of parsimonious water balance models.

Introduction

Understanding the role of climate, soil, vegetation, and topography interactions in controlling the long-term water balance is a fundamental research need in catchment hydrology, critical for the prediction of both water quality and quantity in ungauged catchments, especially under the influence of human-induced climatic and land use changes (Manabe, 1969; Milly, 1994). A catchment serves to partition the incoming rainfall fields into runoff, evaporation and soil–moisture storage; this partitioning can be expressed formally through the water balance equation, and is manifested in various characteristic signatures of catchment response (Wagener et al., 2007). The catchment response to an individual storm event, apart from its dependence on storm characteristics and catchment properties, can depend strongly on antecedent wetness, which represents the memory embedded in the water balance equation, the accumulated net effect of many previous storms. Understanding of these climatic and landscape controls is important for predictions of floods and droughts, as well as water quality, providing a causal link between the water balance equation and characteristics of both the magnitude and frequency of floods and droughts (Robinson and Sivapalan, 1997; Gupta and Waymire, 1998; Sivapalan et al., 2001; Jothityangkoon and Sivapalan, 2001).

Budyko (1974) quantified mean annual water balance in terms of the ratio of mean annual evaporation to mean annual precipitation, E/P. Based on world-wide data on a large number of catchments Budyko demonstrated that E/P is determined, to first order, by the ratio of mean annual potential evapotranspiration to mean annual precipitation, E_p/P (the so-called climatic Dryness Index), a measure of climatic aridity. Fig. 1 presents, as illustration, the estimated annual water balance for a number of selected catchments in Australia, New Zealand and USA on the resulting *Budyko* diagram, i.e., E/P plotted against E_p/P (based on data taken from Atkinson et al., 2002; Farmer et al., 2003), along with the mean

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0022-1694/$ - see front matter
doi:10.1016/j.jhydrol.2009.03.030

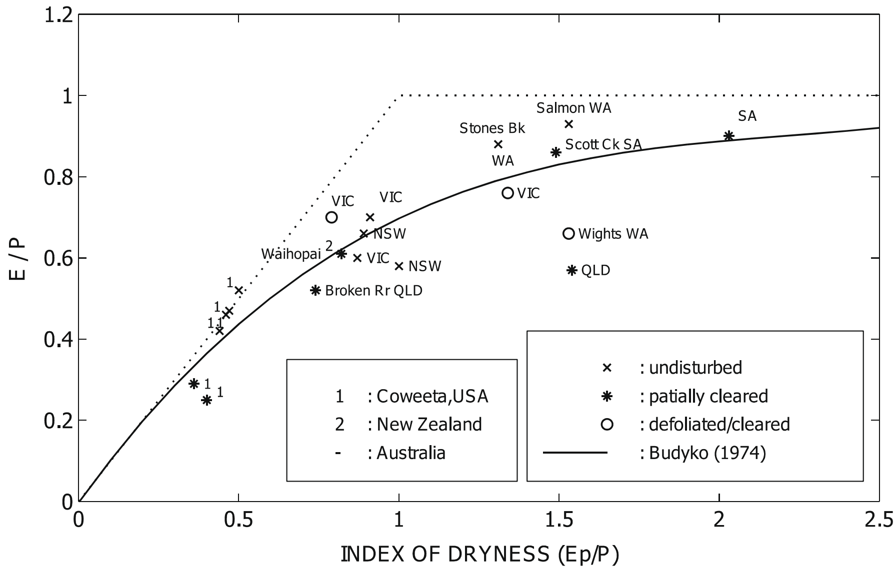

Fig. 1. Budyko curve and diagram of mean annual water balance as a function of the dryness index, E_p/P, of catchments from different regions and different classifications of vegetation cover E is evapotranspiration, P is precipitation and E_p is potential evapotranspiration. Points without number are catchments from different states of Australia: New South Wales (NSW), Queensland (QLD), South Australia (SA), Victoria (VIC) and Western Australia (WA).

curve estimated by Budyko using world-wide data. Clearly, there is considerable scatter in the water balance estimates around the *Budyko curve*, which may variously be caused by other aspects of climate (e.g., seasonality and storminess), landscape properties, and human-induced changes to land cover. For example, the water balance estimates for Salmon and Wights catchments, two paired experimental catchments in the south-west of Western Australia, differ significantly due to vegetation clearing that occurred in Wights while Salmon was kept in its native condition (Stokes, 1985).

Milly (1994) investigated the nature of climate and landscape interactions governing the mean annual water balance through the use of a simple conceptual bucket model (Manabe, 1969). Using this model he explored the physical basis of the Budyko curve, gaining insights into the competition between rainfall and atmospheric demand (i.e., water and energy) and the regulating influence of soil–moisture storage. Milly's (1994) results also demonstrated that a simple Manabe-type model is adequate to capture the critical process controls on mean annual water balance. However, his original work concentrated on humid catchments, located in the eastern half of the USA. The question arises whether such a simple model is still adequate to capture water balance variability at smaller time scales (i.e., within the year), and also inter-annual variability, especially when we extend the analysis to include both humid and semi-arid catchments.

This paper attempts to extend Milly's (1994) work to investigate broad climatic and landscape controls on annual water balance, and especially inter-annual variability of annual runoff, and how these controls differ between humid and semi-arid catchments. We explore these controls by carrying out comparative analyses of four catchments selected in New Zealand (NZ), Western Australia (WA), South Australia (SA) and Queensland (QLD), which experience a wide range of climates, from temperate (NZ), to Mediterranean (WA), dry Mediterranean (SA) and temperate–tropical (QLD). We do this by analyzing rainfall–runoff data from these catchments and interpreting the observed inter-annual variability of annual runoff through the prism of a simple rainfall–runoff model which is a slight extension of the model used by Milly (1994). On the basis of quasi-analytical and numerical solutions of the water balance equation underpinning this simple model, we investigate the roles of both climate factors (i.e., storminess and seasonality of rainfall) and soil and vegetation factors (i.e., soil depth, soil drainage properties and vegetation cover) in controlling both the mean annual water balance and the inter-annual variability of annual runoff. In spite of the use of data from actual catchments, this remains an exploratory study, with the aim being to explore the broad controls on the inter-annual variability of observed annual water balance. This is not, by any means, a model development exercise, which explains the use of simple, conceptual models.

The paper begins with the presentation of a simple bucket model that includes the generation of runoff by surface runoff (by saturation excess) and subsurface flow, and presents analytical or quasi-analytical solutions of the resulting water balance equation. These solutions are used to explore the water balance behaviors that are possible under different combinations of climatic and landscape properties, leading to the concept of "hydrologic regimes", which is illustrated through application of realistic model parameters and inputs. Next, the simple water balance model is driven by rainfall inputs that include different types of hypothetical *intra-annual* (i.e., within-year) variability of rainfall intensities and the results are used to explore the controls on observed *inter-annual* (i.e. between-year) variability. The analyses are repeated with and without the carry-over of storage between storm events, to illustrate the critical role played by the interactions between climatic seasonality and soil–moisture storage. The paper concludes with the results of sensitivity analyses aimed at investigating the effects of both climate properties (i.e. seasonality and storminess) and landscape properties (i.e. soil depth, vegetation cover and drainage time scale) on the annual water balances.

A simple linear rainfall–runoff model

We first present our simple water balance model, which has been based on previous work by Atkinson et al. (2002), Farmer et al. (2003) and Eder et al. (2003). Because of the need or desirability to incorporate intra-annual (seasonal) variability of water balance, this model extends the bucket models of Manabe (1969) and Milly (1994) and incorporates both subsurface runoff and sat-