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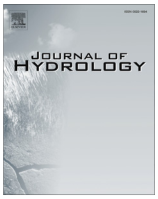

A similarity index for storm runoff due to saturation excess overland flow

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SUMMARY

An index for the determination of hydrologic similarity is proposed and demonstrated. The index is based on the steady state assumption and is applicable for small- to medium-sized catchments where storm runoff is generated principally by the saturation excess mechanism – a key runoff generation mechanism in humid regions. The index uses variables that can be derived from rainfall and streamflow measurements and topographic and soil hydraulic attributes. The index is applied to eight gauged catchments located in southeast Australia. Comparisons of similarity index values with groupings obtained from a peaks-over-threshold (POT) analysis of daily maxima of hourly runoff series show good agreement. A sensitivity analysis of the index and the POT series indicated that these results are reasonably robust provided catchments are allowed to have partial memberships in all of the groupings identified.

1. Introduction

Hydrologic similarity is a key concept for fields as diverse as surface water quality management, aquatic ecology, catchment conservation planning, and engineering hydrology (Huang and Ferng, 1990; Hosking and Wallis, 1997). The concept is based on the premise that if the rainfall–runoff processes in two catchments are alike their hydrologic responses to rainfall will be similar (Blöschl, 2005). It provides a basis for catchment classification, informing the design of experimental and monitoring networks, regionalisation, improved understanding of the dominant controls on catchment function, and greater insight into the potential impacts of environmental change on hydrologic response (Wagener et al., 2007, 2008; Sawicz et al., 2011).

Although considerable effort has been put into empirical and theoretical studies of catchment classification and hydrologic similarity during the last four decades, no universally agreed measures have been identified (e.g. Chery, 1967; Rodriguez-Iturbe and Valdes, 1979; O'Loughlin, 1981, 1986; Dooge, 1986; Sivapalan et al., 1987, 1990; McDonnell et al., 2007; Wagener et al., 2007, 2008; Lyon and Troch, 2010). A number of approaches have been proposed including (Blöschl, 2005; He et al., 2011): using geographical proximity as an indicator of similarity under the assumption that the rainfall–runoff relationship is likely to vary smoothly in space (e.g. Merz and Blöschl, 2005; Zhao et al., 2012); clustering of catchments based on their landscape, climate and streamflow attributes under the assumption that if these characteristics are similar across catchments their hydrologic responses will also be similar (e.g. Nathan and McMahon, 1990; Hosking and Wallis, 1997; Bates et al., 1998; Rao and Srinivas, 2008); and similarity indices (defined as one or more dimensionless or dimensional numbers reflecting the structure of runoff generation and routing) that are based on the presumption that catchments could be expected to a similar hydrologic response if they are associated with the same value of a similarity index (e.g. Chery, 1967; Rodriguez-Iturbe and Valdes, 1979; O'Loughlin, 1981, 1986; Sivapalan et al., 1987, 1990; Larsen et al., 1994; Berne et al., 2005; Harman and Sivapalan, 2009; Lyon and Troch, 2010). Many of these studies considered the infiltration excess (Horton) mechanism, which is most common in semi-arid and arid lands, or subsurface flow.

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This paper develops and applies a similarity index for catchments where the dominant streamflow generation mechanism is overland flow due to saturation excess, a key runoff generation mechanism in humid regions (Dunne, 1983). We begin with the analytical relationship of Aryal et al. (2002) that, under the assumption of steady state conditions, describes the saturation behaviour of hillslopes based on a similarity parameter expressed in terms of their topographic, soil hydraulic and climatic attributes. We show that a reformulation of this relationship leads to a similarity index that can be determined using only readily available data and inferable variables. While our work is somewhat similar in spirit to that of Sivapalan et al. (1987) it is quite different in the above and other respects. They derived five similarity parameters and three dimensionless auxiliary conditions using a combination of numerical simulation and dimensional reasoning and some variables for which field data are not widely available. The parameters characterise similarity in terms of the dominance of either the infiltration excess or the saturation excess overland flow mechanism. As they have pointed out it is doubtful that any two catchments could jointly satisfy all of the dimensionless parameters (Sivapalan et al., 1987). In a follow up study, Larsen et al. (1994) found that two out of the five similarity parameters that represented normalised catchment averaged value of saturated hydraulic conductivity at the soil surface and a term describing its decay with soil depth were sufficient to discriminate between actual catchments on the basis of their dominant runoff generation mechanisms.

This paper has three objectives. The first and second are based on ideas put forward by Beven et al. (1988), Wood et al. (1990) and Larsen et al. (1994): to explore the classification of catchments by similarity in their runoff generation response, and to examine the extent to which this classification is consistent with any groupings identified during analyses of flood frequency distributions. The third objective is to assess the sensitivities of classifications obtained by various techniques to variations in parameter values. The paper is divided into seven sections. Section 2 provides a derivation of the similarity index, while Section 3 describes the eight study catchments and data used. Section 4 details the methods used to: compute the similarity index; perform a flood frequency analysis; conduct classification analyses using a suite of algorithms; perform hypothesis tests to determine the statistical significance of the differences between the sample means of the index values for the study catchments; and to carry out a sensitivity analysis. Results illustrating the capability and utility of the similarity index are presented in Section 5. A discussion of the results is provided in Section 6 and our conclusions presented in Section 7. Appendix A lists the notation and dimensions for the key parameters and variables used throughout the investigation.

2. Derivation of catchment similarity index

Saturation excess overland flow occurs when, on a part of a catchment, runoff is generated by direct precipitation on topsoil that has become saturated during a storm or exfiltration as saturation occurs. It is usually confined to the base of hillslopes, areas with thin soil cover and areas where hydraulic conductivity decreases with depth. Exfiltration is usually, but not always, a minor contributor to storm event response. The spatial extent of the saturated area depends on the moisture content of the topsoil before, during and after precipitation. At the onset of a storm event, precipitation that falls on unsaturated soil infiltrates and increases the moisture content until saturation occurs. With continued precipitation, the extent the runoff source areas expands and any direct precipitation on these areas becomes runoff. Between storm events, the soil moisture declines and the runoff source areas contract.

The focus of our study is the steady state saturation behaviour of catchments. Our similarity index is based on the following assumptions: the surface soil is underlain by a lower permeability layer; downslope flow is predominantly in the saturated zone above a low permeability layer and is driven by a hydraulic gradient equal to the local surface slope; and local vertical recharge is effectively instantaneous. The above assumptions are similar to those used in previous analyses of saturation on hillslopes and popular rainfall–runoff models. These include the use of steady state analysis by Horton (1936), the Kirkby topographic index (Kirkby, 1975) and TOPMODEL (e.g. Beven and Kirkby, 1979; O'Loughlin, 1986; Sivapalan et al., 1987; Moore and Grayson, 1991; Barling et al., 1994; Ambroise et al., 1996; Fan and Bras, 1998; Troch et al., 2002). Finally, we note that the above assumptions have been frequently applied in situations where no verifying field data are available.

Under the assumptions listed above, Aryal et al. (2002) derived a similarity criterion for the extent of hillslope saturation based on its topographic, soil hydraulic and climatic attributes:

$$\frac{A_s}{A_t} = 1 - \frac{g(X)}{\frac{q}{Z}\frac{L}{KS}\delta(X)} \tag{1}$$

where A_s/A_t is the ratio of saturated area to the total area of the hillslope, L is the hillslope length, S is the overall slope; Z is the soil thickness, K is the saturated hydraulic conductivity, q is the net drainage flux defined as slowly varying residual rainfall minus all losses (O'Loughlin, 1986; Woods and Sivapalan, 1997), $g(X)$ is a profile shape function that gives different hillslope profiles, $\delta(X)$ is the planform shape function which describes different simplified shapes in plan that are expressed in terms of a convergence ratio, and X is the non-dimensional distance from the hillslope outlet.

Consider the combined parameter $V = (L/KSZ)\delta(X)/g(X)$. It follows from Eq. (1) that if V is large a smaller value of q is needed to cause the same degree of saturation. If the distribution of V for a given catchment has an elongated upper tail then, for a given q, a large number of hillslopes of that catchment are likely to become saturated at or near X. Aryal et al. (2002) tested this formulation using topographic data for and field measurements of Z and K from three catchments near Canberra, Australia, and found that that the catchment response to storm events showed remarkable similarity or dissimilarity according to the distribution of V.

A simple reformulation of Eq. (1) permits application of the similarity criterion to gauged catchments even if field measurements of Z and K are not available. Under conditions where storm runoff from infiltration excess is negligible, the quickflow depth (QF) produced by the total net rainfall (P_n, the portion of gross catchment rainfall that reaches saturated areas) can be a good indicator of the extent of saturated areas in a catchment for a given event (O'Loughlin, 1981; Steenhuis et al., 1995; Woods and Sivapalan, 1997). Thus, substituting $\mathrm{QF}/P_n = A_s/A_t$ into Eq. (1) and rearranging terms yields

$$\omega = (1 - \mathrm{QF}/P_n)/T_e = Sg(X)/qL\delta(x) \tag{2}$$

where ω is a catchment similarity index and $T_e = KZ$ denotes the effective soil transmissivity for the catchment. Clearly the index is a variable which has a different value for each storm event. The main idea here is that catchments are declared similar to each other if the corresponding probability distributions of ω differ slightly and dissimilar if the distributions do not match well. Further details are given in Section 4.

Eq. (2) is easily amendable to physical interpretation. Soil transmissivity and subsurface storage have dominant roles in catchment saturation behaviour. In the case of the former, for a given rainfall input, catchments with high transmissivities are able to avoid saturation for extended periods between and during storm