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Role of rainstorm intensity underestimated by data-derived flood models: Emerging global evidence from subsurface-dominated watersheds

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ABSTRACT

Intense rainstorms are a prevalent feature of current weather. Evidence is presented showing that simulation of flood hydrographs shown to be dominated by subsurface flow requires watershed model parameterisation to vary between periods of different rainstorm intensity, in addition to varying with antecedent basin storage. The data show an emerging global relation between flood response and the intensity of rainstorms. Flood responses are quantified as watershed residence times (strictly time constants of nonlinear transfer-function models) identified directly from information contained within 15-min rainfall and streamflow observations. The emerging monotonic, curvilinear relation indicates that (subsurface) watershed residence time decreases as mean intensity rises, and is seen over a wide range of synoptic conditions from temperate and tropical climates. Projected increases in rainstorm intensity would then result in a greater likelihood of river floods in subsurface-dominated watersheds than is currently simulated by systems models omitting this additional nonlinearity.

Software availability

Program title: CAPTAIN
Developers: Peter Young, Wlodek Tych, Diego Pedregal, James Taylor and Paul McKenna (Lancaster University) Contact e-mail: p.young@lancaster.ac.uk or c.taylor@lancaster.ac.uk
First available: February 2004 (Version 5 released on Internet)
Hardware: PC platforms supporting Matlab™
Software: Captain Toolbox for Matlab™: download from http://www.lancaster.ac.uk/staff/taylorcj/tdc/download.php
Toolbox requirements: Most of the functionality is available using the basic Matlab package

1. Introduction

Drainage basins temporarily store each pulse of rainfall to give a streamflow output more damped than that of the rainfall input. With physics-based watershed models the damping is produced primarily by combination of the prevailing antecedent moisture states with the unsaturated permeability distributions (Bear et al., 1968; Ali et al., 2012). With systems models of basins the damping in the rainfall (r) or effective rainfall (r_{eff}) to streamflow (q) signal is often quantified using residence times (or time constants) of a transfer-function or impulse-response function (Young, 1998; Box et al., 2008). The r_{eff} is the rainfall signal after a nonlinear transformation to account for the effects of antecedent watershed storage on hydrograph response (e.g., Whitehead et al., 1979; Young and Beven, 1994; Ye et al., 1998; McIntyre et al., 2011).

There is a general perception that stream hydrographs are flashier and more likely to produce over-bank flows in periods and/or regions experiencing more intense rainfall events. A very small number of studies have demonstrated an apparent link between the properties of hydrograph shape and averaged rainfall intensity characteristics for a specific storm period. Minshall (1960) showed that different measures of the shape of calculated Unit Hydrographs (Sherman, 1932) altered with changes in the hourly rainfall intensity (inches/h) averaged over individual storms. As a specific example, this study showed that the time for the hydrograph to recess to 40 percent of the peak-flow reduced as the average hourly

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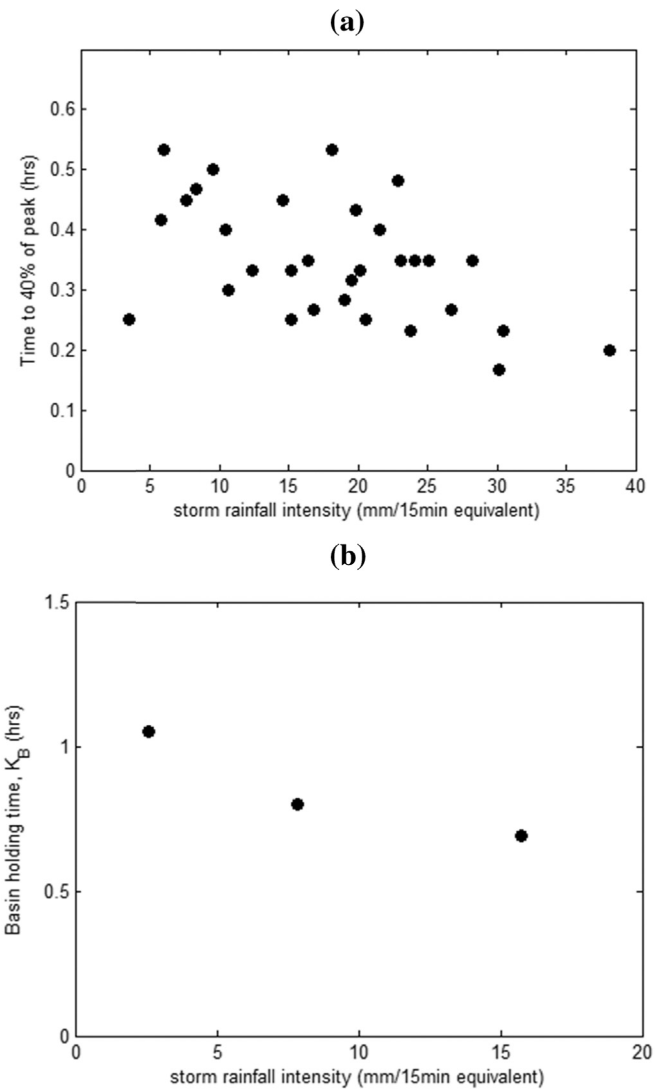

Fig. 1. Relationship of measures of hydrograph shape with rainfall intensity averaged over a storm period from two previous studies. (a) Time from the Unit Hydrograph peak to the 'point on the streamflow recession at 40% of the peak' against rainfall intensity (inches/h) averaged over the specific storm (converted to mm/15min equivalent), adapted from Table 3 in Minshall (1960). (b) Basin 'holding time' of the Instantaneous Unit Hydrograph against rainfall intensity (cm/h) averaged over the specific storm (converted to mm/15min equivalent), adapted from Fig. 6 in Wang et al. (1981).

storm rainfall intensity increased (Fig. 1a). Similarly, Wang et al. (1981) showed that the basin 'holding time' (K_B) reduced as the average hourly storm rainfall intensity (inches/h) increased (Fig. 1b). In other words, change in hyetograph shape (i.e., temporal evolution of rainfall totals through a storm) between different types of storm can produce different hydrograph shapes and hence nonlinearity in the rainfall to streamflow response (Rodríguez-Iturbe et al., 1982).

Several studies undertaken in regions with more intense tropical rainfall events (e.g., Noguchi et al., 1997; Chappell et al., 2006, 2012; Hugenschmidt et al., 2014) have demonstrated that very flashy stream hydrographs can be produced almost entirely from subsurface flow pathways, i.e., without the need for activation of significant volumes of overland flow (on slopes) during storms. Consequently, nonlinear rainfall-streamflow response generated in such basins would be entirely related to shallow or deeper groundwater flow pathways. Even after correcting for the widely acknowledged nonlinear effects of antecedent wetness on rates of subsurface flow (Graham et al., 2010), it is *our research hypothesis that additional nonlinearities in rainfall-streamflow response dominated only by subsurface flow may be generated by changes in hyetograph shape*. If this hypothesis is valid, it would require explicit model parameterisation or temporal shifts in existing systems model parameterisations to represent and so better simulate streamflow through storms with contrasting conditions. The rainfall intensity regime for a period of contiguous storms is likely to vary with synoptic meteorological typology in time and across the globe. Those in the tropics tend to have greater intensities than those prevailing in temperate regions primarily due to differences in regional convection (Wohl et al., 2012). Equally large variations are seen within the tropics; for example synoptic conditions associated with tropical cyclones tend to have greater average intensities than those associated with local thunderstorms (Francis and Gadgil, 2006; Zipser et al., 2006; Shepherd et al., 2007). To reiterate, non-stationarity in systems model parameters (see e.g., Kundzewicz and Napiórkowski, 1986) characterising rainfall-streamflow responses in subsurface-flow dominated watersheds caused by temporal variations in rainfall intensity regime, would be in addition to those caused by changes in antecedent moisture (or seen in basins with overland flow activation).

While previous studies provide some observational evidence for the potential effects of storm-averaged rainfall intensity on the non-stationarity of hydrograph residence times (Fig. 1ab), the absence of a generic numerical relationship (for basins dominated only by subsurface flow) may be responsible for the lack of a wider recognition of the phenomenon. In part this may be due to the limited range of hydrograph responses and storm-types examined previously (see e.g., Minshall, 1960; Wang et al., 1981; Rodríguez-Iturbe et al., 1982). Consequently, a greater diversity of synoptic meteorological conditions was examined in this study to attempt to *quantify the first approximation of a generic relationship between rainfall intensity characteristics and storm hydrograph shape for subsurface-dominated flood responses.*

2. Experimental data sets

In this study selected rainfall and streamflow records were those associated with a set of experimental basin systems (each <5 km^2) known to be dominated by shallow subsurface paths (sometimes called 'interflow'), in addition to experiencing a broad spectrum of synoptic conditions. One such system is the South Creek basin in a humid tropical region of Australia (e.g., Chappell et al., 2012). Two other example experimental basins in the tropics (Fig. 2) with hydrograph responses shown to be dominated by shallow subsurface paths, are the Baru basin on Borneo Island (e.g., Kretzschmar et al., 2014) and Saimane basin of the larger Aghanashini basin in India (Bonell et al., 2010; Krishnaswamy et al., 2012). These have contrasting rainfall intensity regimes, with the Baru being dominated by local thunderstorms and Saimane by Tropical Convergence Zone (TCZ) events in the summer monsoon. To capture the effects of typically lower intensity rain-events in temperate regions, three basins from across upland UK are incorporated in the analysis (Fig. 2). The Hafren, Greenholes and Nant-y-Craflwyn basins are dominated by shallow water-paths (Bell, 2005; Chappell and Lancaster, 2007; Jones and Chappell, 2014) and frontal rainfall. Further basin details are given in Table 1. While rainfall-streamflow responses for only six experimental basins are studied, the 16 periods of contiguous storms analysed do cover a diverse range of synoptic conditions (Table 2).

The primary hyetograph characteristic evaluated was the average rainfall depth from all 15-min intervals with measured rainfall in the selected periods of contiguous storms of the same