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Research article

# An empirical assessment of which inland floods can be managed

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ABSTRACT

Riverine flooding is a significant global issue. Although it is well documented that the influence of landscape structure on floods decreases as flood size increases, studies that define a threshold flood-return period, above which landscape features such as topography, land cover and impoundments can curtail floods, are lacking. Further, the relative influences of natural versus built features on floods is poorly understood. Assumptions about the types of floods that can be managed have considerable implications for the cost-effectiveness of decisions to invest in transforming land cover (e.g., reforestation) and in constructing structures (e.g., storm-water ponds) to control floods. This study defines parameters of floods for which changes in landscape structure can have an impact. We compare nine flood-return periods across 31 watersheds with widely varying topography and land cover in the southeastern United States, using long-term hydrologic records (≥20 years). We also assess the effects of built flow-regulating features (best management practices and artificial water bodies) on selected flood metrics across urban watersheds. We show that landscape features affect magnitude and duration of only those floods with return periods ≤10 years, which suggests that larger floods cannot be managed effectively by manipulating landscape structure. Overall, urban watersheds exhibited larger (270 $m^3$/s) but quicker (0.41 days) floods than non-urban watersheds (50 $m^3$/s and 1.5 days). However, urban watersheds with more flow-regulating features had lower flood magnitudes (154 $m^3$/s), but similar flood durations (0.55 days), compared to urban watersheds with fewer flow-regulating features (360 $m^3$/s and 0.23 days). Our analysis provides insight into the magnitude, duration and count of floods that can be curtailed by landscape structure and its management. Our findings are relevant to other areas with similar climate, topography, and land use, and can help ensure that investments in flood management are made wisely after considering the limitations of landscape features to regulate floods.



## 1. Introduction

Riverine flooding is a significant global issue for millions of people. Flooding worldwide affects 178 million people; losses exceeded US$ 40 billion in 2010 (Jha et al., 2012) and continue to increase (Milly et al., 2002; Patterson and Doyle, 2009; Highfield et al., 2014). Floods exacerbate stream bank erosion, with adverse consequences for transportation infrastructure (Dutton, 2012) and water quality, particularly for downstream users (Brabec et al., 2002). Extreme floods exact especially high tolls (Pielke, 1999; Tran et al., 2010). Inland flooding highlights society's vulnerability to natural disasters and the importance of policies and land use planning to managing hazards and risks (Kaźmierczak and Cavan, 2011). Mixed evidence on the effectiveness of flood control structures, in addition to their high installation and maintenance costs (Thurston et al., 2003), legislative and institutional barriers (Roy et al., 2008), and long-term adverse impacts on aquatic environments (Booth et al., 2002), raise important questions about the efficacy of current flood control strategies. If managing floods were easy or straightforward, it would not be an issue.

Whether forests mitigate catastrophic flooding and whether the damages from these events are consequences of the loss of natural land cover continue to be highly contentious topics (FAO-CIFOR,

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2005; Laurance, 2007). Bradshaw et al. (2007) found that flood frequency is positively related to the deforestation rate across 56 developing countries, after controlling for rainfall and slope among other factors. In contrast, Lecce and Kotecki (2008) found no relation between human-induced land cover changes and flood severity in their analysis of relations among river flow, population growth, number of housing units, and area under cultivation in North Carolina from 1930 to 2000. The perception that natural ecosystems mitigate extreme floods has significant implications for land use management and planning (Calder and Aylward, 2006), particularly for upstream communities blamed for flood damages downstream (Tran et al., 2010). Recent catastrophic floods in China (Trac et al., 2007), Colombia (Aldana-Vargas, 2011), and Bangladesh (Mishra et al., 2012) have led to investments in costly reforestation projects, with little evidence of their effectiveness in reducing floods (Hofer, 2005).

Equally contentious is the assumption that engineered structures prevent river flooding and its concomitant damage (Tobin, 1995). Such structures act locally in the sense that peak flows are controlled only at their specific locations (Lehner et al., 2011b). Numerous historical floods (e.g., along the Mississippi, Yangtze, and Yellow rivers) have been followed by construction of expensive flood control structures, yet many of these structures exacerbated damage (Koebel, 1995; Pielke, 1999; Criss and Shock, 2001; Tollan, 2002). While small floods can be contained in the areas benefited by these structures, often the designed flood-return period (e.g., 100-year flood for levees and dams) promotes a false sense of security, which encourages development in high-risk areas (Highfield et al., 2013). In the United States for example, the National Flood Insurance Program considers land behind a 100-year flood levee to be protected, which has facilitated construction on these lands, as they are perceived as safe (Ludy and Kondolf, 2012). However, flood control structures fail occasionally, causing widespread damage locally and downstream (Pielke, 1999; Doyle et al., 2008), as was the case with China's Banqiao Dam in 1975 (Graham, 1999).

Inland floods are primarily driven by precipitation patterns (Kochenderfer et al., 2007; Lecce and Kotecki, 2008; Tran et al., 2010). Although natural and anthropogenic features can alter flood characteristics (Eng et al., 2013), these influences decrease as flood-return period increases (Kundzewicz, 1999). Smaller floods are more responsive to landscape structure (i.e., landscape features manageable by humans) (Leopold, 1968; Hollis, 1975; Smith et al., 2002a; Wissmar et al., 2004; Kochenderfer et al., 2007), with lower-peaked and longer duration floods in forested watersheds but higher-peaked and shorter duration floods in urban watersheds (Magilligan and Stamp, 1997; Findlay and Taylor, 2006; Hawley and Bledsoe, 2011). Magilligan and Stamp (1997) modeled hydrologic alterations in a small watershed in Georgia by reconstructing past land cover, and found greater temporal variability among 2-year floods than among 100-year floods. Urbanization affects the magnitude and duration of flows up to the 5-year flood in semi-arid environments. Hawley and Bledsoe (2011) and Sturdevant-Rees et al. (2001) found no evidence of forested watersheds reducing peak runoff volumes for the 100-year flood. Similarly, artificial water bodies affect flooding only up to the point where runoff equals their storage capacity (Sordo-Ward et al., 2012). Collectively, these studies suggest there is a flood-size threshold, above which watersheds with different landscape characteristics respond the same (Fig. 1). To date, such a threshold has not been measured.

Return period is an objective criterion for distinguishing what types of floods can be managed by manipulating landscape features. Key metrics used to describe flooding regimes across spatial and temporal scales include flood duration, magnitude and count (Poff et al., 1997; Olden and Poff, 2003). Flood duration is the length of time a particular flood exceeds a certain flow threshold. Flood magnitude is the amount of discharge passing a fixed location, and flood count is the number of floods exceeding a certain flow threshold. Aquatic ecosystems are sensitive to the amount, variability and timing of recurrent floods (Poff and Ward, 1989), while humans are impacted mostly by high magnitude floods (Yen, 1995). Long-duration flooding significantly lowers property values and causes immediate damage (Filatova and Bin, 2014).

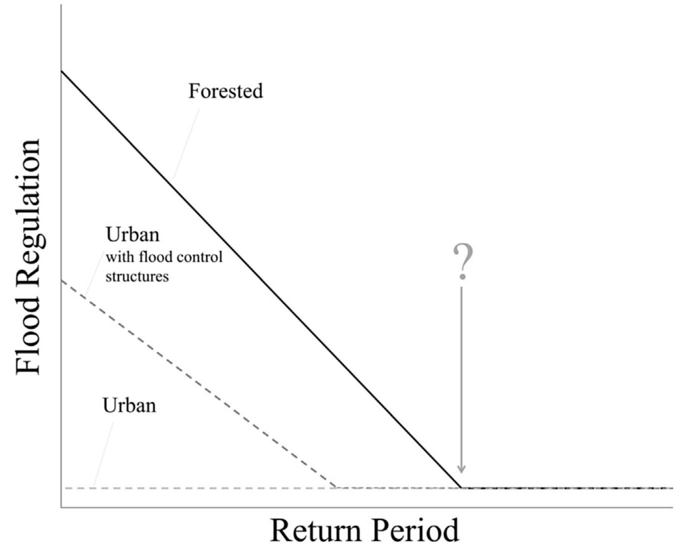


**Fig. 1.** Conceptual relations between a landscape's capacity to regulate floods and return period for hypothetical urban, urban with flood control structures, and forested watersheds. All watersheds have little capacity to regulate very large floods.

To inform decision makers and managers on how to make flood control strategies more cost-effective, we need a clearer understanding of which floods can be curtailed by landscape structure and where flow-regulating features are more effective. To date, no studies have provided empirical evidence of a) a threshold, in terms of flood-return interval, where landscape structure can and cannot curtail floods or b) engineered structures curtailing river flooding. In this study, we examine floods at nine return periods in selected watersheds in the southeastern US using data from long-term gaging stations. Our specific objectives are to (1) define watershed types in relation to flooding, 2) identify a threshold of manageable floods based on flood magnitude, duration and count, and 3) assess effects of flow-regulating features on flooding in urban watersheds.

## 2. Methods

### 2.1. Study area

The 31 gaged watersheds selected in this study represent diverse landscapes in the southeastern US, particularly Virginia (VA) and North Carolina (NC), yet share a similar climate (Patterson et al., 2012). Recent population growth has been concentrated in urban areas (Young, 2014; Borders, 2014), with little change in non-urban areas (Mogollón, 2014). These spatially explicit patterns of growth allow us to compare flood regimes among watershed types for the past 20 years. Our study design included widely varying topography and land use, as watersheds were distributed across major physiographic provinces; most watersheds were in the Piedmont region and others were in the Coastal Plain, Valley and Ridge, and Blue Ridge regions (Fig. 2; see Table A1 in Supplementary Materials).

We selected these watersheds based on size ($\leq$80 km$^2$) and