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4 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 ($270 \text{ m}^3/\text{s}$) but quicker (0.41 days) floods than non-urban watersheds ($50 \text{ m}^3/\text{s}$ and 1.5 days). However, urban watersheds with more flow-regulating features had lower flood magnitudes ($154 \text{ m}^3/\text{s}$), but similar flood durations (0.55 days), compared to urban watersheds with fewer flow-regulating features ($360 \text{ m}^3/\text{s}$ 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.

Keywords: flooding, flood management, flood-return period, flow-regulating features, landscape change, southeastern United States

Highlights

- Floods with return periods ≤ 10 years can be managed by manipulating the natural or built environment
- Built flow-regulating features lower flood magnitude but do not lengthen flood duration
- Forested watersheds regulate small floods more effectively than watersheds with flow-regulating features

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 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 (Tran 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 (Figure 1). To date, such a threshold has not been measured.

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.

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).

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 (Figure 2; see Table A1 in Supplementary Materials).

Fig. 2. Map illustrating the type and location of the 31 study watersheds, by physiographic province, across North Carolina and Virginia.

We selected these watersheds based on size ($\leq 80\text{km}^2$) and availability of instantaneous discharge record (period ≥ 20 years). We selected instantaneous records, as opposed to daily averages, to capture the peaks of floods that might be obscured in daily average data (Rice and Hirsch 2012). We limited the analysis to relatively small watersheds to highlight the effect of land cover on flooding, as the influence of anthropogenic disturbance on stream flow strongly decreases with increasing watershed size (Tollan 2002, Bloschl et al. 2007, Chang and Franczyk 2008, Petrow and Merz 2009).

Each watershed was delineated in ArcGIS 10.1 (ESRI 2012) using the National Hydrography Database plus version 2, 30-m flow accumulation and direction layers; pour points were derived from the gage locations provided in the United States Geological Survey's (USGS) flow records.

2.2. Hydrologic Analysis

We downloaded peak and instantaneous discharge records from the USGS Water for the Nation Database (USGS 2013). Using the peak annual discharge records, we used USGS's PeakFQ program to derive the discharge values for 1.005- (henceforth 1-year flood), 1.5-, 2-, 5-, 10-, 20-, 50- and ≥ 100 -year floods and manually estimated 80% discharge of a 1-year flood. We defined the lowest flood as 80% of a 1-year flood, which happens, on average, multiple times a year. This arbitrary threshold enabled us to assess small changes in flooding over time (Huang et al. 2008) at a flow below the bank-full discharge (Poff and Ward 1989, Bunn and Arthington 2002). Striving to represent trends in hydrology, as opposed to yearly variation in precipitation, we used at least 21 years of peak discharge records to derive return periods in PeakFQ.

Available periods of instantaneous records ranged from 20 to 28 years for a watershed, but we limited the analysis to 1991-2013, as this period held a continuous record for most watersheds. We defined a complete water-year discharge record as one having at least 300 days of data. We tabulated the count, magnitude and duration of floods (independent events); a flood could not last < 24 hours (see Figure A1 in Supplementary Material). Based on the nine flood-return period thresholds derived from the peak discharge records, we compiled the count, magnitude and duration of independent floods for each return period per water year. We define flood count as the number of times per water year the discharge of an independent event equaled or exceeded 80% of the discharge of a 1-year flood. Flood magnitude is the discharge above 80% of a 1-year flood. Flood duration is the length of time when discharge exceeds the flood threshold per flood event.

2.3. Land Cover Analysis

To classify each watershed by its dominant land cover, we first assembled comparable and publicly available land cover databases for the five time periods available. The 1992-Enhanced database is the product of merging the Land Use Data and Analysis 1970-1985 database, known as GIRAS (Geographic Information Retrieval and Analysis System) and the National Land Cover Database (NLCD) 1992 (Nakagaki et al. 2007). The 1992-Enhanced database provides a representation of land cover for the early 1990s. The different classification methodologies used between NLCD 1992 (i.e., unsupervised) and NLCD 2001 (i.e., supervised) make these two layers directly incomparable. However, the retrofit products of 1992 and 2001 make the data for these two time periods compatible (Fry et al. 2009). We also used the 2006 (Fry et al. 2011) and 2011 (Jin et al. 2013) NLCDs.

We aggregated land cover classes from the NLCD for five time periods (1992-Enhanced, 1992-Retrofit, 2001-Retrofit, 2006 and 2011) into three major groups: forest, urban and agriculture (see Table A2 in Supplementary Materials). These groups accounted for 97-100% of the land cover in the study watersheds, except one with 15% barren land; other land covers were mainly water and barren lands. In aggregating major land cover classes by watershed, we minimized the error produced in comparing the land cover databases (Price et al. 2003). To classify each watershed by its dominant land cover, we conducted hierarchical cluster analyses (Rousseeuw, 1987) based on the k-means procedure using the percentages of forest, urban and agriculture for the five time periods in JMP® Pro 10 (SAS Institute Inc. Cary, NC).

2.4. Flood-return Period Threshold

Before examining relations between flood metrics and landscape structure, we first assessed the temporal and spatial autocorrelation structure of our flood metrics. Finding no temporal or spatial autocorrelation enabled us to treat the yearly records as independent observations (see Supplementary Materials for more information). Not controlling for such autocorrelation can reduce the effective number of samples available to test trends (Douglas et al. 2000).

We used generalized linear mixed models (GLMMs) to evaluate the flood threshold for which changes in landscape structure can influence flooding. GLMMs handle non-normal data and incorporate random effects (Bolker et al. 2008). Prior to running the GLMMs, we examined the flood magnitude, duration and count distributions for each flood-return period for goodness-of-fit to a number of possible distribution and selected the most appropriate one based on the overdispersion parameter (see Supplementary Materials for more information). To examine how different flood-return periods respond to variation in dominant land cover type, we ran one GLMM per flood-return period (80% of a 1-, 1-, 1.5-, 2-, 5-, 10-, 20-, 50- and ≥ 100 -year floods) per flood metric (count, duration and magnitude). We used gage identification number (ID) as a random effect, and dominant land cover (from the cluster analysis) and flood-return interval as categorical fixed effects. For each return period, we compared the least-squares means of the watersheds with different dominant land-cover types to determine the direction and magnitude of the effect of dominant land cover on flood count, duration and magnitude using Bonferroni-adjusted confidence intervals.

2.5. Other Climatic and Landscape Features

Since other climatic and landscape features also influence floods (Wilby and Keenan 2012) we summarized the precipitation, hill slope and soil type for each land-cover category from our cluster analysis. We derived mean annual precipitation from the PRISM database from 1991 to 2012 (PRISM Climate Group 2013), mean hill slope from the National Hydrography Database (NHD 2013), and percentages of sandy and loamy soils (A and B soil hydrologic group) from SSURGO (NRCS 2012). We processed this information in ArcGIS version 10.1 (ESRI 2012).

2.6. Flow-regulating Features and Flooding

We assessed the effect of flow-regulating features on flood magnitude and duration by comparing urban watersheds ($\geq 30\%$ urban cover) with different areal proportions of BMPs (e.g., wet and dry ponds, bioretention areas, stormwater wetlands, and sand filters) and artificial water bodies (e.g., farm ponds, golf course ponds, water supply reservoirs; henceforth, AWBs) to forested watersheds. We selected flood records based on the maximum flood-return period for which landscape structure can curtail floods (derived from the first study objective).

We derived locations of BMPs and AWBs (jointly, flow-regulating features) from multiple sources: United States Army Corps of Engineers' National Inventory of Dams (USACE 2012), Global Reservoirs and Dams Database (Lehner et al. 2011a), National Anthropogenic Barrier Dataset (Ostroff et al. 2012), Federal Emergency Management Agency's National Flood Hazard Layer (FEMA 2013), National Hydrograph Database on Waterbodies (USGS 2012), the North Carolina Department of Environment and Natural Resources' dam inventory (NCDENR 2013), Virginia Database (personal communication Mark Bradford, Virginia Department of Conservation and Recreation), and county BMP databases (from contacts at individual counties). We used Google Earth aerial imagery to verify the existence of, map the surface area of, and date BMPs and AWBs. We used surface area as a surrogate for volumetric capacity, as information on volumetric capacity was largely unavailable. We standardized BMP and AWB area across urban watersheds by calculating the cumulative percentage of BMP (% BMP) and AWB (% AWB) surface area by watershed area per year from 1991 to 2013. We weighted flow-regulating capacity of AWBs and BMPs equally, because although AWBs are not constructed to control floods, they store water during floods, and are ubiquitous across the landscape (Smith et al. 2002b, Ignatius and Jones 2014).

To compare urban watersheds with different proportional coverage of flow-regulating features, we summed %BMP and %AWB, and divided the sums into three categories based on natural breaks in the data: low ($\leq 0.02\%$), medium (0.16% to 0.22%), and high (0.43% to 2.04%). Watersheds did not change

category during the period of study. We compared the three flow-regulating feature categories in urban watersheds to our nine forested watersheds ($\geq 89\%$ forested). We examined the effect of these four categories (Low, Medium, High and Forested) on selected flood metrics with GLMMs. We used gage ID and watershed size as random effects, and the four categories and mean annual precipitation as fixed effects. Prior to running the GLMMs, we examined the appropriate distribution of flood metrics and determined that a lognormal transformation (link=identity) best described magnitude and mean duration. We compared the least-square means of the four categories using Bonferroni-adjusted confidence intervals.

3. Results

3.1. Land Cover Analysis

Our cluster analysis of watershed land-cover composition revealed four major watershed types: forested (n=9; 89-98% forest), semi-forested (n=7; 50-80% forest), rural (n=6; 28-53% agriculture; 32-64% forest) and urban (n=9; 40-100% urban; 0-53% forest) (see Figure A3 in Supplementary Material). Based on the cluster analysis distances, urban watersheds were the most different from other watershed types; forested and semi-forested watersheds were the most similar. Of the 31 watersheds, only three changed types over the 23 years. Two watersheds changed from 1990 to 1992, one from semi-forested to urban (02142900) and the other from rural to urban (02099000). The third watershed shifted from rural to semi-forested (01673550) from 2001 to 2006.

3.2. Flood-return Period Threshold

3.2.1. Flood Magnitude

We found urban watersheds had significantly higher flood magnitudes up to the 2-year flood compared to non-urban watersheds, and this trend continued, albeit non-significant, for the 5- and 10-year floods (Table 1; Figure 3). Flood magnitude differences between urban and non-urban watersheds diminished as return period increased. At 80% of a 1-year flood, flood magnitude was four times greater in urban watersheds than non-urban watersheds, nearly three times greater for the 1-year flood, and two times greater for the 1.5- and 2- year floods. The 5-year flood was 1.5 times greater in urban watersheds, but this difference was not significant; the 10-year flood was equal in magnitude for urban and non-urban watersheds.

Table 1. Least-square means and Bonferroni confidence intervals for nine flood-return periods in four watershed types for three flood metrics¹.

Flood-return period	Count (number of floods)				Magnitude (m ³ /s)				Duration (days)			
	Urban	Rural	Semi-forested	Forested	Urban	Rural	Semi-forested	Forested	Urban	Rural	Semi-forested	Forested
80% Q1	2.23 ± 1.1 ^a	2.14 ± 1.1 ^a	2.19 ± 1.1 ^a	1.73 ± 1.1 ^a	20.5 ± 1.1 ^a	4.69 ± 1.1 ^b	3.57 ± 1.1 ^c	5.05 ± 1 ^b	0.04 ± 1.4 ^a	0.1 ± 1.3 ^b	0.16 ± 1.3 ^b	0.13 ± 1.4 ^b
Q1	5.76 ± 1.2 ^a	6.51 ± 1.2 ^a	6.65 ± 1.2 ^a	4.56 ± 1.2 ^a	107.7 ± 1.2 ^a	39.35 ± 1.2 ^b	34.05 ± 1.2 ^b	39.48 ± 1.2 ^b	0.25 ± 1.2 ^a	0.6 ± 1.2 ^b	0.86 ± 1.2 ^b	0.65 ± 1.3 ^b
Q1.5	0.57 ± 1.2 ^a	0.68 ± 1.2 ^a	0.53 ± 1.2 ^a	0.59 ± 1.1 ^a	25.64 ± 1.2 ^a	10.1 ± 1.2 ^b	7.52 ± 1.2 ^b	12.53 ± 1.2 ^b	0.44 ± 1.3 ^a	1.22 ± 1.3 ^b	1.54 ± 1.3 ^b	1.22 ± 1.3 ^b
Q2	1.34 ± 1.1 ^a	1.55 ± 1.1 ^a	1.26 ± 1.1 ^a	1.29 ± 1.1 ^a	37.56 ± 1.2 ^a	17.25 ± 1.3 ^b	12.41 ± 1.3 ^b	16.95 ± 1.2 ^b	0.47 ± 1.3 ^a	1.62 ± 1.3 ^b	1.97 ± 1.3 ^b	1.68 ± 1.3 ^b
Q5	0.10 ± 1.3 ^a	0.16 ± 1.3 ^a	0.15 ± 1.3 ^a	0.08 ± 1.3 ^a	9.34 ± 1.7 ^a	5.92 ± 1.8 ^a	6.32 ± 1.8 ^a	4.27 ± 1.6 ^a	0.07 ± 4.6 ^a	0.49 ± 7.1 ^b	0.27 ± 4.6 ^b	0.16 ± 4.6 ^c
Q10	0.06 ± 1.3 ^a	0.07 ± 1.4 ^a	0.05 ± 1.5 ^a	0.07 ± 1.3 ^a	7.04 ± 2 ^a	4.25 ± 2.3 ^a	2.84 ± 2.2 ^a	6.48 ± 2 ^a	0.05 ± 1.3 ^a	0.22 ± 1.9 ^b	0.15 ± 1.2 ^b	0.23 ± 1.3 ^b
Q20	0.01 ± 1.8 ^a	0.01 ± 2.8 ^a	0.02 ± 1.9 ^a	0.02 ± 1.8 ^a	1.71 ± 4.5 ^a	0.18 ± 6.2 ^a	1.55 ± 5.2 ^a	2.42 ± 5.7 ^a	0.00 ± 3 ^a	0.00 ± 4.6 ^a	0.02 ± 2.9 ^a	0.01 ± 2.6 ^a
Q50	0.01 ± 2.2 ^a	0.00 ± 2.2 ^b	0.00 ± 2.2 ^c	0.004 ± 3.3 ^a	0.00 ± 102 ^a	0 ± 2.1E+9 ^a	0 ± 4.9E+9 ^a	0 ± 3.E+4 ^a	0.00 ± 3.9 ^a	0.00 ± 0.0 ^a	0.00 ± 0.0 ^a	0.00 ± 5.5 ^a
≥Q100	0.01 ± 2.7 ^a	0.00 ± 0.0 ^a	0.01 ± 2 ^a	0.0 ± 0.0 ^a	0.00 ± 46.6 ^a	0.0 ± 46.6 ^b	0.00 ± 122 ^a	0.00 ± 46.6 ^c	0.00 ± 4.7 ^a	0.00 ± 4.7 ^b	0.03 ± 2.1 ^a	0.00 ± 4.7 ^c

¹ Means with the same superscript are not significantly different.

Figure 3. Mean flood count, magnitude, and duration, with standard error bars, for four watershed types across nine flood-return periods, increasing from left to right.

Surprisingly, forested, semi-forested and rural watersheds shared similar flood magnitude responses across flood-return periods, particularly for small floods (Figure 3), but different features seem to drive the similarity. Our forested watersheds overall receive higher mean annual rainfall (1308 mm) and have steeper slopes (25.6°), probably due to orographic effects, as these watersheds are mainly in the mountainous Blue Ridge and Valley and Ridge physiographic provinces. Steeper slopes and greater rainfall would result in rapid surface runoff, contributing to higher flood magnitudes. In contrast, semi-forested and rural watersheds receive lower mean annual precipitation (1121mm and 1085mm, respectively) and have flatter slopes (9.8° and 9.6°, respectively), as they are mainly in the Piedmont and Coastal Plain provinces, resulting in lower surface runoff and potentially less flooding. Semi-forested and rural watersheds also have greater flow-regulating features (0.83% and 0.90%, respectively), than forested watersheds (0.13%), yet forested watersheds have more extensive forest vegetation, which also regulates surface flow. Higher precipitation and steeper slopes in forested watersheds, and the presence of flow-regulating features in semi-forested and rural watersheds, help explain the similarities in responses of flood magnitude and duration among forested, semi-forested and rural watersheds (Table 2).

Table 2. Summary of landscape features influencing flood metrics for four watershed types¹.

Watershed type	Mean annual precipitation (mm)	% Sandy and loamy soils	Mean hill slope (degrees)	% Artificial water bodies	% Best management practices
Forested	1308	71	25.61	0.09	0.04
Semi-forested	1121	57	9.87	0.68	0.15
Rural	1085	63	9.58	0.78	0.12
Urban	1067	57	7.33	0.41	0.37

¹ Percentages derived for sandy and loamy soils, artificial water bodies and best management practices are based on watershed area.

For floods larger than the 10-year flood, there were no differences or trends in flood magnitude among watershed types, except for the ≥ 100 -year flood. We do not attribute observed differences in magnitude of ≥ 100 -year floods among the four watershed types to different land cover. Rather, we think they simply reflect where these rare events happened during our 23-year study. There were three ≥ 100 -year floods, two in semi-forested watersheds in 1996 and 2008 and one in an urban watershed in 2010. The significant differences among urban, rural, semi-forested and forested watersheds for the ≥ 100 -year flood do not follow the same pattern observed for small floods among the four watershed types (Table 1).

3.2.2. Flood Duration

Flood duration was significantly shorter in urban than non-urban watersheds for floods smaller than the 10-year flood (Table 1; Figure 3). The difference in flood duration between urban and non-urban watersheds was similar for all floods smaller than the 10-year flood. On average, non-urban watersheds exhibited flood durations nearly three times longer than urban watersheds.

We found no significant differences among non-urban watersheds. Semi-forested watersheds had longer floods up to the 2-year flood, while rural watersheds had longer floods for the 5- and 10-year floods. A greater areal extent of flow-regulation features in rural and semi-forested watersheds, in addition to the topographic and climatic differences discussed above, explains the slight, albeit non-significant, differences in flood duration among non-urban watersheds.

We found no differences in flood duration among watershed types for the 20- and 50- year floods; however, the ≥ 100 -year flood did differ. As we found for flood magnitude, differences among urban,

rural, semi-forested, and forested for the ≥ 100 -year flood do not follow the same patterns observed for small floods among the four watershed types (Table 1).

3.2.3. Flood Count

The number of floods for most of the flood-return periods was not different among watershed types. Urban watersheds had greater counts of the 80% of a 1-year flood, semi-forested watersheds had greater counts of the 1-year flood, and rural watersheds had greater counts of the 1.5-, 2- and 5- year floods. The number of floods per watershed type was similar for longer return periods, except for the 50-year flood, which differed among urban, rural, semi-forested and forested watersheds (Table 1). These differences are not likely related to land cover, but instead seem to reflect the five 50-year floods that occurred in forested and urban watersheds during our study period; four occurred in urban watersheds in 1996, 1997, 2010 and 2011, and one occurred in a forested watershed in 2004.

3.3. Flow-regulating Features and Flooding

Flow-regulating features had measurable impact on some floods in urban watersheds. We chose to compare the magnitude and duration of <5 -year floods between forested and urban watersheds with low, medium, and high percentage of flow-regulating features so we could use a flood threshold that was present for both flood metrics. The extent of flow-regulating features was negatively related to magnitude and positively related to duration in urban watersheds but watersheds with extensive flow-regulating features still had larger, shorter floods than forested watersheds (Table 3). Urban watersheds with few flow-regulating features had significantly larger floods than watersheds with extensive flow-regulating features, but non-significant differences in flood duration. The differences in flood magnitude and duration between forested and urban watersheds decreased with increasing extent of flow-regulating features. Forested watersheds had flood magnitudes 14% as large as urban watersheds with a low percentage of flow-regulating features and 33% as large as urban watersheds with a high percentage of such features. Flood duration of forested watersheds was nearly seven times longer than urban watersheds with a low percentage of flow-regulating features and nearly three times longer than urban watersheds with a high percentage of such features.

Table 3. Least-square means and Bonferroni-adjusted confidence intervals for two flood metrics in four watershed types that differ in areal extent of flow-regulating features.

Watershed type	Magnitude (m^3/s)	Duration (days)
Low	359.7 ± 1.3^a	0.23 ± 1.6^a
Medium	296.4 ± 1.3^{ab}	0.44 ± 1.6^a
High	154.6 ± 1.2^b	0.55 ± 1.3^a
Forested	49.7 ± 1.1^c	1.49 ± 1.3^b

¹ Means with the same superscript are not significantly different.

4. Discussion

4.1. Which Inland Floods Can Be Managed?

We assembled empirical evidence to show that landscape structure, especially vegetation cover, can affect the duration and magnitude of floods up to a 10-year flood, while the number of floods, presumably driven by precipitation patterns, is not impacted by landscape structure (Figure 3). Urban watersheds have higher and shorter floods than non-urban watersheds, despite ubiquitous flow-regulating features.

Further, despite featuring greater precipitation, steeper topography, and fewer technological features to regulate surface runoff, our forested watersheds exhibited flood magnitudes similar to semi-forested and rural watersheds. Land cover is apparently ineffective at regulating floods larger than the 10-year flood; these floods seem to be determined by other large-scale drivers such as precipitation and temperature (Sagarika et al. 2014). Our results provide insight into which floods landscape managers can expect to curtail and which floods are largely outside their control. While previous studies have shown that small floods are more sensitive to landscape changes than large floods (Hawley and Bledsoe 2011) and small-flood frequency increases with urbanization (Findlay and Taylor 2006), no study has compared such a wide range of watershed types and used long-term hydrologic records to identify flood manageability thresholds.

We limited the size of our watersheds ($< 80\text{km}^2$) and restricted our study to the southeastern US, but suggest that our results widely apply to similar-sized and larger watersheds with similar climate, topography, and land use. Other studies, examining watersheds up to 250 km^2 , have also found differences in the magnitude and duration of small floods between watershed types (Smith et al. 2002a, Hawley and Bledsoe 2011). Sturdevant-Rees et al. (2001) found no evidence of forested watersheds reducing peak runoff volumes for the 100-year flood in watersheds ranging from 200 to 7800 km^2 . These studies suggest that regardless of watershed size, small floods respond differently to land cover than larger floods. Further studies of flood-return periods in other watersheds are needed to confirm the general applicability of our results, especially regarding effects of watershed size, climate, and physiography.

4.2. Confounding Factors

Our reliance on long-term hydrologic records limited our ability to choose arrays of watersheds that varied in land cover and physiographic characteristics. Ideally, we would have controlled for topography and precipitation among watersheds, but doing so would have seriously constrained our sample size because so few watersheds have long-term flow records. In our study, almost all forested watersheds were in the mountains, while all urban watersheds were in low-elevation regions. This disparity underscores the need for more extensive long-term monitoring of stream flows and/or additional modeling capacity to predict flows from existing data on precipitation and landscape structure. Within urban watersheds, a common approach is to use flood-frequency equations derived from gaged watersheds to estimate flood-return period in ungaged watersheds (Moglen and Shivers 2006). In rural watersheds, regionalization models can estimate stream flow and the impacts of land cover change, yet the accuracy of these is highly dependent on gaged neighboring watersheds (Croke et al. 2004). Increasing the number of gages and maintaining long term stream-flow gages can increase our flood forecasting ability, yet budgets to support gage-based monitoring of stream flow are shrinking (Hamilton and Campbell 2013).

Our ability to detect differences in flood metrics among non-urban watersheds was confounded by uncontrolled differences in land cover, physiographic characteristics, and flow-regulating features. We expected rural, followed by semi-forested, watersheds to have shorter and higher floods than forested watersheds, as these had less forest cover (Lana-Renault et al. 2011). Agriculture-dominated watersheds have 8-33% larger flood peaks compared to forested watersheds (Poff et al. 2006). However, our finding of similar flood magnitude and duration among forested, semi-forested and rural watersheds, suggests that widespread flow-regulating features in rural (0.90%) and semi-forested (0.83%) watersheds partially counteracts the effects of urbanization (average of 13% and 8% urban cover, respectively) and agriculture (average of 41% and 18% agricultural cover) in these watersheds. Our inability to detect differences among non-urban watersheds suggests that land cover is not the only driver of flooding, but that topography, soils, precipitation and flood-control structures also play important roles. We look forward to seeing future studies that control for physiographic features among non-urban watersheds to provide clearer insight into the roles of land cover and flow-regulating features in regulating floods.

4.3. Managing Urban Floods

Managing floods in increasingly urbanized watersheds is a widespread problem (Brown et al. 2009). The particular impact of impervious surface on flows and flooding is widely documented (Beighley and Moglen 2003, Moglen and Kim 2007). Potential solutions include relatively non-technical tactics such as reforestation and highly engineered tactics such as stormwater ponds. The cost and effectiveness of such tactics vary widely but are often not clearly understood. In some cases, investment in infrastructure for flood control has decreased casualties and damages. For example, for every dollar invested in reducing flood risk, the USACE has prevented \$7.17, controlling for inflation, in damage from 1928 to 2009 (USACE 2011). However, other studies show that property damage from flooding continues to increase despite costly investments (Milly et al. 2002, Patterson and Doyle 2009, Highfield et al. 2014). Other studies found no evidence of reforestation efforts mitigating floods (Kochenderfer et al. 2007). Our findings provide new insight into the circumstances under which such tactics may be cost-effective.

The large differences we observed in the magnitude and duration of ≤ 10 -year floods between forested and urban watersheds confirm the great impact impervious surfaces have on floods, even when forested watersheds appear to be more susceptible to flooding (e.g., greater precipitation, steeper slopes). Further, although flow-regulating features were ubiquitous in urban watersheds, floods in forested watersheds were less flashy. Our results suggest that increasing forest and wetland cover (or other natural vegetation) can effectively increase the infiltration, evapotranspiration and retention capacities of urban watersheds, thereby reducing the flashiness of small floods.

Storage-based mechanisms to lower runoff and reduce flooding have dominated stormwater management since the 1990s, primarily because of their water quality benefits (Balascio and Lucas 2009). Within our study watersheds, most BMPs (97%) store water: wet ponds (76%), flood control dams (11%) and dry ponds (10%); 60% of them are in-channel. Urban watersheds with extensive flow-regulating features exhibited longer duration and lower-peaked floods than watersheds with few flow-regulating features, suggesting BMPs do lower peak flows (Table 3; Figure 1). However, urban watersheds had, on average, ≤ 2 -year floods that were three times larger than but only 33% as long as floods in non-urban watersheds. These differences in small floods between urban and non-urban watersheds suggest limited effectiveness of flow-regulating features in urban watersheds, at least as they are currently implemented (e.g., among our watersheds, the highest areal coverage of flow-regulating features was 0.78%). Thus, urban stormwater management to date, focused on storing runoff, has not entirely counteracted the effects of expanding impervious surfaces on flood magnitude and duration.

The major land cover difference between urban and non-urban watersheds is the extent of impervious surface, which alters the magnitude and duration, but not the number, of floods. Storage-based stormwater management intends to retain runoff from impervious surfaces, but these structures only marginally decrease watershed-wide peak flows, while significantly impacting watershed health (Booth and Jackson 1997, Emerson et al. 2005). Complementing storage-based efforts with infiltration-based mechanisms (e.g., rainwater harvesting, green roofs, permeable pavement, and bioretention areas) can reduce surface runoff and impacts on aquatic environments (Deutsch et al. 2005, Williams and Wise 2006, Davis 2008, Czemiel Berndtsson 2010, Damodaram et al. 2010, EPA 2013), especially for small storms. Although we expect widespread installation of infiltration-based BMPs across urban watersheds to increase the duration of small floods, our results showed no effect of these BMPs, perhaps due to their rarity in our study area (covering $< 0.02 \text{ km}^2$).

Finding the most effective set of stormwater management tactics may require greater monitoring and documentation efforts. We found no single database that contained all existing flow-regulating features. County stormwater management offices, particularly in urban areas, stated that unifying such data was a top priority (stormwater management personnel, personal communications). A detailed database on flow-regulating features, describing the capacity to retain, evaporate or infiltrate water, would allow

stormwater managers to analyze the landscape configuration and distribution of flow-regulating features in relation to sources of runoff and areas with high flood risk across watersheds (Strecker et al. 2001). To estimate capacities of reservoir, modeling approaches are available to better estimate inflow and runoff compared to our simple surrogate of reservoir capacity based on surface area (Valipour et al., 2013). In contrast, most BMP studies simply assess effectiveness on a site-by-site basis (Davis 2008, Hancock et al. 2010), which provides limited insight into how an entire stormwater management strategy contributes to controlling floods and improving water quality and stream health (Harrell and Ranjithan 2003, Emerson et al. 2005).

4.4. Management and Policy Implications

Empirical evidence regarding the extent to which landscape structure, both natural and built, can regulate floods is valuable but largely unavailable to managers and decision-makers. Understanding the limits of interventions to control floods at the watershed scale can guide investment in flood reduction strategies. For example, states or communities might choose to invest in non-structural efforts such as education and zoning to reduce the socioeconomic damage of floods rather than invest in watershed reforestation, which may have negligible effects on large floods (>10-year floods). In the United States, FEMA's community rating system (CRS) program incentivizes local communities to adopt non-structural flood control strategies (e.g., floodplain management planning, property acquisition and relocation, and flood warning programs) in exchange for federal flood insurance discounts. Highfield et al. (2014) showed that communities participating in the CRS program reduced damages by 88% compared to non-participating communities. In the United Kingdom, models of flood exposure and damage reduction led Dawson et al. (2011) to conclude that while non-structural approaches (e.g., land use planning and insurance) to flood control are effective, their success depends on socioeconomic changes and governance arrangement. The opportunity costs of reforesting urban watersheds to mitigate floods are high, though the collateral benefits of reforestation are many (e.g., decreased erosion and desertification, increased carbon sequestration, and improved human health). Thus, our results do not support applications of ecosystem service research that presume the flood-regulation capacity of ecosystems to be important in reducing or mitigating catastrophic floods (Ennaanay et al. 2011). Natural features of ecosystems seem to be most important in regulating small floods (≤ 10 -year return period), not large ones.

Damage from catastrophic floods is well documented; however, more recurrent small floods can also cause significant damage, particularly in high-density urban areas, as small floods sculpt channel dimensions (Green and Penning-Rowsell 1989, Doyle et al. 2007, Lantz et al. 2012). Aside from damage to property, floods greater than the bank-full discharge (1- to 3-year floods), can disrupt transportation systems (e.g., flooded roads) and incrementally destabilize stream banks along roads and bridges (Jacobson 2011, Dutton 2012). In Charlotte, NC, the number of properties reached by a 10-year flood (i.e., flood with 10% chance of occurring in a given year), is significant in residential and commercial areas (Figure 4) (FEMA and State of North Carolina 2014). To reduce damage within the 10-year floodplain, structural flood-control measures can be cost-effective. Yet to reduce flood damage from larger floods, developing sound floodplain management programs and implementing appropriate flood insurance rates and incentives may be more cost-effective than structural approaches (Brody et al. 2011).

Our study shows that purposeful (as well as inadvertent) changes to the landscape can alter the magnitude and duration of ≤ 10 -year floods, wherein extensive forests and wetlands are more effective at regulating floods than localized engineered features (Table 1). Natural vegetation delays and reduces the amount of runoff to streams by promoting evapotranspiration, interception and infiltration (Lana-Renault et al. 2011, Brown et al. 2013). This result is globally important because so many people live along rivers and deltas, and their vulnerability to floods can be decreased by managing landscape structure (Vorosmarty et al. 2009). Setting aside land for forest and wetlands to regulate small floods is beneficial for downstream

communities, but can adversely impact upstream communities that depend on those areas. In such cases, payments for ecosystem services can be used to compensate upstream communities for the foregone opportunities of using the land (Brauman et al. 2007). When natural vegetation is removed to accommodate economic development, up-slope management actions could complement floodplain management to further reduce property damage during small floods. A comprehensive flood management strategy would require a combination of structural and non-structural approaches, wherein vegetative and engineered tactics are aimed at managing small floods and non-structural tactics are used for larger floods. In agricultural watersheds, best management practices, including proper irrigation practices, could also significantly affect floods while increasing crop yields (Valipour et al, 2015). Further research is needed to understand a) how the spatial configuration of vegetative and engineered tactics within a watershed influences flood-control capacity and b) the relative effectiveness of deploying a few large features (e.g., dams) versus many small features (e.g., detention ponds and rainwater gardens) in managing small floods.

Figure 4. Extent of inland flooding for the 2-, 5-, 10- and 25-year flood in a study watershed (Gage ID: 02146300) in the city of Charlotte, North Carolina (FEMA and State of North Carolina 2014).

With our study results, we strive to provide managers with new information to inform decisions concerning flood-control investments and decisions related to flood regulation (e.g., territorial planning, urbanization licenses, etc.). Recognizing key sources of uncertainty and options for reducing it are important for managers' choices. Some tactics to reduce uncertainty in our study include increasing the sample size (e.g., adding more watersheds to the study), finding greater temporal coverage of land cover during our period of study, and finding more accurate information regarding flow-regulating features.

Ideally, we would want to know the storage capacity of each flow-regulating feature. However, because we could find no such data, we used surface area as a surrogate for storage capacity. Precise measures of the storage capacity of each flow-regulating feature could eventually allow us to assess the effectiveness in regulating floods among different features, which in turn could help flood managers make more informed choices.

5. Conclusions

Few studies have quantified the river flows for which changes in landscape structure can curtail floods across a large number of watersheds. This is a globally relevant knowledge gap given that > 500 million people live along floodplains (Vorosmarty et al. 2009). Our study shows that for floods recurring at intervals >10 years (i.e., large floods), flood magnitude and duration do not differ among watersheds with different land cover compositions. For floods recurring at intervals ≤ 10 years (i.e., small floods), urban watersheds generate larger and shorter floods than non-urban watersheds. However, adding engineered flow-regulating features, particularly storage-based features, to urban watersheds can significantly reduce flood magnitudes, but not flood durations, for floods smaller than a 5-year flood. These patterns suggest that management efforts to decrease the socioeconomic and environmental impacts of small floods can be grouped into two main strategies: 1) increase the incidence of infiltration- and storage-based flow-regulating features throughout urban watersheds, where space is limited, and 2) increase forest and wetland cover of all watersheds to reduce runoff by enhancing water retention, infiltration and evapotranspiration. Because large floods seem to be beyond the influence of conventional interventions, a greater focus on managing flood risk and damage (e.g., land use planning and zoning, education and outreach, and early warning systems) might be a more effective strategy to lower the socioeconomic costs of large floods (Hansson et al. 2008, Brody et al. 2011).

6. Acknowledgments

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7. Appendix A: Supplementary Material

Table A1. Selected stream-flow gages in North Carolina (NC) and Virginia (VA), along with gage identification number (ID), station name, state, drainage area, and physiographic province.

Gage ID	Station Name	State	Drainage Area (km ²)	Province
0208650112	Flat River Tributary near Willardville	NC	3.0	Piedmont

02146470	Little Hope Creek at Seneca Place at Charlotte	NC	6.8	Piedmont
03450000	Beetree Creek near Swannanoa	NC	14.1	Blue Ridge
02146211	Irwin Creek at Statesville Avenue at Charlotte	NC	15.5	Piedmont
0208732885	Marsh Creek near New Hope	NC	17.7	Piedmont
02146700	McMullen Creek at Sharon View Road near Charlotte	NC	18.0	Piedmont
0214253830	Norwood Creek near Troutman	NC	18.6	Piedmont
0210166029	Rocky River at State Route 1300 near Crutchfield Crossroads	NC	19.2	Piedmont
02096846	Cane Creek near Orange Grove	NC	19.5	Piedmont
01658500	South Fork Quantico Creek near Independent Hill	VA	19.7	Piedmont
02102908	Flat Creek near Inverness	NC	19.8	Coastal Plain
02097464	Morgan Creek near White Cross	NC	21.6	Piedmont
02038850	Holiday Creek near Andersonville	VA	22.1	Piedmont
02055100	Tinker Creek near Daleville	VA	30.3	Valley and Ridge
0344894205	North Fork Swannanoa River near Walkertown	NC	37.6	Blue Ridge
02099000	East Fork Deep River near High Point	NC	38.3	Piedmont
01613900	Hogue Creek near Hayfield	VA	41.2	Valley and Ridge
02142900	Long Creek near Paw Creek	NC	42.5	Piedmont
01620500	North River near Stokesville	VA	44.8	Valley and Ridge
02093800	Reedy Fork near Oak Ridge	NC	53.4	Piedmont
0209741955	Northeast Creek at State Route 1100 near Genlee	NC	54.6	Piedmont
02036500	Fine Creek at Fine Creek Mills	VA	58.0	Piedmont
01654000	Accotink Creek near Annandale	VA	61.9	Piedmont
01673550	Totopotomoy Creek near Studley	VA	66.0	Coastal Plain
02143040	Jacob Fork at Ramsey	NC	66.6	Piedmont
01662800	Battle Run near Laurel Mills	VA	66.8	Blue Ridge
03478400	Beaver Creek at Bristol	VA	69.7	Valley and Ridge
03455500	West Fork Pigeon River above Lake Logan near Hazelwood	NC	71.5	Blue Ridge
02142000	Lower Little River near All Healing Springs	NC	73.0	Piedmont
02111000	Yadkin River at Patterson	NC	74.6	Blue Ridge
02146300	Irwin Creek near Charlotte	NC	79.5	Piedmont

Figure A1. Schematic definition of flood magnitude, flood count and flood duration. A given discharge (Q) was considered a flood if it exceeded 80% of the discharge that recurs at a 1.005-year interval (referred to as 1-year flood).

Table A2. Reclassified land-cover types based on the classification of five land-cover datasets.

Reclassified Land Cover	1992-Enhanced	1992-Retrofit	2001-Retrofit	2006 and 2011
Forest	Deciduous Forest	Deciduous Forest	Forest	Deciduous Forest
	Evergreen Forest	Evergreen Forest	Wetland	Evergreen Forest
	Mixed Forest	Mixed Forest		Mixed Forest
	Woody Wetlands	Woody Wetlands		Woody Wetlands
	Emergent Herbaceous Wetlands	Emergent Herbaceous Wetlands		Emergent Herbaceous Wetlands
Urban	Low Intensity Residential	Low Intensity Residential		Developed, Open Space
	High Intensity Residential	High Intensity Residential		Developed, Low Intensity
	Commercial/Industrial/Transportation	Commercial/Industrial/Transportation	Urban	Developed, Medium Intensity
	LULC ¹ Residential	Urban/Recreational Grasses		Developed, High Intensity
	NLCD ² /LULC Forested Residential			
Agriculture	Urban/Recreational Grasses			
	Pasture/Hay	Pasture/Hay	Agriculture	Grassland/Herbaceous
	Row Crops	Row Crops	Grass/Shrub	Pasture/Hay
	LULC Orchards/Vineyards/other			Cultivated Crops

¹ LULC is land use and land cover; ² NLCD is National Land Cover Database

Hydrologic Analysis

Before running the GLMMs, we examined the flood magnitude, duration and count distributions for each flood-return period for goodness-of-fit to a number of possible distributions. We used the overdispersion parameter (i.e., $\hat{c} = \text{Pearson Chi-Square/df}$) of the intercept-only model to test the distribution fit of flood metrics at each return period using distributions from the exponential family, and to test the assumption of parameter homogeneity (Anderson 2008). Violating the parameter homogeneity assumption leads to a small sample variance which results in a false sense of precision (Anderson 2008). A small overdispersion parameter ($\hat{c} \leq 1$) suggests the data suitably fits the selected distribution. For small return periods (≤ 2 years), we found that lognormal (link=identity) and Poisson (link=log) distributions best describe flood duration and count, while the negative-binomial distribution best describes flood magnitude. Greater return periods (> 2 years) were zero-heavy; thus, the negative-binomial distribution (link=log) best describes flood duration, while negative-binomial (link=log) and Poisson (link=log) distributions best describe flood magnitude and count (Table A3). By selecting an appropriate distribution, we can with greater certainty make statistical inferences about our flood metrics.

Table A3. Selected distributions and their overdispersion parameters (in parenthesis) for nine flood-return periods for flood duration, count and magnitude. All but one of the overdispersion parameters ($\hat{c}$) for the distributions were within the range ($\hat{c} \leq 1$) indicating that the flood metrics are a good fit for the given distribution (Anderson 2008).

Return Period	Duration	Count	Magnitude
80% Q1	Poisson (0.44)	Lognormal (0.28)	Negative Binomial (0.63)
Q1	Lognormal (0.77)	Lognormal (0.33)	Negative Binomial (0.79)
Q1.5	Lognormal (0.54)	Negative Binomial (0.95)	Negative Binomial (0.28)
Q2	Lognormal (0.60)	Lognormal (0.18)	Negative Binomial (0.27)
Q5	Negative Binomial (0.64)	Negative Binomial (0.99)	Negative Binomial (0.26)
Q10	Negative Binomial (0.87)	Poisson (0.98)	Negative Binomial (0.21)
Q20	Negative Binomial (0.40)	Negative Binomial (0.98)	Negative Binomial (0.22)
Q50	Negative Binomial (0.14)	Negative Binomial (0.33)	Negative Binomial (0.16)
$\geq Q100$	Negative Binomial (0.09)	Poisson (1.0)	Poisson (5.35)

Since we tabulated flood metrics by water year, all floods had to be assigned to a single water year. We had 29 events that spanned water years (1.6% of the records). We split these into independent floods by water year. For example, if a flood occurred from September 30th to October 1st, we counted it as two events (flood count = 1 for each water year), and summed the corresponding duration and magnitude for each event. Twelve watersheds had one to seven years of missing discharge data, for a total of 44 years missing (6% of the entire record). One watershed had seven consecutive years of missing data (gage failed in 2006), one had six consecutive years (1992-1997), three gages had four consecutive years, four gages had two or three consecutive years, and three had one year of missing data. We interpolated the missing years for a given watershed, instead of discarding these watersheds, by taking the average of the

two years preceding and succeeding the missing values. We verified that the interpolated records fell within the range of values for watersheds that had discharge records for each water year.

Spatial and Temporal Autocorrelation

Before examining relations between flood metrics and landscape structure, we first assessed the temporal and spatial autocorrelation structure of our flood metrics. Not controlling for such autocorrelation can reduce the effective number of samples available to test trends (Douglas et al. 2000). We visually inspected plots of temporal autocorrelation (Figure A2). When strong autocorrelation is present the covariance function between previous time periods will be large and consistently exceed the critical values for the null hypothesis of no autocorrelation. In our case autocorrelations attenuated quickly; information from the previous year provides little knowledge about the next period. Additionally, we used the Durbin –Watson (DW) statistic to assess the strength of autocorrelation; a null hypothesis of no autocorrelation ($DW \approx 2$) was tested. DW statistics indicated no significant temporal autocorrelation among years of flow data (Table A4, Figure A2).

Table A4. Selected statistics to assess the temporal and spatial autocorrelation structure of stream flow data.

Flood Metrics	Temporal ¹			Spatial ²	
	DW Statistic	P-Value	τ^2	σ^2	ϕ
Count	2.27	0.75	0.043 (0.039, 0.048)	0.0001 (<0.0001 , 0.0002)	23.7 (1.31, 48.4)
Duration	2.17	0.66	0.044 (0.04, 0.05)	0.0001 (<0.0001 , 0.0002)	17.5 (0.2, 48.4)
Magnitude	1.92	0.42	0.51 (0.45, 0.56)	0.004 (<0.0001 , 0.005)	25.0 (0.7, 48.9)

¹ For the temporal autocorrelation analysis, the Durbin-Watson (DW) statistic and P-value are used to assess data for the presence of no autocorrelation, where values near 2 suggest no autocorrelation.

²Three spatial autocorrelation statistics are reported with the mean and 95% confidence interval (in parentheses); τ^2 is the variance and ϕ and σ^2 are parameters that control the covariance induced by the spatial structure. The parameters ϕ and σ^2 need to be considered jointly, because if ϕ is large relative to the distance between sites spatial autocorrelation is high; however, if σ^2 is small the contribution from the spatial structure is insignificant.

Figure A2. Temporal autocorrelation plots for flood magnitude, count, and duration. When strong autocorrelation is present the autocorrelation covariance function (ACF) between previous time periods with lag, k , is large and consistently outside the dashed bands, which approximate confidence interval for the null hypothesis of no correlation. In our case the correlations attenuate quickly; information from one year provides little knowledge about the next year.

We tested the spatial autocorrelation structure of the flow data by running a single set of Markov chain Monte Carlo (MCMC) simulations for the flood metrics. We used the following spatial model,

$$\tilde{Y}_t = X_t\beta + Z\theta + \epsilon_t,$$

where $\tilde{Y}_t$ is a transformed flood metric, X_t is a matrix containing watershed characteristics and β is a vector of estimated coefficients relating those characteristics to the flood metrics. The matrix Z corresponds to a vector of random effects, θ , which quantifies the effects of individual watersheds. Finally, the error term, $\epsilon_t \sim N(0, \sigma^2 H(\phi) + \tau^2 I)$, where $N(\mu, \sigma^2)$ denotes a normal distribution with mean μ and variance σ^2 and I is an identity matrix. The spatial error structure is contained in $\sigma^2 H(\phi)$, where $H(\phi)$ is a spatial covariance matrix such as $\exp(-d/\phi)$, where d = Euclidean distance between two points.

We assessed the effect of spatial autocorrelation in the model using two parameters that control the covariance induced by the spatial structure, ϕ and σ^2 , and compared them to τ^2 which is the variance. Hence, the spatial structure is controlled by the function of two parameters, $\sigma^2 H(\phi)$. Discerning the spatial structure requires considering them jointly; interpreting them individually can be misleading. For example, ϕ can be large relative to the distance between sites which means spatial autocorrelation is high; however, if σ^2 is small the spatial covariance will be small. The appropriate comparison is between the covariance from the spatial structure, $\sigma^2 H(\phi)$, and the observation variance, τ^2 . Given that $\tau^2 I$ is several orders of magnitude larger than the elements of $\sigma^2 H(\phi)$ (Table A4), we found no significant spatial autocorrelation structure in the data. The lack of significant temporal or spatial autocorrelation in our data enabled us to treat the yearly records as independent observations.

Figure A3. Hierarchical cluster identifying the four dominant watershed types (forested, semi-forested, rural and urban) derived from areal percentages of forested, urban and agricultural land cover for five time periods.

Supplementary Material References

- Anderson, D. R. 2008. Model Based Inference in the Life Sciences: A Primer on Evidence. Springer, New York City.
- Douglas, E. M., R. M. Vogel, and C. N. Kroll. 2000. Trends in floods and low flows in the United States: impact of spatial correlation. *Journal of Hydrology* 240:90–105.

8. References

- Aldana-Vargas, C. 2011, October 19. Reforestación, a toda máquina. *Portafolio.co*. Bogota. <http://www.portafolio.co/columnistas/reforestacion-toda-maquina>
- Balascio, C. C., and W. C. Lucas. 2009. A survey of storm-water management water quality regulations in four Mid-Atlantic States. *Journal of Environmental Management* 90(1):1–7.
- Beighley, R. E., and G. E. Moglen. 2003. Adjusting measured peak discharges from an urbanizing watershed to reflect a stationary land use signal. *Water Resources Research* 39(4):1–11.

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- Bloschl, G., S. Ardoin-Bardin, M. Bonell, M. Dorninger, D. Goodrich, D. Gutknecht, D. Matamoros, B. Merz, P. Shand, and J. Szolgay. 2007. At what scales do climate variability and land cover change impact on flooding and low flows? *Hydrological Processes* 1247(January):1241–1247.
- Bolker, B. M., M. E. Brooks, C. J. Clark, S. W. Geange, J. R. Poulsen, M. H. H. Stevens, and J.-S. White. 2008. Generalized linear mixed models: a practical guide for ecology and evolution. *Trends in Ecology & Evolution* 24(3):127–135.
- Booth, D. B., D. Hartley, and R. Jackson. 2002. Forest cover, impervious-surface area, and the mitigation of stormwater impacts. *Journal of the American Water Resources Association* 38(3):835–947.
- Booth, D. B., and C. R. Jackson. 1997. Urbanization of aquatic systems: degradation thresholds, stormwater detection, and the limits of mitigation. *Journal of the American Water Resources Association* 33(5):1077–1090.
- Borders, S. 2014, March 30. Census data shows No.Va. drives Virginia growth. *The Cavalier Daily*. Charlottesville, VA. <http://www.cavalierdaily.com/article/2014/03/census-shows-nova-drives-va-growth>
- Brabec, E., S. Schulte, and P. L. Richards. 2002. Impervious surfaces and water quality: A review of current literature and its implications for watershed planning. *Journal of Planning* 16(4):499–514.
- Bradshaw, C. J. a., N. S. Sodhi, K. S.-H. Peh, and B. W. Brook. 2007. Global evidence that deforestation amplifies flood risk and severity in the developing world. *Global Change Biology* 13(11):2379–2395.
- Brauman, K. a., G. C. Daily, T. K. Duarte, and H. a. Mooney. 2007. The Nature and Value of Ecosystem Services: An Overview Highlighting Hydrologic Services. *Annual Review of Environment and Resources* 32(1):67–98.
- Brody, S. D., W. E. Highfield, and J. E. Kang. 2011. *Rising Waters: The Causes and Consequences of Flooding in the United States*. Page 195. Cambridge University Press.
- Brown, A. E., A. W. Western, T. A. McMahon, and L. Zhang. 2013. Impact of forest cover changes on annual streamflow and flow duration curves. *Journal of Hydrology* 483:39–50.
- Brown, R. R., N. Keath, and T. H. F. Wong. 2009. Urban water management in cities: historical, current and future regimes. *Water Science and Technology* 59:847–855.
- Bunn, S. E., and A. H. Arthington. 2002. Basic principles and ecological consequences of altered flow regimes for aquatic biodiversity. *Environmental Management* 30(4):492–507.
- Calder, I. R., and B. Aylward. 2006. Forest and Floods : Moving to an Evidence-based Approach to Watershed and Integrated Flood Management. *Water International* 31(1):1–13.
- Chang, H., and J. Franczyk. 2008. Climate change, land use change, and floods: Towards an integrated assessment. *Geography Compass* 2(5):1549–1579.
- Criss, R. E., and E. L. Shock. 2001. Flood enhancement through flood control. *Geology* 29(10):875.

- Croke, B. F. W., W. S. Merritt, and a. J. Jakeman. 2004. A dynamic model for predicting hydrologic response to land cover changes in gauged and ungauged catchments. *Journal of Hydrology* 291:115–131.
- Czemiel Berndtsson, J. 2010. Green roof performance towards management of runoff water quantity and quality: A review. *Ecological Engineering* 36(4):351–360.
- Damodaram, C., M. H. Giacomoni, C. Prakash Khedun, H. Holmes, A. Ryan, W. Saour, and E. M. Zechman. 2010. Simulation of Combined Best Management Practices and Low Impact Development for Sustainable Stormwater Management. *Journal of the American Water Resources Association* 46(5):907–918.
- Davis, A. P. 2008. Field Performance of Bioretention: Hydrology Impacts. *Journal of Hydrologic Engineering* 13(2):90–95.
- Dawson, R. J., T. Ball, J. Werritty, A. Werritty, J. W. Hall, and N. Roche. 2011. Assessing the effectiveness of non-structural flood management measures in the Thames Estuary under conditions of socio-economic and environmental change. *Global Environmental Change* 21(2):628–646.
- Deutsch, B., H. Whitlow, M. Sullivan, and A. Savineau. 2005. A Green Roof Vision Based on Quantifying Storm Water and Air Quality Benefits. Pages 379–384 in The Cardinal Group Toronto, editor. *Proceedings of the 3rd North American: Green Roof Conference on Greening Rooftops for Sustainable Communities*. Washington, DC.
- Douglas, E. M., R. M. Vogel, and C. N. Kroll. 2000. Trends in floods and low flows in the United States: impact of spatial correlation. *Journal of Hydrology* 240:90–105.
- Doyle, M. W., D. Shields, K. F. Boyd, P. B. Skidmore, and D. Dominick. 2007. Channel-Forming Discharge Selection in River Restoration Design. *Journal of Hydraulic Engineering* 133(7):831–837.
- Doyle, M. W., E. H. Stanley, D. G. Havlick, M. J. Kaiser, G. Steinbach, W. L. Graf, G. E. Galloway, and J. A. Riggsbee. 2008. Aging Infrastructure and Ecosystem Restoration. *Science* 319:286–287.
- Dutton, P. D. 2012. Factors influencing roadside erosion and in-stream geomorphic stability at road-stream crossings for selected watersheds, North Shore, Minnesota, USA. Master's Thesis Natural Resources Science and Management, University of Minnesota.
- Emerson, C. H., C. Welty, and R. G. Traver. 2005. Watershed-Scale Evaluation of a System of Storm Water Detention Basins. *Journal of Hydrologic Engineering* 10(June):237–242.
- Eng, K., D. M. Wolock, and D. M. Carlisle. 2013. River flow changes related to land and water management practices across the conterminous United States. *The Science of the Total Environment* 463-464:414–22.
- Ennaanay, D., M. Conte, K. Brooks, J. Nieber, M. Sharma, S. Wolny, and G. Mendoza. 2011. Valuing land cover impact on storm peak mitigation. Page Pages 73–88 in P. Kareiva, H. Tallis, T. H. Ricketts, G. C. Daily, and S. Polasky, editors. *Natural Capital: Theory and Practice of Mapping Ecosystem Services*. Oxford University Press.

- EPA. 2013. Proposed National Rulemaking to Strengthen the Stormwater Program. Alexandria, VA.
<http://cfpub.epa.gov/npdes/stormwater/rulemaking.cfm>.
- ESRI. 2012. ArcGIS Desktop. Environmental Systems Research Institute, Redlands, CA.
- FAO-CIFOR. 2005. Forests and floods: Drowning in fiction or thriving on facts ? Page 40 Forest Perspectives 2RAP Public. Indonesia Printer, Bangkok.
http://www.cgiar.org/insightdev/upload/291/145_BCIFOR0501.pdf
- FEMA. 2013. Map Service Center.
<https://msc.fema.gov/webapp/wcs/stores/servlet/info?storeId=10001&catalogId=10001&langId=-1&content=productDFIRM&title=DFIRM Databases&parent=productInfo&parentTitle=Product Information>.
- FEMA and State of North Carolina. 2014. Flood Insurance Study. Pages 1–93. Charlotte, NC.
<ftp://ftp1.co.mecklenburg.nc.us/luesa/stormwater/Flood%20Insurance%20Study/FIS/37119CV001C.pdf>
- Filatova, T., and O. Bin. 2014. Advances in Social Simulation 229:249–258.
- Findlay, S. J., and M. P. Taylor. 2006. Why rehabilitate urban river systems? Area 38(3):312–325.
- Fry, J. A., M. J. Coan, C. G. Homer, D. K. Meyer, and J. D. Wickham. 2009. Completion of the National Land Cover Database (NLCD) 1992 – 2001 land cover change retrofit product. Page 18. U.S. Geological Survey Open-File Report 2008–1379. <http://pubs.usgs.gov/of/2008/1379/>
- Fry, J., G. Xian, S. Jin, J. Dewitz, C. Homer, L. Yang, C. Barnes, N. Herold, and J. Wickham. 2011. Completion of the 2006 National Land Cover Database for the Conterminous United States. Photogrammetric Engineering and Remote Sensing 77(9):858–864.
- Graham, W. J. 1999. A Procedure for Estimating Loss of Life Caused by Dam Failure DSO-99-06. Denver, Colorado.
- Green, C. H., and E. C. Penning-Rowsell. 1989. Flooding and the Quantification of “Intangibles.” Water and Environment Journal (8):27–30.
- Hamilton, P., and J. Campbell. 2013. Measuring the Flow: The Importance of Streamgages.
http://www.usgs.gov/blogs/features/usgs_top_story/measuring-the-flow-part-1-the-importance-of-streamgages/.
- Hancock, G. S., J. W. Holley, and R. M. Chambers. 2010. A Field-Based Evaluation of Wet Retention Ponds: How Effective Are Ponds at Water Quantity Control? Journal of the American Water Resources Association 46(6):1145–1158.
- Hansson, K., M. Danielson, and L. Ekenberg. 2008. A framework for evaluation of flood management strategies. Journal of Environmental Management 86(3):465–80.
- Harrell, L. J., and S. R. Ranjithan. 2003. Detention Pond Design and Land Use Planning for Watershed Management. Journal of Water Resources Planning and Management 129:98–106.

- Hawley, R. J., and B. P. Bledsoe. 2011. How do flow peaks and durations change in suburbanizing semi-arid watersheds? A southern California case study. *Journal of Hydrology* 405(1-2):69–82.
- Highfield, W. E., S. D. Brody, and R. Blessing. 2014. Measuring the impact of mitigation activities on flood loss reduction at the parcel level: the case of the clear creek watershed on the upper Texas coast. *Natural Hazards*:1–18.
- Highfield, W. E., S. A. Norman, and S. D. Brody. 2013. Examining the 100-year floodplain as a metric of risk, loss, and household adjustment. *Risk Analysis* 33(2):186–91.
- Hofer, T. 2005. What are the impacts of deforestation in the Himalayas on flooding in the lowlands? Rethinking an old paradigm. *Water Resources for the Future* 137:1–13.
- Hollis, G. E. 1975. The effect of urbanization on floods of different recurrence interval. *Water Resources Research* 11(3):431–435.
- Huang, S., S. Cheng, J. Wen, and J. Lee. 2008. Identifying peak-imperviousness-recurrence relationships on a growing-impervious watershed, Taiwan. *Journal of Hydrology* 362(3-4):320–336.
- Ignatius, A., and J. Jones. 2014. Small reservoir distribution, rate of construction, and uses in the upper and middle Chattahoochee basins of the Georgia piedmont, USA, 1950–2010. *International Journal of Geo-Information* 3(2):460–480.
- Jacobson, C. R. 2011. Identification and quantification of the hydrological impacts of imperviousness in urban catchments: a review. *Journal of Environmental Management* 92(6):1438–48.
- Jha, A. K., R. Block, and J. Lamond. 2012. *Cities and Flooding: a Guide to Integrated Urban Flood Risk Management for the 21st Century*. Page 631. Washington, D. C.
- Jin, S., L. Yang, P. Danielson, C. Homer, J. Fry, and G. Xian. 2013. A comprehensive change detection method for updating the National Land Cover Database to circa 2011. *Remote Sensing of Environment* 132:159–175.
- Kaźmierczak, A., and G. Cavan. 2011. Surface water flooding risk to urban communities: Analysis of vulnerability, hazard and exposure. *Landscape and Urban Planning* 103(2):185–197.
- Kochenderfer, J. N., M. B. Adams, G. W. Miller, and J. D. Helvey. 2007. Factors Affecting Large Peakflows on Appalachian Watersheds: Lessons from the Fernow Experimental Forest. Pages 1–24. Research Paper NRS-3 Newtown Square, PA. http://www.nrs.fs.fed.us/pubs/rp/rp_nrs3.pdf
- Koebel, J. W. 1995. An historical perspective on the Kissimmee River Restoration Project. *Restoration Ecology* 3(3):149–159.
- Kundzewicz, Z. W. 1999. Flood protection — sustainability Issues. *Hydrological Sciences Journal* 44(4):559–571.
- Lana-Renault, N., J. Latron, D. Karssenberg, P. Serrano-Muela, D. Regüés, and M. F. P. Bierkens. 2011. Differences in stream flow in relation to changes in land cover: A comparative study in two sub-Mediterranean mountain catchments. *Journal of Hydrology* 411(3-4):366–378.

- Lantz, V., R. Trenholm, J. Wilson, and W. Richards. 2012. Assessing market and non-market costs of freshwater flooding due to climate change in the community of Fredericton, Eastern Canada. *Climatic Change* 110(1-2):347–372.
- Laurance, W. F. 2007. Forests and Floods. *Nature* 449(September):409–410.
- Lecce, S. A., and E. S. Kotecki. 2008. The 1999 Flood of the Century in Eastern North Carolina: Extraordinary Hydro-Meteorological Event or Human-Induced Catastrophe? *Physical Geography* 29(2):101–120.
- Lehner, B., C. R. Liermann, C. Revenga, C. Vorosmarty, B. Fekete, P. Crouzet, P. Doll, M. Endejan, K. Frenken, J. Magome, C. Nilsson, J. C. Robertson, R. Rodel, N. Sindorf, and D. Wisser. 2011a. Global Reservoir and Dam Database, Version 1 (GRanDv1): Reservoirs, Revision 01. <http://sedac.ciesin.columbia.edu/data/set/grand-v1-reservoirs-rev01>.
- Lehner, B., C. R. Liermann, C. Revenga, C. Vörösmarty, B. Fekete, P. Crouzet, P. Döll, M. Endejan, K. Frenken, J. Magome, C. Nilsson, J. C. Robertson, R. Rödel, N. Sindorf, and D. Wisser. 2011b. High-resolution mapping of the world's reservoirs and dams for sustainable river-flow management. *Frontiers in Ecology and the Environment* 9(9):494–502.
- Leopold, L. B. 1968. Hydrology for Urban Land Planning - A guidebook on the hydrologic effects of urban land use. Pages 1–18. Washington, D. C. <http://pubs.usgs.gov/circ/1968/0554/report.pdf>
- Ludy, J., and G. M. Kondolf. 2012. Flood risk perception in lands “protected” by 100-year levees. *Natural Hazards* 61(2):829–842.
- Magilligan, F. J., and M. L. Stamp. 1997. Historical land-cover changes and hydrogeomorphic adjustment in a small Georgia watershed. *Annals of the Association of American Geographers* 87(4):614–635.
- Milly, P. C. D., R. T. Wetherald, K. A. Dunne, and T. L. Delworth. 2002. Increasing risk of great floods in a changing climate. *Nature* 415(6871):514–7.
- Mishra, O. P., M. Ghatak, A. Kamal, and R. Kumar. 2012. Flood Risk Management in South Asia. Pages 1–182 SAARC Workshop on Flood Risk Management in South Asia. New Delhi.
- Moglen, G. E., and S. Kim. 2007. Are Threshold-Based Policies a Good Idea? *Journal of the American Planning Association* 73(2):161–172.
- Moglen, G. E., and D. E. Shivers. 2006. Methods for Adjusting U.S. Geological Survey Rural Regression Peak Discharges in an Urban Setting. Reston, VA.
- Mogollón, B. 2014. Recent changes in stream flashiness and flooding in North Carolina and Virginia. Master's Thesis in Fish and Wildlife Conservation, Virginia Tech.
- Nakagaki, N., C. V. Price, J. A. Falcone, K. J. Hitt, and B. C. Ruddy. 2007. Enhanced National Land Cover Data 1992 (NLCDe 92). Sacramento, CA. <http://water.usgs.gov/GIS/metadata/usgswrd/XML/nlcde92.xml>.
- NCDENR. 2013. North Carolina Dam Inventory. <http://portal.ncdenr.org/web/lr/dams>.

- 1
2
3
4 NHD. 2013. Digital elevation model, flow accumulation and direction rasters.
5 <http://nhd.usgs.gov/data.html>.
6
7
8 NRCS. 2012. Soil Survey Geographic database (SSURGO). <http://websoilsurvey.nrcs.usda.gov/>.
9
10 Olden, J. D., and N. L. Poff. 2003. Redundancy and the choice of hydrologic indices for characterizing
11 streamflow regimes. *River Research and Applications* 19(2):101–121.
12
13 Ostroff, A., D. Wieferich, A. Cooper, and D. Infante. 2012. National Anthropogenic Barrier Dataset.
14 <https://www.sciencebase.gov/catalog/item/get/512cf142e4b0855fde669828>.
15
16
17 Patterson, L. a., and M. W. Doyle. 2009. Assessing Effectiveness of National Flood Policy Through
18 Spatiotemporal Monitoring of Socioeconomic Exposure. *Journal of the American Water Resources*
19 *Association* 45(1):237–252.
20
21
22 Patterson, L. A., B. Lutz, and M. W. Doyle. 2012. Streamflow Changes in the South Atlantic, United
23 States During the Mid- and Late 20th Century. *Journal of the American Water Resources*
24 *Association* 48(6):1126–1138.
25
26 Petrow, T., and B. Merz. 2009. Trends in flood magnitude, frequency and seasonality in Germany in the
27 period 1951–2002. *Journal of Hydrology* 371(1-4):129–141.
28
29
30 Pielke, R. A. 1999. Nine fallacies of floods. *Climatic Change* 42(2):413–438.
31
32 Poff, N. L., J. D. Allan, M. B. Bain, J. R. Karr, K. L. Prestegard, B. D. Richter, R. E. Sparks, and J. C.
33 Stromberg. 1997. The natural flow regime. *Bioscience* 47(11):769–784.
34
35 Poff, N. L., B. P. Bledsoe, and C. O. Cuhaciyan. 2006. Hydrologic variation with land use across the
36 contiguous United States: Geomorphic and ecological consequences for stream ecosystems.
37 *Geomorphology* 79(3-4):264–285.
38
39
40 Poff, N. L., and J. . Ward. 1989. Implications of Streamflow Variability and Predictability for Lotic
41 Community Structure: A regional analysis of streamflow patterns. *Canadian Journal of Fisheries and*
42 *Aquatic Sciences* 46:1805–1817.
43
44
45 Price, C., N. Nakagaki, K. Hitt, and R. Clawges. 2003. Mining GIRAS: Improving on a national treasure
46 of land use data. ESRI 2003 International User Conference. San Diego, California.
47
48 PRISM Climate Group. 2013. Precipitation grids. <http://prism.oregonstate.edu>.
49
50
51 Rice, K. C., and R. M. Hirsch. 2012. Spatial and temporal trends in runoff at long-term streamgages
52 within and near the Chesapeake Bay Watershed. Page 56 p.
53
54 Rousseeuw, Peter J. "Silhouettes: a graphical aid to the interpretation and validation of cluster analysis."
55 *Journal of computational and applied mathematics* 20 (1987): 53-65.
56
57
58 Roy, A. H., S. J. Wenger, T. D. Fletcher, C. J. Walsh, A. R. Ladson, W. D. Shuster, H. W. Thurston, and
59 R. R. Brown. 2008. Impediments and solutions to sustainable, watershed-scale urban stormwater
60
61
62
63
64
65

- management: lessons from Australia and the United States. *Environmental Management* 42(2):344–59.
- Sagarika, S., A. Kalra, and S. Ahmad. 2014. Evaluating the effect of persistence on long-term trends and analyzing step changes in streamflows of the continental United States. *Journal of Hydrology* 517:36–53.
- Smith, J. A., M. L. Baeck, J. E. Morrison, P. Sturdevant-Rees, D. F. Turner-Gillespie, and P. D. Bates. 2002a. The Regional Hydrology of Extreme Floods in an Urbanizing Drainage Basin. *Journal of Hydrometeorology* 3:267–282.
- Smith, S. V., W. H. Renwick, J. D. Bartley, and R. W. Buddemeier. 2002b. Distribution and significance of small, artificial water bodies across the United States landscape. *The Science of the Total Environment* 299(1-3):21–36.
- Sordo-Ward, A., L. Garrote, F. Martín-Carrasco, and M. D. Bejarano. 2012. Extreme flood abatement in large dams with fixed-crest spillways. *Journal of Hydrology* 466-467:60–72.
- Strecker, E. W., M. M. Quigley, B. R. Urbonas, J. E. Jones, and J. K. Clary. 2001. Determining urban storm water BMP effectiveness. *Journal of Water Resources Planning and Management* 127(127):144–149.
- Sturdevant-Rees, P., J. A. Smith, J. Morrison, and M. L. Baeck. 2001. Tropical storms and the flood hydrology of the central Appalachians. *Water Resources Research* 37(8):2143–2168.
- Thurston, H. W., H. C. Goddard, D. Szlag, and B. Lemberg. 2003. Controlling Storm-Water Runoff with Tradable Allowances for Impervious Surfaces. *Journal of Water Resources Planning and Management* (129):409–418.
- Tobin, G. A. 1995. The levee love affair: a stormy relationship? *Water Resources Bulletin American Water Resources Association* 31(3):359–367.
- Tollan, A. 2002. Land use change and floods: what do we need most, research or management? *Water Science & Technology* 45(8):183–190.
- Trac, C. J., S. Harrell, T. M. Hinckley, and A. C. Henck. 2007. Reforestation programs in Southwest China: Reported success, observed failure, and the reasons why. *Journal of Mountain Science* 4(4):275–292.
- Tran, P., F. Marincioni, and R. Shaw. 2010. Catastrophic flood and forest cover change in the Huong river basin, central Viet Nam: a gap between common perceptions and facts. *Journal of Environmental Management* 91(11):2186–200.
- USACE. 2011. Appendix B: Corps of Engineers Civil Works Program Statistics from the National Water Resources Challenges Facing the U.S. Army Corps of Engineers. Washington, DC. http://www.nap.edu/openbook.php?record_id=13136&page=32
- USACE. 2012. National Inventory of Dams. <http://geo.usace.army.mil/pgis/f?p=397:1:0>.

- 1
2
3
4 USGS. 2012. National Hydrography Dataset Waterbodies. <http://nhd.usgs.gov/data.html>.
5
6
7 USGS. 2013. National Water Information System. <http://nwis.waterdata.usgs.gov/nwis>.
8
9 Valipour, M., Ziatabar Ahmadi, M., Raeini-Sarjaz, M., Gholami Sefidkouhi, M. A., Shahnazari, A.,
10 Fazlola, R., & Darzi-Naftchali, A. (2015). Agricultural water management in the world during past
11 half century. *Archives of Agronomy and Soil Science*, 61(5), 657-678.
12
13 Valipour, Mohammad, Mohammad Ebrahim Banihabib, and Seyyed Mahmood Reza Behbahani.
14 "Comparison of the ARMA, ARIMA, and the autoregressive artificial neural network models in
15 forecasting the monthly inflow of Dez dam reservoir." *Journal of Hydrology* 476 (2013): 433-441.
16
17
18 Vorosmarty, C. J., J. Styvitski, J. Day, A. de Scherbinin, L. Giosan, and C. Paola. 2009. Battling to save
19 the world's river deltas. *Bulletin of the Atomic Scientists* 65:31-43.
20
21 Wilby, R. L., and R. Keenan. 2012. Adapting to flood risk under climate change. *Progress in Physical*
22 *Geography* 36(3):348-378.
23
24
25 Williams, E. S., and W. R. Wise. 2006. Hydrologic impacts of alternative approaches to storm water
26 management and land development. *Journal of the American Water Resources Association*
27 6450(04108):443-455.
28
29
30 Wissmar, R. C., R. K. Timm, and M. G. Logsdon. 2004. Effects of changing forest and impervious land
31 covers on discharge characteristics of watersheds. *Environmental Management* 34(1):91-8.
32
33 Yen, B. C. 1995. Hydraulics and effectiveness of levees for flood control. *Hydrometeorology, Impacts*
34 *and Management of Extreme Floods*. U.S.-Italy Research Workshop, Perugia, Italy.
35 <http://www.engr.colostate.edu/ce/facultystaff/salas/us-italy/papers/44yen.pdf>
36
37
38 Young, W. 2014, March 27. N.C.'s growth concentrated in a small group of counties. *News and Record*.
39 Winston-Salem, NC. [http://www.news-record.com/news/article_24f29622-b5c2-11e3-b6b8-](http://www.news-record.com/news/article_24f29622-b5c2-11e3-b6b8-0017a43b2370.html)
40 [0017a43b2370.html](http://www.news-record.com/news/article_24f29622-b5c2-11e3-b6b8-0017a43b2370.html)
41
42
43
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