Mapping technological and biophysical capacities of watersheds to regulate floods

Beatriz Mogollón

Current post: Environment and Climate Change Integration Specialist, Low Carbon Resilient
Development Program USAID/USFS, Bogotá, Colombia.

Conducted work while in: Department of Fish and Wildlife Conservation, Virginia Tech, Blacksburg, VA
24061-0321, mogollon@vt.edu

Amy M. Villamagna

Department of Environmental Sciences and Policy, Plymouth State University, Plymouth, NH 03264-
1595, amvillamagna@mail.plymouth.edu

Emmanuel A. Frimpong

Department of Fish and Wildlife Conservation, Virginia Tech, Blacksburg, VA 24061-0321,
frimp@vt.edu

Paul L. Angermeier

U.S. Geological Survey, Virginia Cooperative Fish and Wildlife Research Unit, Virginia Tech,
Blacksburg, VA 24061-0321, biota@vt.edu

Corresponding author: Beatriz Mogollón, mogollon@vt.edu, 617-314-7373

Abstract

Flood regulation is a widely valued and studied service provided by watersheds. Flood regulation benefits people directly by decreasing the socio-economic costs of flooding and indirectly by its positive impacts on cultural (e.g., fishing) and provisioning (e.g., water supply) ecosystem services. Like other regulating ecosystem services (e.g., pollination, water purification), flood regulation is often enhanced or replaced by technology, but the relative efficacy of natural versus technological features in controlling floods has scarcely been examined. In an effort to assess flood regulation capacity for selected urban watersheds in the southeastern United States, we: (1) used long-term flood records to assess relative influence of technological and biophysical indicators on flood magnitude and duration, (2) compared the widely used runoff curve number (RCN) approach for assessing the biophysical capacity to regulate floods to an alternative approach that acknowledges land cover and soil properties separately, and (3) mapped technological and biophysical flood regulation capacities based on indicator importance-values derived for flood magnitude and duration. We found that watersheds with high biophysical (via the alternative approach) and technological capacities lengthened the duration and lowered the peak of floods. We found the RCN approach yielded results opposite that expected, possibly because it confounds soil and land cover processes, particularly in urban landscapes, while our alternative approach coherently separates these processes. Mapping biophysical (via the alternative approach) and technological capacities revealed great differences among watersheds. Our study improves on previous mapping of flood regulation by (1) incorporating technological capacity, (2) providing high spatial resolution (i.e., 10-m pixel) maps of watershed capacities, and (3) deriving importance-values for selected landscape indicators. By accounting for technology that enhances or replaces natural flood regulation, our approach enables watershed managers to make more informed choices in their flood-control investments.

Keywords: ecosystem services; flood duration and magnitude; flood regulation; mapping; technological replacement

1. Introduction

Regulating ecosystem services are in global decline (Millennium Ecosystem Assessment 2005), but in many cases the services formerly provided by nature have been enhanced or replaced by technology (Fitter 2013). For example, services once provided by wild pollinators are now provided by commercial pollinator colonies (Sumner and Boriss 2006, Garibaldi et al. 2014). In response to deteriorating water quality from intensive use and land cover change (Postel and Thompson 2005, Figuepron et al. 2013), the water purification service previously provided by natural ecosystems has been replaced and enhanced by water treatment processes (Kraus-Elsin et al. 2010, Chowdhury et al. 2013). Unfortunately, studies quantifying and mapping regulating services rarely acknowledge the role of technology, despite its prevalence in enhancing or replacing diminished ecosystem services (Reyers et al. 2013). Excluding the technological enhancements of a service potentially omits important functions of the landscape and obscures the role of management in altering the provision and quality of services (Burkhard et al. 2014). Full understanding of the capacity of a landscape to provide a service requires integrating all natural and technological characteristics germane to that service.

The capacity of a watershed to regulate stream flow and floods is widely valued and studied (Posthumus et al. 2010, Eigenbrod et al. 2011, Schulp et al. 2012, Laterra et al. 2012, Jackson et al. 2013). Some studies assume natural ecosystems can reduce and moderate extreme floods, thereby reducing damage to people, property and infrastructure (Chan et al. 2006, Ennaanay et al. 2011, Nedkov and Burkhard 2012, Logsdon and Chaubey 2013). However, many studies conversely show that landscape features (e.g., land cover and soil permeability) play a negligible role in ameliorating extreme floods, which are usually driven by high precipitation (Sullivan et al. 2004, Chang and Franczyk 2008, Lecce and Kotecki 2008), but can regulate small floods (Findlay and Taylor 2006, Huang et al. 2008, Hawley and Bledsoe 2011, Mogollón 2014).

Regulation of recurrent small floods is important because they can catalyze stream bank erosion (Dutton 2012), impair water quality (Brabec et al. 2002), and incur substantial socioeconomic costs (Green and Penning-Rowsell 1989, Lantz et al. 2012). While some quantity of small floods provides sediment and nutrients to floodplains important for agriculture (Emanuelsson and Moller 1990), altering small-flood regimes can negatively affect the biotic health of streams (Paul and Meyer 2001), which in turn influences cultural benefits such as fishing, wildlife watching, and esthetically pleasing environments (Villamagna et al. 2014).

Particularly in human dominated landscapes, the capacity of watersheds to regulate floods depends on both the natural biophysical configuration (e.g., land cover, soil characteristics, and topography) and technological features (e.g., flood control dams, wet and dry ponds, bioretention areas, sand filters, and constructed wetlands). Technological features are common in urban landscapes (Smith et al. 2002b, Downing et al. 2006, Ignatius and Jones 2014) and can significantly alter stream flows and reduce small floods (Goff and Gentry 2006, Su et al. 2010; Javaheri and Babbar-Sebens 2014). As watersheds urbanize, the biophysical capacity that formerly provided flood regulation is often replaced or enhanced by technological features, usually intended to reduce flashy floods (Davis 2008, Burns et al. 2012). Technological features are embedded in the landscape; excluding them from assessments of flood regulation capacity underestimates watershed capacity to regulate floods and limits the ability of managers to make cost-effective choices regarding how to meet flood control objectives. Herein, we define flood regulation as a reduction in the magnitude of peak flow by lengthening the time it takes for precipitation to flow through the system (i.e., the duration of a flood).

Flood regulation as an ecosystem service is commonly studied through mapping efforts (Nedkov and Burkhard 2012, Radford and James 2012, Schulp et al. 2012, Laterra et al. 2012, Jackson et al. 2013, Koschke et al. 2013). Spatially assessing flood regulation is particularly useful because the benefits are spatially dependent (i.e., directly conveyed downstream). Maps can illustrate the spatial distribution of service capacity (i.e., where regulation occurs), which can be compared to the demand for the service (i.e., where regulation is needed) (Nedkov and Burkhard 2012, Villamagna et al. 2013). Most previous studies of flood regulation map only biophysical features (e.g., soils, vegetation, land use/cover) (Posthumus et al. 2010, Nedkov and Burkhard 2012, Schulp et al. 2012), but ignore common technological features germane to flood control (Smith et al. 2002b, Downing et al. 2006, Ignatius and Jones 2014). Currently, managers in the U.S. are limited to using the Federal Emergency Management Agency's (FEMA's) 1%-flood floodplain maps (i.e., the 100-year flood) to guide efforts to prevent and reduce the loss of lives and property, and maintain a functional floodplain (Tingle 1999). However, spatially explicit maps of biophysical and technological capacities could provide a watershed-scale assessment, not limited to the 1%-flood scenario, that could better inform flood-control investments.

Examining the roles of landscape indicators in flood regulation is imperative to provide insight into which landscape processes influence floods and how those processes can be manipulated to achieve flood-control objectives. The relative importance of biophysical and technological indicators in regulating floods varies among watersheds (Jencso et al. 2009, Eng et al. 2013), but this variation is poorly understood. For example, watershed slope might be more influential in a mountainous area than in a flatter landscape where vegetation might play a bigger role (Barron et al. 2011). However, most studies mapping service capacity have not differentially weighted spatial indicators to reflect their relative importance (Nedkov and Burkhard 2012, Villamagna et al. 2014). Analyzing long-term flow records by watershed may provide insight into the relative importance of landscape indicators in regulating floods if the watersheds assessed are relatively homogenous and the data representing the indicators are of good quality. Each indicator's relative importance is place-specific, reflecting topography, climate and land cover. Deriving importance-values is an objective methodology to rank indicators (Anderson 2008), and particularly useful in mapping ecosystem services. While this methodology cannot reveal how much of the variation in long-term

discharge is explained by each indicator, it provides a relative measure of importance among indicators, such that managers can focus efforts of flood-regulation on manageable, high-ranking indicators.

A landscape's ability to control surface runoff is an important part of its flood regulation capacity. A common method to map runoff potential in flood regulation and water supply studies in the U.S. (Ennaanay et al. 2011, Schulp et al. 2012, Laterra et al. 2012, Simonit and Perrings 2013, Koschke et al. 2013) is based on the Natural Resources Conservation Service's runoff curve number (RCN), a dimensionless estimate of direct runoff derived from data on rainfall infiltration, evapotranspiration, and surface storage by soil and vegetation (Rallison 1980). RCN is widely used because of its simplicity and general acceptance (Ponce and Hawkins 1996), but a major shortcoming in using RCN to map runoff potential is that it conflates landscape processes governing water runoff (e.g., infiltration, retention, evapotranspiration) (Garen and Moore 2005, Ogden and Stallard 2013). Erroneously portraying the spatial distribution of runoff-related processes can misinform ecosystem service maps and mislead decision-makers regarding cost-effectiveness of flood-control tactics. This shortcoming in using RCN in assessments of flood regulation warrants a comparison to a new alternative approach that distinguishes among the three main landscape processes that determine overland runoff: infiltration, evapotranspiration and retention.

The goal of this study is to use river flooding records to estimate the relative importance of selected landscape features in regulating floods, and then use those to map biophysical and technological capacities of watersheds to regulate floods. We focus on urban areas, as they have the most altered flooding patterns, the greatest extent of flow-regulating features, and the greatest societal demand for flood regulation (Poff et al. 2006). Our specific objectives are to (1) examine relationships among selected biophysical and technological indicators and flood metrics, (2) derive an importance-value for each biophysical and technological indicator based on selected flood metrics, (3) assess the RCN indicator and an alternative set of indicators to characterize biophysical capacity, and (4) map biophysical and technological flood regulation capacities for selected watersheds based on indicator importance-values derived from flood metrics. We conclude by discussing the landscape indicators that regulate floods, the methods and models available to characterize flood-regulation capacity, the use of flood-regulation capacity maps by watershed managers and planners, and the transferability and limitations of our methodology.

2. Methods

2.1. Study Area

With the majority of the urban population in the southeastern United States concentrated in the piedmont region (e.g., Atlanta, GA; Columbia, SC; Charlotte, NC; Richmond, VA) we selected eight gaged urban watersheds in the piedmont of North Carolina (NC) representing a wide range of biophysical and technological features germane to flood regulation. Study watersheds were selected based on size (≤ 80 km²) and availability of long-term instantaneous discharge data (≥ 20 years; Table 1; Fig. 1). Five watersheds were located in Charlotte, and the other three in Durham, Raleigh and Greensboro respectively. We limited the analysis to 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, Blöschl et al. 2007, Chang and Franczyk 2008, Petrow and Merz 2009). The watersheds ranged from 60% to 100% urban land cover (includes open space, low-, medium- and high-intensity development) and from 0% to 34% forested land cover (includes mixed, deciduous and evergreen forests, shrubs, and emergent herbaceous and woody wetlands). The watersheds share a similar mean annual precipitation (1018 - 1122 mm), but the percentage of area covered by sandy and loamy soils, which facilitate water infiltration, ranges widely (12% to 77%).

Table 1. Selected stream-flow gages in North Carolina.

Gage ID	Station Name	Drainage Area (km ²)	% Forested ¹	% Urban ²	Precipitation (mm) ³	% Sandy and Loamy Soils ⁴
2146470	Little Hope Creek at Seneca Place in Charlotte	6.8	0%	100%	1018.2	73.50%
2146211	Irwin Creek at Statesville Avenue in Charlotte	15.5	19.55%	75.29%	1035.8	65.30%
208732885	Marsh Creek near New Hope	17.7	4.49%	94.44%	1118	77.30%
2146700	McMullen Creek at Sharon View Road near Charlotte	18	3.07%	96.81%	1043.3	58.00%
2099000	East Fork Deep River near High Point	38.3	18.63%	67.76%	1047.9	49.60%
2142900	Long Creek near Paw Creek	42.5	22.75%	66.96%	1032.7	48.40%
209741955	Northeast Creek at State Route 1100 near Genlee	54.6	34.16%	59.50%	1122.8	11.90%
2146300	Irwin Creek near Charlotte	79.5	8.74%	87.41%	1024	62.50%

¹ Includes deciduous, evergreen and mixed forests, woody and emergent herbaceous wetlands and scrub/shrubs from the 2011 National Land Cover Database (NLCD) (Jin et al. 2013)

² Includes open space, low-, medium-, and high-intensity development from the 2011 NLCD

³ Mean annual precipitation from 1991 to 2012 from PRISM (Parameter-elevation Regressions on Independent Slopes Model) Climate Group (2013)

⁴ Derived from estimating the percent cover of soil hydrologic groups A and B from the Soil Survey Geographic Database (SSURGO) database

Fig. 1. Map illustrating (A) the location of the eight gaged urban piedmont watersheds (outlined in black) in North Carolina and (B) the land cover types surrounding the study watersheds and their proximity to major cities (in bold). The identification numbers of the stream gages are provided in italics.

2.2. Flood metrics and landscape indicators

In Sections 2.2.1- 2.2.4, we describe how we selected the flood metrics and biophysical and technological indicators. We also describe how we used the two flood metrics and selected indicators to derive indicator importance-values, and then map biophysical and technological capacities to regulate floods. Flood regulation can be measured by a suite of indicators that characterize spatial and temporal aspects of floods. The utility of these indicators depends directly upon the ease of monitoring and the availability of data.

2.2.1. Flood Metrics

We used long-term (≥ 20 years) discharge records to evaluate the relative importance of landscape features in regulating floods. We selected magnitude and duration to characterize floods because these metrics are widely impacted by changes to the landscape (Moglen and Beighley 2002, Huang et al. 2008). Generally, studies in urban areas report an inverse relationship between magnitude and duration (i.e., the greater the magnitude, the shorter the duration of floods; Hawley and Bledsoe 2011). Together, these metrics represent how flood regimes respond to landscape features.

To evaluate small flood events that occur, on average, multiple times per year we used the 80% of a 1.005-year flood as the lowest flood threshold. This arbitrary threshold enabled us to assess small changes in the flood regime over time (Huang et al. 2008) at a flow below the bank-full discharge (Poff and Ward 1989; Bunn and Arthington 2002). To derive this lowest flood threshold, we downloaded peak and instantaneous

discharge records from the United States Geological Survey (USGS) Water for the Nation Database (USGS 2013). We used USGS's Peak FQ program with peak discharge records to derive the discharge values for the 1,005-year flood (i.e., a flood with 99.5% probability of occurring any given year; henceforth, a 1-year flood), and manually estimated 80% discharge of a 1-year flood. 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 (Flynn et al. 2006).

We used instantaneous records to derive flood magnitude and duration from 1991 to 2013, as this period held a continuous record for most of the watersheds. We selected instantaneous discharge records to capture the peaks of floods that might be obscured in daily average data (Rice and Hirsch 2012). We defined a complete water-year discharge record as one having at least 300 days of data. We compiled the magnitude and duration of independent floods (a flood could not last < 24 hours) per water year. Flood magnitude is the amount of discharge above 80% of a 1-year flood, and flood duration is the length of time when discharge exceeds the flood threshold per flood event (Olden and Poff 2003). We tabulated the flood metrics by water year (i.e., designated from October 1st to September 30th due to typically low runoff during late fall), but had four events that occurred from one water year to the next, accounting for 0.2% 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, and summed the corresponding duration and magnitude for each event. We excluded flood events that surpassed the 5-year flood, as events beyond this size are driven by larger-scale factors (i.e., climatic regimes) (Hawley and Bledsoe 2011, Mogollón 2014).

For watersheds with discontinuous 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.

2.2.2. Biophysical and Technological Processes and Indicators

We identified biophysical (runoff, evapotranspiration, soil infiltration, water retention, surface flow, and natural water storage) and technological (flow-regulation) processes that regulate floods in urban environments, and selected a spatially-explicit indicator to represent each process from publicly available data (Leopold 1968, Smith et al. 2002b, Sun et al. 2005, Chang and Franczyk 2008) (Fig. 2; Table 2). We first assessed the relation between selected indicators and flood metrics using generalized linear mixed models (GLMMs) (Bolker et al. 2008). We then used flood magnitude and duration metrics to derive importance-values for each indicator, and applied the importance-value to spatial indicators to map biophysical and technological flood regulation capacities. Our spatial analyses were carried out in ESRI's ArcGIS v. 10.1 (ESRI Inc., Redlands, CA) and our statistical analyses in SAS v. 9.3 (SAS Institute Inc. Cary, NC).

Table 2. Indicators used to calculate the biophysical and technological flood regulation capacities and expected responses (arrows) of flood magnitude and duration to these indicators.

Category	Process	Indicator	Magnitude	Duration	Data Years ¹	Indicator Range; Standardization ²	Description
Biophysical	Evapotranspiration	Evapotranspiration Rate (ET)	↓	↓	1990, 1992, 2001, 2006, 2011	224 -994 mm yr ⁻¹ ; Standardize 0-1	Resample land cover 30-m to 10m-pixels, reclassify NLCD to ET rate (mm yr ⁻¹) based on Table 3 in Singh et al. (2013)
	Water retention	Available Water Storage (AWS)	↓	↑	-	0 – 28.5cm; Standardize 0-1	Available water volume stored for plant uptake in mm in the first 150cm of soil from SSURGO
	Soil infiltration	Saturated Hydraulic Conductivity (K_{sat})	↓	↑	-	0 - 92 $\mu\text{m s}^{-1}$; Standardize 0-1	Saturated Hydraulic Conductivity in $\mu\text{m s}^{-1}$ from SSURGO
	Runoff	Runoff Curve Number (RCN)	↑	↓	1990, 1992, 2001, 2006, 2011	25 - 95.72; 1 minus standardized 0-1 RCN	Intersection of SSURGO's soil hydrologic group (10-m resolution) and NLCD land cover (30-m resolution)
	Natural water storage	% Stream	↓	↑	-	0.2 – 1.5%; Streams = 1, else = 0	Hydrography and Johnson and Fecko (2006) equation
	Surface flow rate	Slope	↑	↓	-	0 – 44.3°; 1 minus standardized 0-1 Slope	From 10-m resolution DEM, derived in degrees
Technological	Flow regulation	% Best Management Practices (BMPs)	↓	↑	1965 - 2013	0.02 – 1.8%; BMP = 1, else = 0	Wet and dry ponds, bioretention areas, stormwater wetlands, sand filters, and infiltration devices
		% Artificial Water bodies (AWBs)	↓	↑	1944 - 2012	0.15 – 1.1%; AWB = 1, else = 0	Farm ponds, golf ponds, and water supply reservoirs

¹ Dashes indicate that indicators do not change over time

² We standardized each indicator to take values 0-1, where values near 1 mean high capacity

Fig. 2. Landscape processes that regulate floods (A) and the indicators selected to represent those processes (B). The bold labels in both panels represent technological processes and indicators; others represent biophysical processes and indicators. In panel B, the indicators with an asterisk are components of the runoff curve number (i.e., if water is not evapotranspired, retained or infiltrated, it runs off). “BMPs” refer to best management practices; “AWBs” refer to artificial water bodies.

2.2.3. Biophysical processes and indicators

2.2.3.1. Runoff

Surface runoff is the excess water that is not infiltrated, evapotranspired or retained; instead, it flows over the land into streams (Lana-Renault et al. 2011). A common approach used to represent overland runoff is the runoff curve number (RCN), where a high value (e.g., 100) indicates high runoff potential (Villamagna and Angermeier 2015). The RCN is derived using land cover and soil characteristics, and does not account for topography (i.e., slope) that dictates the rate at which water flows over the land. Given equal precipitation conditions, we expect greater flood magnitude and shorter flood duration as runoff curve number (RCN) increases (Simonit and Perrings 2013).

Values of the RCN appear in a pre-existing table that relates the value of surface runoff for land cover and soil type combinations to a dimensionless value from 0-100 (Table A1). We derived the RCN for our eight watersheds by intersecting SSURGO (Soil Survey Geographic Database) soil hydrologic groups (NRCS 2012) with land cover types from five time periods (1990, 1992, 2001, 2006 and 2011) (Arnold et al. 2012). We used the 1992-enhanced National Land Cover Database (NLCD) representing the 1990 time period (Nakagaki et al. 2007), retrofit 1992-2001 for 1992 and 2001 (Fry et al. 2009), 2006 (Fry et al. 2011) and 2011 (Jin et al. 2013) NLCD as data sources. For the years without land cover data, we interpolated the associated RCN value using the available dataset before and after the year of interest. We estimated the mean RCN for each year from 1991 to 2013 for each watershed.

2.2.3.2. Evapotranspiration

Evapotranspiration (ET) is the water released into the atmosphere from land surfaces (evaporation) and vegetation (transpiration). ET has a substantial impact on river flows and floods, and can account for more than 50% of rainfall in the southeastern US (Sun et al. 2005). To represent evapotranspiration, we used the relationship reported by Singh et al. (2013), where each land-cover type from the NLCD is assigned an annual ET rate (mm yr⁻¹). The estimates reported here are for Colorado which underestimate the real ET

rate of the southeastern U.S. by around 200 mm (Sanford and Selnick 2013), as the southeastern U.S. is lower in elevation and, on average, has longer days and growing season (Lu et al. 2003). While yearly variation in meteorological conditions likely affect rates of ET across years, we are primarily interested in the relative differences in ET among land cover types. Our use of average ET values is consistent with our aim to examine *general* relationships between land cover and flood regulation capacity. We expect flood magnitude and flood duration to decrease as ET rate increases (Sun et al. 2005). We used the aforementioned NLCD datasets to derive an annual ET rate for each of the five time periods. We estimated an ET rate for the years without land cover data by interpolating NLCD values using the most recent available dataset before and after the year of interest. We estimated the mean ET rate for each year from 1991 to 2013 for each watershed.

2.2.3.3. Soil Infiltration

During soil infiltration water moves through soils; sand and clay soils have high and low infiltration potential, respectively. We used SSURGO's saturated hydraulic conductivity (K_{sat}) as an indicator of soil infiltration (NRCS 2012). K_{sat} measures the amount of water flowing through the soil in a given time, ranging from 0 to 705 $\mu\text{m s}^{-1}$. We expect K_{sat} to be positively related to flood duration and inversely related to flood magnitude (Ogden et al. 2000). Notably, we did not account for processes that occur once water infiltrates the soil. Groundwater flow paths vary in their lengths and residence times, and limited understanding of how these vary over space and time prohibited us from incorporating these processes in a spatially explicit way (Hester and Gooseff 2011). While groundwater could potentially influence flooding, we presume our study watersheds to behave similarly because they are predominantly urban and in the same physiographic province (Markewich et al. 1990, Rose and Peters 2001). We estimated the mean K_{sat} for each watershed and assumed the K_{sat} estimates remained constant through time.

2.2.3.4. Water Retention

Water retention reflects soil's capacity to retain water. Under unsaturated conditions, soil retention can play an important role in regulating floods in urban areas (Smith et al. 2002a). Small soil particles such as silt have greater capacity to retain water than larger particles such as sand. We used SSURGO's available water storage (AWS) indicator which measures the amount of water available for plants (in mm) that can be stored in the first 150 cm of soil (NRCS 2012). We expect flood magnitude to decrease and flood duration to increase as AWS increases (Zhang et al. 2008). We estimated the mean AWS for each watershed and assumed AWS remained constant through time.

2.2.3.5. Surface Flow Rate

Slope influences how quickly surface water runoff occurs. Regardless of the land cover or soil type, runoff is faster and there is less water retention across steeper slopes compared to flatter terrain. To spatially represent the rate at which water runs off, we used a 10-m Digital Elevation Model (DEM) from the National Hydrography Database (NHD 2013) to derive the mean hill slope for each watershed using ESRI's ArcGIS Slope tool, and we used the same values through time. We expect flood magnitude to increase and flood duration to decrease with steeper slopes (Harden and Scruggs 2003).

2.2.3.6. Natural Water Storage

Natural water storage across landscapes occurs in streams or ponds that permanently or temporarily collect water. Satellite-derived, land cover databases underestimate the true area of such water features, particularly streams (Di Sabatino et al. 2013). We used previous research to estimate the area of each watershed covered by streams. We derived a flow network from 10-m flow accumulation and direction rasters (NHD 2013), identified stream segments using stream confluences, and then calculated the drainage

area for each stream segment. We used this derived segment-level drainage area to estimate the widths of streams, based on the Piedmont physiographic province equation (Johnson and Fecko 2008) that relates watershed drainage area to stream width. We then used that estimated stream width to estimate the stream area of each segment, and calculated the percentage of stream (henceforth referred to as percent stream) area in each watershed. We expect flood magnitude to decrease and flood duration to increase as percent stream increases (Downing et al. 2006). We did not identify any natural ponds in our study watersheds.

2.2.4. Technological processes and indicators

Flow-regulating features are ubiquitous across the landscape and are widely used to control and store water (Smith et al. 2002b, Downing et al. 2006, Ignatius and Jones 2014). We used best management practices (BMPs) and artificial water bodies (AWBs) as indicators of flow-regulation. The primary distinction is that BMPs are intended to regulate stormwater, while AWBs store water although storage is not their main purpose. BMPs include flood control dams, wet and dry ponds, bioretention areas, stormwater wetlands, and sand filters; AWBs include farm ponds, golf course ponds, and water supply reservoirs among others. We include BMPs and AWBs under technological capacity because these are man-made features that replace or enhance flow-related ecosystem services (e.g., recreation, water supply or flood control).

We created a spatial database of BMPs and AWBs from the following sources: National Inventory of Dams (USACE 2012), Global Reservoirs and Dams Database (Lehner et al. 2011), National Anthropogenic Barrier Dataset (Ostroff et al. 2012), Federal Emergency Management Agency (FEMA 2013), National Hydrograph Database on Waterbodies (USGS 2012), North Carolina Database (NCDENR 2013), and BMP databases from selected counties. We used Google Earth imagery to verify the existence of, classify, map the surface area of, and date BMPs and AWBs. We used surface area as a surrogate of volumetric capacity, as information on volumetric capacity was largely unavailable. We standardized BMPs and AWBs across watersheds by calculating the cumulative percentage of BMP and AWB (henceforth % BMP and % AWB, respectively) surface area, by watershed area per year, from 1991 to 2013 for each watershed. We expect flood magnitude to decrease and flood duration to increase as % BMP and % AWB increase (Zahran et al. 2008).

2.3. Deriving biophysical and technological indicator importance-values

After deriving the indicators, we assessed biophysical and technological capacities separately. We assessed biophysical capacity in two ways to isolate the effect of RCN: the first includes RCN, slope and streams (henceforth B1), and the second includes ET, K_{sat} , AWS, slope and streams (henceforth B2). We separated RCN from ET because they both were derived from the same land cover database, and because RCN represents runoff potential while ET, K_{sat} , and AWS represent the non-runoff potential (i.e., evapotranspiration, infiltration and retention). Technological capacity includes BMPs and AWBs. The indicators that change through time are RCN, ET, BMPs and AWBs. Fig. 3 shows a flow-diagram of the steps we followed to derive indicator importance-values.

Deriving importance-values provides an understanding of which indicators are most important in regulating the magnitude and duration of floods. We assessed the importance-values of biophysical and technological indicators via regressions and relations to flood metrics. Flood magnitude and duration fit lognormal distributions with an over-dispersion parameter of 0.5 and 0.26, respectively (Anderson 2008). We used GLMMs to derive importance-values of B1, B2 and technological indicators, as these models handle non-normal data and incorporate random effects (Bolker et al. 2008). Variance in indicator importance-values depends on which other indicators are included in the model. While we examine flood data over a 23-year period, our intention is not to describe trends in flooding through time, but instead to use these records to assess the relative effects of landscape features on flooding. We included watershed ID as a random effect, and B1, B2, technological indicators, and mean annual precipitation, as fixed effects. We ran an intercept-

only model in addition to seven models for B1, 31 models for B2, and three models for technological capacity; these represent all possible combinations of indicators within each group for flood magnitude and duration. Mean annual precipitation for each year, from 1991-2012, was included in all models (PRISM Climate Group 2013), except for the intercept-only models. We used the model AICc (Akaike Information Criterion, corrected for small sample size) values to derive AICc weights for the indicators within B1, B2 and technological models and derived the importance-value of each indicator by adding the AICc weights from each model where the indicator was present within B1, B2 and technological models (Anderson 2008). The model AICc allowed us to assess the quality of each model relative to other models (Burnham and Anderson 2002). We conducted this process for both flood metrics, such that we derived four estimates of biophysical capacity (B1 and B2, for flood magnitude and duration) and two estimates of technological capacity (for flood magnitude and duration).

Fig. 3. Flow-diagram showing the four-step process for developing importance-values for selected indicators of flood regulation. A hypothetical model with three indicators (A, B and C) is shown; actual indicators were derived from hydrologic and spatial data. “GIS” refers to geographic information system. “Int” refers to intercept. “AICc” refers to Akaike Information Criterion, corrected for small sample size.

2.4. Mapping flood regulation capacity

Below we describe how we spatially standardized and applied the importance-value to each indicator within the B1, B2 and technological capacity models. We mapped the biophysical and technological flood regulation capacity for current condition (circa 2011-2013). We used ArcGIS v. 10.1 (ESRI Inc., Redlands, CA) to standardize the indicators and map capacities. We used 10-m-pixel resolution, which matched the resolution of most data; however, we had to resample the land cover databases (used in ET and RCN) from 30- to 10-m pixels. For many streams, BMPs and AWBs covered $<100 \text{ m}^2$, so we were likely to further underestimate these if we mapped at a 30-m-pixel resolution.

All indicators had different ranges, which precluded meaningful comparisons if left unstandardized. We standardized the indicators from 0 to 1 with the equation,

$$(X - X_{min}) / (X_{max} - X_{min})$$

where values near 1 mean relatively high flood regulation capacity, and values near 0 mean relatively low flood regulation capacity. These relative measures of capacity have been widely used in ecosystem service mapping (Nedkov and Burkhard 2012, Larondelle et al. 2014, Villamagna et al. 2014). We subtracted the standardized values from 1 for RCN and slope to portray flood regulation instead of flood potential (e.g., values near 1 mean high capacity to retain water). Without volumetric storage data, we relied on the surface area of streams, BMPs, and AWBs as a surrogate. Data for these three indicators were standardized as binary values, where 1 represented presence and 0 represented absence. With this standardization, every 10-m pixel in each watershed had a value for each indicator.

After standardizing the indicators from 0 to 1, we scaled, in the same way as mentioned above, the importance-values within the B1, B2 and technological capacity models such that the indicator with the highest importance-value, within each model, equaled 1. Using Raster Calculator in ArcGIS, we multiplied the standardized importance-value by the corresponding indicator and added the indicators within the B1, B2 and capacity technological models to estimate watershed-level capacity. We derived standardized biophysical and technological flood regulation capacity maps using the importance-values derived for both flood magnitude and duration. To compare B1, B2 and technological flood regulation capacities, we re-standardized each from 0 to 1, as each capacity had a different number of indicators.

3. Results

Beyond reporting our results that are based on a small sample size, we demonstrate an applicable methodology that integrates hydrologic long-term records with biophysical and technological capacities. Below, we summarize (1) relationships among selected biophysical and technological indicators and flood metrics, (2) importance-values for each indicator, (3) how the RCN and the alternative approach represented biophysical flood regulation, and (4) how we used importance-values derived from flood records to map biophysical and technological capacities to regulate floods.

3.1. Biophysical and technological indicators

Most biophysical indicators were not significantly related to flood metrics, yet some performed as expected (Table 3). In particular, the parameter estimates for RCN, slope, and ET had a positive relation and AWS and K_{sat} had a negative relation to flood magnitude, yet were bounded by zero which precluded us from understanding their precise relation. % stream was positively related to flood magnitude, although we expected a negative relation. For flood duration, slope had a positive relation yet was bounded by zero, while RCN, % stream, ET, AWS and K_{sat} were positively related. We expected RCN and ET to be negatively relate to flood duration.

Table 3. Parameter estimates ($\pm$ one standard error) of generalized linear mixed models that test relations between selected biophysical and technological indicators and flood magnitude and duration (n=184) in eight watersheds, each with 23 years of data; the sign describes the relationship between explanatory and response variables.

Component	Indicator	Magnitude ($m^3/s/km^2$)	Duration (days)
Biophysical	ET	0.002 ± 0.002	0.01 ± 0.003
	AWS	0.06 ± 0.17	0.43 ± 0.17
	K_{sat}	-0.003 ± 0.03	0.06 ± 0.03
	RCN	0.04 ± 0.05	0.14 ± 0.04
	% Stream	1.64 ± 1.01	1.94 ± 1.38
	Slope	0.82 ± 0.99	0.01 ± 1.36
Technological	% BMP	-0.08 ± 0.27	-0.35 ± 0.38
	% AWB	-0.17 ± 0.74	-0.33 ± 1

The two technological indicators were not significantly related to flood magnitude or duration, yet %AWB and %BMP had the expected negative relation to flood magnitude and an unexpected negative relation to flood duration (Table 3). The majority (76%) of BMPs within our study watersheds were wet ponds, followed by flood control dams (11%) and dry ponds (10%). The majority (60%) of AWBs were reservoirs, followed by farm ponds (34%) and golf course ponds (6%).

3.2. Indicator importance-values

Biophysical indicator importance-values differed between flood magnitude and duration (Table 4). Percent stream exhibited the greatest importance-value for flood magnitude, while land cover indicators (RCN for B1 and ET for B2) had the greatest importance-values for flood duration. There was no consistency in importance-values derived for flood magnitude versus duration (e.g., slope showed high importance for flood magnitude, but low importance for flood duration).

Table 4. Unscaled and scaled importance-values for selected biophysical and technological indicators of flood magnitude and duration. Importance-values were scaled by dividing the indicators within each component by the largest importance-value, such that the maximum of the scaled importance-values is 1 for B1, B2 and technological components.

Components	Indicators	Magnitude		Duration	
		Unscaled	Scaled	Unscaled	Scaled
Biophysical	RCN	0.38	0.59	0.98	1.00
	B1 Slope	0.45	0.70	0.46	0.47
	% Stream	0.64	1.00	0.28	0.29
	ET	0.37	0.62	0.95	1.00
	K _{sat}	0.32	0.54	0.36	0.38
	B2 AWS	0.30	0.50	0.51	0.54
	Slope	0.42	0.70	0.31	0.33
	% Stream	0.59	1.00	0.57	0.60
	% BMP	0.56	0.99	0.49	0.76
Technological	% AWB	0.57	1.00	0.64	1.00

Technological indicator importance-values were similar between flood magnitude and duration (Table 4). Both indicators had similar importance-values for flood magnitude, while %BMP was not as important as %AWB for flood duration.

3.3. Approaches to characterizing biophysical capacity

Overall, we found RCN did not have the expected association with flood duration, and we found a non-significant relation to flood magnitude (Table 3). An increase in RCN was associated with an increase in flood duration. In the B1 capacity model, the inverse of RCN was derived such that a greater runoff potential had a lower capacity. In comparing B1 capacity to flood metrics, we found that as B1 capacity increased, flood magnitude increased and flood duration decreased, which suggests that RCN is driving more of the relationship than the other two indicators in the model (i.e., percent stream and slope) (Table 4, Figs. 4 and 5). In comparison, the alternative approach (i.e., B2) partly yielded the expected association with flood magnitude and duration. While the parameter estimates of ET, K_{sat}, and AWS were bounded by zero for flood magnitude, we found K_{sat} and AWS had the expected positive relation to flood duration, and

ET had an unexpected positive relation to flood duration (Table 3). As expected, we found that as B2 increased, flood magnitude decreased and flood duration increased (Figs. 4 and 5).

Fig. 4. Scatterplots showing relations between flood response metrics (mean magnitude and duration from 1991 to 2013) and mean B1, B2 and technological capacity values based on 2011-2013 data for eight watersheds. Plots reflect importance-values derived from flood magnitude.

Fig. 5. Scatterplots showing relations between flood response metrics (mean magnitude and duration from 1991 to 2013) and mean B1, B2 and technological capacity values based on 2011-2013 data for eight watersheds. Plots reflect importance-values derived from flood duration.

Exploring these patterns in individual watersheds provides insight into why the RCN approach provides the relationship opposite from what we expected. The watershed with the second highest B1 capacity for both flood magnitude- and duration-derived capacities (ID 02146470) had the highest flood magnitude and shortest duration (Figs. 4 and 5). This watershed had the second greatest percentage of sandy and loamy soils (74%), had 100% urban cover and was the smallest watershed (Table 1). In contrast, the watershed with the lowest B1 capacity for both flood metrics (ID 0209741955) had the lowest flood magnitude and longest flood duration. This watershed had the greatest forest cover percentage (34%), least urban cover (60%), and the smallest percentage of sandy and loamy soils (11.9%). These results suggest (1) the RCN indicator perhaps masks the important effects of land cover, and/or (2) greater subsurface flows from high-infiltration sandy and loamy soils might contribute to more, not less, flooding at the pour point where we measured flood magnitude and duration. In separating the soil and land cover effects, we found flood magnitude decreased and duration increased with increasing B2 capacity (Figs. 4 and 5), which is consistent with the notion of how watersheds regulate floods.

3.4. Maps of Biophysical and Technological Flood Regulation Capacity

Because B1 capacity results were confounded by the RCN, we focused further analysis on the spatial distribution of B2 and technological flood regulation capacities for derived importance-values. Overall, flood duration increases and flood magnitude decreases as B2 and technological capacities increase for capacity values derived from both flood metrics (Figs. 4 and 5). Spatial differences in B2 between flood

magnitude and duration are apparent (Figs. 6 and 7). The low B2 capacity of watershed 02146470 and 02146700 in both maps contrasts with the high B2 capacity of watershed 0208732885. Magnitude-derived B2 shows distinct areas of low capacities which correspond to highly impervious surfaces (e.g., roads, airports, parking lots). These patterns are mainly driven by ET, K_{sat} and AWS because slope is relatively uniform throughout the watersheds. In contrast, the distribution of duration-derived B2 is driven mainly by ET, where patches of higher capacity are distributed throughout each watershed. Spatial patterns of biophysical capacity can help managers identify areas where enhancing evapotranspiration, K_{sat} and AWS processes (e.g., re-vegetation), leads to lower-peaked and longer-duration floods.

Fig. 6. Maps showing the spatial distribution of flood magnitude-derived importance-values for B2 and technological capacity for eight urban watersheds in North Carolina, labeled with their stream gage identification number (ID).

Fig. 7. Maps showing the spatial distribution of flood duration-derived importance-values for B2 and technological capacity for eight urban watersheds in North Carolina, labeled with their stream gage identification number (ID).

Differences in the spatial distribution of technological capacity across watersheds are apparent (Figs. 6 and 7). Two watersheds (IDs 02146470 and 02146700) have little technological flood regulation capacity, while three have high levels of technological capacity (IDs 02099000, 029741955, and 0208732885). BMPs and AWBs within the latter group were generally located along stream corridors, and uniformly distributed in the upper and lower parts of the watersheds. In watersheds with high percentages of BMPs and AWBs, spatial patterns of technological capacity can guide future development in the area; in watersheds with few technological features, capacity maps can help managers prioritize area where these technologies are needed most.

The relation between technological and biophysical capacities and flood metrics are illustrated by patterns in watersheds 02099000 and 02142900 through time. As non-urban (forested and agricultural) land cover decreased, BMPs and AWBs increased (Fig. 8). From 1991 to 2013, AWBs increased 0.03% and 0.02%, and BMPs increased 0.26% and 0.98%, for watersheds 02142900 and 02099000, respectively. Meanwhile, non-urban cover decreased 30% and 26%, respectively. That is, the loss of forest and agricultural lands, was met with building more flow-regulating features (AWBs and BMPs). Similar landscape characteristics between these two watersheds (Table 1), allow us to compare the effectiveness of non-urban land cover and flow-regulating features in regulating floods. We would expect watershed 02099000 to have lower and longer floods since it had between 0.5% and 1.3% more flow-regulating features than watershed 02142900. Instead, watershed 02099000 had higher floods ($9.2 \text{ m}^3 \text{ s}^{-1} \text{ km}^{-1} \text{ yr}^{-1}$ versus $5.5 \text{ m}^3 \text{ s}^{-1} \text{ km}^{-1} \text{ yr}^{-1}$) with similar duration ($1.13 \text{ days km}^{-1} \text{ yr}^{-1}$ versus $0.98 \text{ days km}^{-1} \text{ yr}^{-1}$) compared to watershed 02142900. These results suggest that the extent of BMPs in watershed 02099000 did not mitigate the impacts of impervious surface. Instead, non-urban land cover was perhaps more effective at regulating floods, as before 2007, watershed 02142900 had around 7% more non-urban cover than watershed 02099000.

Fig. 8. Plots illustrating the decrease in the percentage of non-urban land cover (forests and agriculture) and increase in the areal percentage of best management practices (BMPs) and artificial water bodies (AWBs) for two watersheds labeled with their gage identification number (ID) from 1991 to 2013.

4. Discussion

Our analysis showed that (1) the RCN approach and B1 capacity did not exhibit the expected relationship to flood metrics, but that the alternative approach produced results consistent with how we think soil and land cover influence flood magnitude and duration, and (2) we could map watersheds' technological and biophysical flood regulation capacities by using long-term hydrologic records to assign relative-importance values to selected landscape indicators. Below, we discuss the landscape features that regulate floods, the methods and models used to characterize flood-regulation capacity, the utility of flood regulation capacity maps to landscape-level managers and planners, and the transferability and limitations of our methods.

4.1. Landscape features that regulate floods

The small number of watersheds we studied (low statistical power) precluded us from clearly demonstrating effects of several factors we expected (and still expect) to influence flooding. Despite finding that the majority of the biophysical and technological variables were not statistically significant, most had the expected relation (Table 3). In all of our AIC models, the variable rankings had greater weights (lower AIC) than the null (intercept-only) model which is sufficient and independent evidence of predictive ability, small sample size notwithstanding (Anderson 2008; Table A.2.). Increasing our sample size would have increased the probability of finding statistically significant relations between biophysical and technological variables and flood metrics. Thus, the statistical non-significance we observed does not invalidate our conceptual model of how watersheds regulate floods or our new methodological approach for testing that model.

Our results confirm the importance of streams to flood regulation, as these are the drainage avenues of watersheds and where most urban flood management takes place (Tingle 1999). In the flood magnitude

models, % streams ranked highest in both the B1 and B2 models and second highest for flood duration's B2 model. Previous studies have not considered stream area when mapping flood regulation, as in most cases they are available as polylines instead of polygons, and are generally underrepresented in land cover classifications because they make up such a small percentage of watershed area (Di Sabatino et al. 2013).

The high ranking of land cover-derived indicators is consistent with previous studies that found land cover to be important in regulating runoff and floods (Poff et al. 2006, Amini et al. 2011, Öztürk et al. 2013). Evapotranspiration and RCN ranked highest in the flood duration B1 and B2 models and third in the B1 and B2 flood magnitude models. These high-ranked indicators in the flood duration models are consistent with previous studies that found significant differences in the duration of < 20-year floods and in the magnitude of < 5-year floods between urban and non-urban watersheds (Mogollón 2014). Overall, our results suggest that flood duration is more sensitive to changes in land cover over a wider range of flood return intervals (up to 20-year floods) than flood magnitude (up to 5-year floods).

In using areal coverage to assess flow-regulating features, instead of volumetric capacity, we may have underestimated the true capacity of BMPs. Contrary to expectations, %AWB ranked higher than %BMP in both models, yet overall they were both highly ranked in the flood duration and magnitude models. BMPs included in this study were constructed for the purpose of flood regulation, and thus we expected these to be more important in both cases. On average, AWBs were three times larger than BMPs. Further work could use volumetric capacity per unit time to differentiate between those flow-regulating features that maintain certain volumes of water (e.g., AWBs), and those that continually change their capacities based on rainfall intensity and frequency (e.g., BMPs) (Strecker et al. 2001).

4.2. Methods and models to characterize flood-regulation capacity

Although our small sample of watersheds precluded us from convincingly showing expected relations between landscape features and flood metrics, our methodology is a useful contribution to the scientific literature because it 1) articulates a reasonable conceptual model of current understanding of flood-regulation capacity (Table 2 and Figure 2), 2) lays out, step-by-step, how existing, widely available data can be used to examine expected model-based relations between landscape features and flood metrics (Figure 3), and 3) is broadly applicable to other conceptual models, data availabilities, and ecosystems. We expect future analyses produced via our methodology, especially if performed across a range of systems, to enhance knowledge of flood-regulating processes through explicit tests of conceptual models and through assessments of data utility.

The accuracy and precision of outputs of spatial analyses are commonly limited by the quality of data inputs; as quality of input data increases, so does quality of output. The data required for our analytical approach can be improved in two main ways: greater spatiotemporal resolution and greater availability of data types that are more mechanistically linked to flood-regulating processes. Our selection of variables to represent biophysical and technological processes was based on our conceptual model of what regulates flooding, the availability of data on these variables during the time frame of our study, and the feasibility of spatializing those data. Other, more mechanistic variables would be desirable, as their relations to selected flood metrics would likely be more definitive; however, some of these are largely unavailable in the spatiotemporal resolution needed for this methodology. For example, antecedent moisture condition is important in regulating floods (Smith et al. 2002a). In our conceptual model, antecedent moisture condition could replace water retention (AWS) and soil infiltration (K_{sat}) capacity. For this variable to enhance our model, we would need to know the condition, per pixel, of the watershed at a high temporal resolution (e.g., hourly or daily time step) to estimate its effect on flood metrics; unfortunately, such data are currently unavailable. Along the same vein, event-specific precipitation data would allow us to better capture the watershed's response in flood magnitude and duration, yet such high resolution data are unavailable for the time frame of our study and for most watersheds. Given that our watersheds were mostly urban, using % impervious land cover would have allowed us to better estimate the effect of impervious cover on selected flood metrics. However, we opted to use evapotranspiration instead because, aside from portraying highly

impervious, low evapotranspiration areas, it also reflects differences among pervious surfaces (e.g., urban forests, parks and open areas) that regulate surface runoff via evapotranspiration and infiltration. Including both % impervious land cover and evapotranspiration would have double-counted areas with extensive impervious surfaces. A key strength of our methodology is that it is flexible enough to accommodate new developments in how floods are thought to operate and in the data available to represent key mechanisms of that operation.

Using two models to represent biophysical capacity allowed us to empirically show different responses between the widely-used RCN approach and an alternative approach that accounted for individual processes that regulate runoff. By comparing the GLMM parameter estimates between RCN and flood metrics, we found RCN was positively related to flood duration, while its parameter estimate was bounded by zero for flood magnitude (Table 3). We expected a positive relation to flood magnitude and a negative relation to flood duration (Simonit and Perrings 2013). None of the previous studies using RCN to portray runoff potential had used empirical flood records to confirm if the processes represented by RCN were related to flooding as expected. In our study, the most urbanized watersheds also had the greatest extent of soils with high infiltration potential (A and B). These were also the watersheds with the highest-peaked and shortest floods. We expected the capacity of water to infiltrate to diminish with increasing impervious surface (Smith et al. 2002a), yet we found a lower runoff potential with increasing urbanization. Our contradictory results suggest the effects of land cover are masked by soils, or that greater subsurface and lateral flows in watersheds with more extensive A/B soils might contribute to higher-peaked and shorter floods at the pour point. Further research is needed to document if the RCN approach is accurate for mapping flood regulation capacity, given the RCN was never intended to be used on a per-pixel basis (Garen and Moore 2005). Our results suggest that flood duration is better explained by the alternative approach of separating evapotranspiration, infiltration and retention processes. However, it remains unclear if this approach also explains flood magnitude, given that our parameter estimates for flood magnitude were bounded by zero. An alternative metric, perhaps more sensitive in urban areas, to represent surface runoff potential is the degree of imperviousness (Schueler et al. 2009). We suspect imperviousness would be a better metric than RCN, as it is solely based on land cover and does not have the confounding soil effects seen with RCN.

4.3. Utility of mapping biophysical and technological flood regulation capacities

Effective flood management requires spatially explicit information and coordination among developers, stormwater managers, and planners, all of whom may lack complete knowledge of flood-related processes. Developers are often required to mitigate impacts from additional impervious surfaces on water quality and quantity but this mitigation is typically localized (EPA 2014). Stormwater managers may focus mainly on controlling floods along floodplains, where flood risks are highest and most property damage occurs (Tingle 1999). Despite their local knowledge of an area, planners may lack understanding of an entire watershed's capacity to regulate floods. Thus, we consider the main utility of mapping biophysical and technological flood-regulation capacities to be that it synthesizes spatially explicit information in a way that allows flood managers to readily identify areas of low and high capacity. This knowledge, especially if based on high resolution (e.g., 10-m pixels) data, facilitates decisions related to implementing stormwater management and other flood control programs. Previous studies have shown that the type, design and location of BMPs and AWBs in a watershed impact the quantity and duration of water storage (Strecker et al. 2001). Thus, the spatial distribution of BMPs and AWBs, viewed in the context of the existing biophysical capacity, can provide a realistic, comprehensive understanding of a watershed's overall capacity to regulate floods. Mapping flood regulation capacity also can be a valuable step toward either restoring a natural flow regime or designing a novel flow regime (Acreman et al. 2014). However, for flood-regulation capacity maps to be useful to managers, a flood management strategy must be in place. Such a strategy would first require an assessment of social demand for flood regulation, including how that demand is distributed across a watershed and relative to landscape features that regulate floods (Nedkov and Burkhard 2012).

4.4. Methodological transferability and limitations

In developing this methodology, we wanted to improve on previous efforts to map flood regulation capacity while maintaining an accessible approach. One of our greatest limitations was our small sample size. Most parameter estimates of biophysical and technological indicators were not statistically significant (i.e., did not clearly affect flooding), and some of the observed significant relations to flood metrics were not as expected. We suspect some results were artifacts of our small sample size and that more definitive patterns would emerge if we included more watersheds in the analysis. Due to our small sample, we did not test for temporal or spatial autocorrelation but realize that not controlling for such autocorrelations can reduce the effective number of samples (Douglas et al. 2000). Furthermore, one watershed (ID 02146211) was nested within the largest watershed (ID 02146300) near Charlotte, NC. We kept both to increase our sample size but we recognize that the landscape attributes and discharge patterns are similar. Despite our small sample size, we believe the methodology developed herein improves on previous efforts to map flood regulation and other ecosystem services.

Using publicly accessible databases makes this methodology accessible to others within the United States, yet the resolution and temporality of the data present limitations. The SSURGO dataset may not be particularly accurate for urban areas, as it was developed from field and aerial photograph records as early as 1958 by the US Department of Agriculture and the US Natural Resources Conservation Service for agricultural purposes (US Department of Agriculture et al. 1995). Yet SSURGO is the most detailed spatial soil database (1:12,000 to 1:63,000 map scale), preferable to the other publicly available soil database such as the State Soil Geographic Database (STATSGO; 1:250,000 map scale). Our use of SSURGO was reasonable because land cover in most of our watersheds changed little over the study period, but this may not be the case for other areas. The ET values used from Singh et al. (2013) were developed based on 2010 Landsat images, and evaluated with field measurements, water balance study, MODIS (Moderate Resolution Imaging Spectroradiometer), and monthly minimum and maximum temperature and precipitation data. We used this same table to derive ET rates for our different time periods, but recognize that ET rates in real landscapes depend on climatic conditions, which vary annually. Analyses like ours would benefit from development of ET databases that incorporate inter-annual variation. In general, databases with high spatial (<1:10,000 map scale) and temporal (annual) resolution are needed to provide robust estimates of flood-regulation capacity.

The flood-regulation capacity values derived in this study are relative to the watersheds assessed. In other words, if we re-ran our analysis with seven instead of eight watersheds, we would get different capacity values but would expect the same general relationships between flood metrics and indicators. We consider that applying the same indicator importance-values to neighboring urban watersheds based on data from the same databases we used is appropriate; however, these importance-values do not apply to non-urban watersheds or watersheds with different topographies and/or climates.

Integral to this study was the use of long-term hydrologic data to derive importance-values. While discharge data are widely available in the U.S., such data might be limiting in areas with few stream gages or gages with short periods of record. In addition, of the publicly available data used in this study, by far the most challenging to compile were the flow-regulating features, for which no one database had accurate, up-to-date information on their distribution and size. Comparing the effectiveness between biophysical and technological capacities would require more detailed information on flow-regulating features, in addition to controlling for other landscape characteristics that influence flooding (Strecker et al. 2001). Herein, we used surface area as a surrogate for volumetric capacity of BMPs and AWBs, which means that a flood control dam and a constructed wetland with equal surface area were weighted the same. We are aware that great variation exists among flow-regulating features, but the lack of available data on storage, infiltration and evapotranspiration capacities, left us unable to include this information. Compiling this information is important not only for watershed coordinators on a local-scale, but also for researchers assessing the effectiveness of flow-regulating features and natural ecosystems across space and time.

4.5. Future alternatives to regulate floods

Flood managers are confronted with trying to decrease flood-related damage, while restoring the timing, variability and quantity of flows that healthy aquatic ecosystems need. The technological tools available to control surface runoff include those that promote infiltration and evaporation near the point where precipitation falls and those that promote infiltration and evaporation after runoff has been intercepted (i.e., storage-based). The majority of flow-regulating features in our study were designed to intercept and store runoff. However, storage-based features increasingly are being complemented with other non-structural and structural mechanisms that balance flood regulation with aquatic ecosystem health (EPA 2013). Storage-based BMPs have, in some instances, decreased the socio-economic costs associated with inland flooding (Brody et al. 2011), but only marginally decreased stream flashiness (Damodaram et al. 2010; Burns et al. 2012). Technological features that keep precipitation local (e.g., rain gardens, green roofs, rainwater harvesting, permeable pavement) have been shown, on small scales, to regulate floods by promoting infiltration, evaporation, or local use before any runoff occurs (Deutsch et al. 2005, Czemiel Berndtsson 2010, Damodaram et al. 2010; Javaheri and Babbar-Sebens 2014). Besides reducing costs associated with recurrent flashy flows along properties near streams, these technological features could promote social benefits associated with healthy waterways (e.g., water quality, urban biodiversity and carbon sequestration). In this sense, the aim of technological approaches to freshwater conservation might be expanded to simultaneously benefit aquatic biota, reduce flood-related damages, and enhance other services provided by free-flowing rivers (Auerbach et al. 2014).

5. Conclusion

In this study we improved on previous efforts to map flood regulation by incorporating technological capacity, providing high resolution (i.e., 10-m pixel) maps of watershed capacities, and deriving importance-values for selected landscape indicators based on a replicable and objective methodology (i.e., GLMM and AIC rankings). These contributions are important as agencies increasingly need methodologies like this one to integrate knowledge of built and natural environments and to assess the value of ecosystem services, particularly services such as flood regulation that can directly impact human well-being (Young 2011). Despite the limitations mentioned in Section 4.4, this methodology can be applied to many other regions and watersheds to map flood regulation capacity using publicly available data.

Flood regulation is included in many studies of ecosystem service bundles (Posthumus et al. 2010), trade-offs and synergies (Lattera et al. 2012) and scenario analyses (Eigenbrod et al. 2011; Jackson et al. 2013). Yet few studies have dissected the processes governing flood regulation (Ennaanay et al. 2011) so it can be represented and analyzed in a spatially explicit way. In an attempt to improve on previous flood-regulation mapping efforts, we identified processes important to flood regulation, selected suitable technological and biophysical indicators from publicly available data, and used long-term flood records to assess the relative influence of those indicators on the magnitude and duration of <5-year floods. We subsequently used the ranking of indicators to map the biophysical and technological capacities of watersheds to regulate floods. We found that biophysical and technological capacities were negatively related to flood magnitude and positively related to flood duration (with the exception of the B1 model containing RCN, as discussed in Section 4.2), which suggests that the indicators used and the ranking process worked as intended.

A major advancement over previous studies was our inclusion of technological features in maps of flood regulation capacity. Particularly in urban environments, technological features are ubiquitous and often intended to mimic the services provided by natural ecosystems (i.e., constructed wetlands, artificial waterbodies) (Javaheri and Babbar-Sebens 2014). Excluding these features from ecosystem service assessments fails to provide an accurate assessment of the services provided. We look forward to other studies that acknowledge and quantify technological replacements or enhancements when mapping and quantifying ecosystem services. To gain a greater understanding of flood regulation and its management, we suggest two focal topics for future research: 1) assessment of the true costs and effectiveness of replacing flood regulation services formerly provided by natural ecosystem with technological alternatives

(Fitter 2013, Garibaldi et al. 2014) and 2) examination of locations in watersheds where interventions to increase flood regulation capacity are most effective, given the spatial heterogeneity of capacity factors (Jensco et al. 2009).

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8. Appendices

Table A.1. Runoff curve number (RCN) values used to map and derive a RCN estimate per watershed based on the Soil Survey Geographic Database's soil hydrologic groups and the National Land Cover Database's 2011 cover types. A and B soils have greater infiltration, and lower runoff potential, than C and D soils. For areas without a soil hydrologic group identity (labeled *None*), we used the mean of the A, B, C and D soil hydrologic groups for each particular land cover.

Land Cover Type	Runoff Curve Number							
	Soil Hydrologic Group							
	A	B	C	D	A/D	B/D	C/D	None
Water	92.0	92.0	92.0	92.0	92.0	92.0	92.0	92.0
Open Space Developed	44.4	66.8	77.2	82.8	63.6	74.8	80.0	67.8
Low Intensity Developed	44.4	66.8	77.2	82.8	63.6	74.8	80.0	67.8
Medium Intensity Developed	59.5	75.6	83.1	87.1	73.3	81.3	85.1	76.3
High Intensity Developed	90.0	93.3	94.9	95.7	92.8	94.5	95.3	93.5
Barren Land	39.0	61.0	74.0	80.0	59.5	70.5	77.0	63.5
Deciduous Forest	45.0	66.0	77.0	83.0	64.0	74.5	80.0	67.8
Evergreen Forest	25.0	55.0	70.0	77.0	51.0	66.0	73.5	56.8
Mixed Forest	36.0	60.0	73.0	79.0	57.5	69.5	76.0	62.0
Shrubland	45.0	66.0	77.0	83.0	64.0	74.5	80.0	67.8
Grassland/Herbaceous	49.0	69.0	79.0	84.0	66.5	76.5	81.5	70.3
Pasture/Hay	40.0	64.0	75.5	81.5	60.8	72.8	78.5	65.3
Cultivated Crops	56.0	72.0	81.0	86.0	71.0	79.0	83.5	73.8
Woody Wetlands	45.0	66.0	77.0	83.0	64.0	74.5	80.0	67.8
Emergent Herbaceous Wetlands	49.0	69.0	79.0	84.0	66.5	76.5	81.5	70.3

Table A.2. AICc values for the B1, B2 and Technological models for flood magnitude and duration. Note that the intercept-only model, in bold, has the largest AICc value in all six groups of models.

Number of Variables	Magnitude	Duration
	AICc	AICc
B1		
Intercept only	381.2	488.0
Int, RCN	374.6	475.5
Int, Slope	374.6	484.0
Int, Stream	373.0	482.2
Int, RCN, Slope	375.6	475.8
Int, RCN, Stream	375.1	477.4
Int, Slope, Stream	374.1	484.3

Int, RCN, Slope, Stream	376.2	477.9
B2		
Intercept only	381.2	488.0
Int, ET	374.4	476.1
Int, Ksat	375.2	481.4
Int, AWS	375.1	479.4
Int, Stream	373.0	482.2
Int, Slope	374.6	484.0
Int, ET, Ksat	376.6	475.4
Int, ET, AWS	376.5	473.2
Int, ET, Stream	374.5	476.8
Int, ET, Slope	375.9	478.2
Int, Ksat, AWS	377.2	480.9
Int, Ksat, Stream	375.1	481.1
Int, Ksat, Slope	376.4	482.5
Int, AWS, Stream	374.9	477.8
Int, AWS, Slope	376.6	481.5
Int, Stream, Slope	374.1	484.3
Int, ET, Ksat, AWS	378.5	474.6
Int, ET, AWS, Stream	376.5	472.1
Int, ET, Stream, Slope	375.6	478.9
Int, Ksat, AWS, Stream	376.9	479.1
Int, Ksat, Stream, Slope	375.7	481.9
Int, AWS, Stream, Slope	376.1	480.0
Int, ET, Ksat, Slope	377.6	476.6
Int, ET, Ksat, Streams	376.6	475.4
Int, ET, AWS, Slope	377.9	475.3
Int, Ksat, AWS, Slope	377.7	482.6
Int, ET, Ksat, AWS, Stream	378.9	476.5
Int, Ksat, AWS, Stream, Slope	376.5	480.8
Int, AWS, Stream, Slope, ET	377.6	474.2
Int, Stream, Slope, ET, Ksat	377.2	476.5
Int, Slope, ET, Ksat, AWS	378.9	476.5
Int, ET, Ksat, AWS, Stream, Slope	378.0	475.1
Technological		
Intercept only	381.2	488.0
Int, AWB	375.2	483.1
Int, BMP	375.2	483.9
Int, AWB, BMP	377.3	485.1