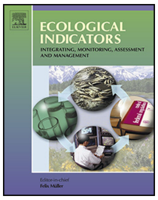
Ecological Indicators 61 (2016) 483–499

Contents lists available at ScienceDirect

Ecological Indicators

journal homepage: www.elsevier.com/locate/ecolind



Mapping technological and biophysical capacities of watersheds to regulate floods

Beatriz Mogollón[a,*,1], Amy M. Villamagna[b], Emmanuel A. Frimpong[c], Paul L. Angermeier[d]

[a] *Low Carbon Resilient Development Program USAID/USFS, Bogotá, Colombia*
[b] *Department of Environmental Sciences and Policy, Plymouth State University, Plymouth, NH 03264-1595, United States*
[c] *Department of Fish and Wildlife Conservation, Virginia Tech, Blacksburg, VA 24061-0321, United States*
[d] *U.S. Geological Survey, Virginia Cooperative Fish and Wildlife Research Unit, Virginia Tech, Blacksburg, VA 24061-0321, United States*

ARTICLE INFO

Article history:
Received 29 January 2015
Received in revised form
22 September 2015
Accepted 30 September 2015
Available online 6 November 2015

Keywords:
Ecosystem services
Flood duration and magnitude
Flood regulation
Mapping
Technological replacement

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.

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; Fiquepron 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

---

* Corresponding author. Tel.: +1 617 314 7373.
E-mail addresses: mogollon@vt.edu (B. Mogollón), amvillamagna@plymouth.edu (A.M. Villamagna), frimp@vt.edu (E.A. Frimpong), biota@vt.edu (P.L. Angermeier).

[1] Conducted work while in: Department of Fish and Wildlife Conservation, Virginia Tech, Blacksburg, VA 24061-0321, United States.

http://dx.doi.org/10.1016/j.ecolind.2015.09.049
1470-160X/

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.