Journal of Environmental Management 220 (2018) 65–76

Contents lists available at ScienceDirect

Journal of Environmental Management

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

Research article

A method to quantify and value floodplain sediment and nutrient retention ecosystem services

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ARTICLE INFO

Keywords:
Floodplain
Stream bank
Ecosystem services
Sediment balance
Nutrient retention
Replacement cost
Difficult run
Virginia

ABSTRACT

Floodplains provide critical ecosystem services to local and downstream communities by retaining floodwaters, sediments, and nutrients. The dynamic nature of floodplains is such that these areas can both accumulate sediment and nutrients through deposition, and export material downstream through erosion. Therefore, estimating floodplain sediment and nutrient retention should consider the net flux of both depositional and erosive processes. An ecosystem services framework was used to quantify and value the sediment and nutrient ecosystem service provided by floodplains in the Difficult Run watershed, a small (151 km^2) suburban watershed located in the Piedmont of Virginia (USA). A sediment balance was developed for Difficult Run and two nested watersheds. The balance included upland sediment delivery to streams, stream bank flux, floodplain flux, and stream load. Upland sediment delivery was estimated using geospatial datasets and a modified Revised Universal Soil Loss Equation. Predictive models were developed to extrapolate field measurements of the flux of sediment, sediment-bound nitrogen (N), and sediment-bound phosphorus (P) from stream banks and floodplains to 3232 delineated stream segments in the study area. A replacement cost approach was used to estimate the economic value of the sediment and nutrient retention ecosystem service based on estimated net stream bank and floodplain flux of sediment-bound N for all streams in the study area. Results indicated the net fluvial fluxes of sediment, sediment-bound N, and sediment-bound P were $-10{,}439$ Mg yr^{-1} (net export), 57,300 kg-N yr^{-1} (net trapping), and 98 kg-P yr^{-1}(net trapping), respectively. For sediment, floodplain retention was offset by substantial losses from stream bank erosion, particularly in headwater catchments, resulting in a net export of sediment. Nutrient retention in the floodplain exceeded that lost through stream bank erosion resulting in net retention of nutrients (TN and TP). Using a conservative cost estimate of $12.69 (USD) per kilogram of nitrogen, derived from wastewater treatment costs, the estimated annual value for sediment and nutrient retention on Difficult Run floodplains was $727,226 ± 194,220 USD/yr. Values and differences in floodplain nitrogen retention among stream reaches can be used to target areas for floodplain conservation and stream restoration. The methods presented are scalable and transferable to other areas if appropriate datasets are available for validation.

1. Introduction

An ecosystem services framework has been increasingly used to link ecosystem functions to human benefits (Fisher et al., 2009). Ecosystem services are broadly defined as the benefits people obtain from ecosystems (MEA, 2005). Floodplains and wetlands provide a wide array of ecosystem services including the provisioning of food and water, the regulation of floodwaters, and the supporting service of nutrient cycling and sediment retention. Quantification and valuation of these services provides land and water resources managers with information to consider societal impacts and tradeoffs associated with management decisions. Providing information on the capacity of floodplains to retain sediment and nutrients is particularly important in settings where multiple jurisdictions are coordinating restoration efforts to address

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https://doi.org/10.1016/j.jenvman.2018.05.013
Received 7 December 2017; Received in revised form 30 April 2018; Accepted 6 May 2018
0301-4797/ Published by Elsevier Ltd.

nutrient and sediment pollution upstream of estuaries such as the Chesapeake Bay. The restoration of the Chesapeake Bay and its tributaries is guided by a series of goals agreed upon by representatives from six states and the District of Columbia. While we focus on understanding the role and value of floodplains within the Chesapeake Bay watershed, the methods we employ can be transferred to inform management efforts in other settings. The U.S. Environmental Protection Agency (US EPA) has identified sediment and nutrients as two of the primary causes of impairment in assessed rivers and streams in the United States, leading to the creation of pollution limits expressed as Total Maximum Daily Loads (TMDLs) for rivers draining into large estuaries like the Chesapeake Bay (US EPA, 2010, 2016). The Chesapeake Bay TMDL is the largest ever developed by the US EPA, setting pollution limits for waterways in Delaware, Maryland, New York, Pennsylvania, Virginia, West Virginia and the District of Columbia. States are implementing best management practices (BMPs) to meet requirements to reduce sediment and nutrient loading to rivers and estuaries. BMPs include practices such as riparian forest buffer planting, stream channel and floodplain restoration, and forest conservation. Enhanced knowledge of sources and sinks for sediments and nutrients can help inform and optimize the placement and types of BMPs implemented to meet TMDLs in Chesapeake Bay and beyond. Reducing sediment and nutrient inputs in the watershed will improve water quality in the rivers, streams, and estuaries ultimately benefiting people via ecosystem services. Water quality improvements benefit people through improved recreation (Keeler et al., 2012; Lipton, 2004), commercial fishing (Keeler et al., 2012; Lellis-Dibble et al., 2008), and aesthetics (Keeler et al., 2012; Phaneuf et al., 2008).

Floodplains within the Chesapeake Bay watershed may provide substantial ecosystem services to local and downstream communities. Floodplains are located at the interface between aquatic and terrestrial environments in areas that can intercept upland sources of sediment and nutrients as well as retain sediment and nutrients from stormwater during overbank flood events, providing two paths to improve downstream water quality (Noe, 2013). For instance, Noe and Hupp (2009) found that Coastal Plain floodplains in the Chesapeake Bay watershed accumulated a substantial portion of the annual river sediment load (trapping the equivalent of 119% of river load), nitrogen load (22%), and phosphorus load (59%). Human actions and management interventions can both positively and negatively impact the types of ecosystem services supplied by floodplains (Schindler et al., 2014). Land use decisions to develop or preserve floodplain areas result in tradeoffs and synergies between society and the ecosystem that vary across temporal and spatial scales (e.g., site versus municipality) (Felipe-Lucia et al., 2014). However, there is limited understanding of the benefits provided by floodplains at the local-county scale where management decisions are made.

This study focuses on floodplain sediment and nutrient retention defined as the storage of nitrogen, phosphorus, and sediment via biological, chemical or geomorphic processes that make constituents not readily accessible to the water column. Floodplain sediment and nutrient retention was quantified as the net of both depositional and erosive processes, including both the accumulation of sediment and nutrients from vertical deposition or lateral accretion and the export of material from the lateral erosion of stream banks. Floodplains in the Chesapeake Bay watershed likely have appreciable value in terms of both sediment and nutrient retention. Estimates of sediment deposited in-channel and on floodplains in the Piedmont near Baltimore, Maryland, range from 45–455 Mg/km/yr (Donovan et al., 2015). The net sediment balance (floodplain deposition and bank erosion) ranges from −37 (net export) to 289 (net floodplain deposition) kg/m/yr in Linganore Creek an agricultural watershed in south central Maryland, −133 to 341 kg/m/yr in Little Conestoga Creek an agricultural watershed in southeast Pennsylvania, −136 to 1097 kg/m/yr in Difficult Run a suburban watershed in northern Virginia (Schenk et al., 2013), and 146 to 593 kg/m/yr in Smith Creek an agricultural watershed in central Virginia (Gillespie et al., 2018). Previous research related rates of bank erosion and floodplain deposition in these watersheds to simple geomorphic characteristics of stream valleys, such as floodplain width, bank height, and channel width, suggesting that these characteristics have the potential to predict floodplain and stream bank water quality functions (Schenk et al., 2013).

We aim to advance the state of knowledge on the ecosystem services that floodplains provide. We present an approach to quantify floodplain sediment and nutrient retention and place an economic value on the service that floodplains provide. Study objectives were to: 1) use existing field and geospatial datasets to develop a predictive model to estimate floodplain sediment (and associated N and P) deposition and bank erosion at each stream reach, and 2) quantify the economic value of the sediment and nutrient retention ecosystem service associated with floodplains in the Difficult Run watershed. Difficult Run was identified as the study location due to the unique availability of data on floodplain sediment and nutrient net retention within the watershed which allows for geospatial predictions of water quality functions and has relevance to Chesapeake Bay restoration efforts. The approach presented is flexible enough to be transferred to other study areas if similar datasets are available.

2. Methods

2.1. Study site

The Difficult Run watershed (151 km^2) is a suburban watershed located in Fairfax County, Virginia, to the west of Washington, D.C. (Fig. 1). Roughly 127,000 people live in the Difficult Run watershed according to area-weighted bock group statistics from the U.S. Census in 2010 (Manson et al., 2017). The area has seen substantial population growth in the past 40 years and population is expected to continue to increase (Hovland et al., 2016). The median household income is $115,717 (U.S. Census Bureau, 2017). Land use in the watershed is predominantly suburban and urban development in the uplands and a forested floodplain in the lowlands that includes parkland (Table 1). The mainstem of Difficult Run is a 6th order stream that drains into the Potomac River and eventually into the Chesapeake Bay. Streams in the watershed are typically pool-riffle systems on gravel to sand beds with substantial amounts of floodplain sediment storage and trapping along the mainstem and substantial bank erosion along headwater streams (Gellis et al., 2017; Hupp et al., 2013). The watershed is located in the crystalline Piedmont with bedrock dominated by gneiss and schist. The U.S. Geological Survey (USGS) operates three streamgages in the watershed, two located on the mainstem, Difficult Run (DIFF) and Fox Lake (FOX), and one located on a tributary draining to the mainstem, South Fork of Little Difficult Run (SFLD) (Fig. 1). The USGS monitored and estimated the total annual load of sediment, nitrogen, and phosphorus from FOX and SFLD during water years 2008–2012 (Jastram, 2014) and water year 2013 in DIFF (Hyer et al., 2016).

2.2. Mapping watershed, floodplain, and channel characteristics

Aerial light detection and ranging (LiDAR) imagery was collected over the study site between April 12–14, 2012 as part of the Fauquier, Fairfax, Frederick (MD), and Jefferson County acquisition for FEMA Region 3 FY12 VA LiDAR (Dewberry, 2012). LiDAR points classified as ground and water were used to create a 3-m digital elevation model (DEM) clipped to the Difficult Run watershed with a 500-m buffer in ArcGIS 10.3.1 (ESRI, Redlands, CA). The DEM was hydrologically conditioned by breaching through pits with no downslope neighboring cells to force surface flow to continuously move downslope using Whitebox Geospatial Analysis Tools (Lindsay and Dhun, 2015; Lindsay, 2016). Pits that were not properly breached (e.g., culverts) were manually adjusted using elevation information from the DEM and aerial imagery to locate culverts under roadways. The final breached DEM