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Characterizing the Extent of Spatially Integrated Floodplain and Wetland Systems in the White River, Indiana, USA

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Abstract

Floodplain delineation may inform protection of wetland systems under local, state, or federal laws. Nationally available Federal Emergency Management Agency Flood Insurance Rate Maps (FIRMs, “100-year floodplain” maps) focus on urban areas and higher-order river systems, limiting utility at large scales. Few other national-scale floodplain data are available. We acquired FIRMs for a large watershed and compared FIRMs to floodplain and integrated wetland area mapping methods based on (1) geospatial distance, (2) geomorphic setting, and (3) soil characteristics. We used observed flooding events (OFEs) with recurrence intervals of 25-50 to >100 years to assess floodplain estimate accuracy. FIRMs accurately reflected floodplain areas based on OFEs and covered 32% of river length, whereas soil-based mapping was not as accurate as FIRMs but characterized floodplain areas over approximately 65% of stream length. Geomorphic approaches included more areas than indicated by OFE, whereas geospatial approaches tended to cover less area. Overall, soil-based methods have the highest utility in determining floodplains and their integrated wetland areas at large scales due to the use of nationally available data and flexibility for regional application. These findings will improve floodplain and integrated wetland system extent assessment for better management at local, state, and national scales.

Keywords

SSURGO soils; geographically isolated wetlands; 100-year floodplain map

INTRODUCTION

Mapping products colloquially known as “100-year floodplains” typically refer to Federal Emergency Management Agency (FEMA) Flood Insurance Rate Maps (FIRMs) that identify areas where an inundation event “...would be exceeded or equaled, on long-term average,

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once in 100 years” (Morlock et al., 2008, p. 3). Clarifications to definitions of “waters of the United States” protected under the U.S. Clean Water Act (CWA) in which a water body (*e.g.*, a wetland) located in whole or in part within the “100-year floodplain” of a jurisdictional water may itself be considered jurisdictional have illuminated the need to determine integrated floodplain and wetland system extent (Clean Water Rule: Definition of “Waters of the United States,” 80 *Federal Register* 37054-37127, June 29, 2015; currently stayed, No. 15-3751 (6th Circuit), Doc. 49-2, Order of Stay). FIRMs are available for only ~55% of the counties in the conterminous United States (U.S.) (U.S. Department of Homeland Security FEMA 100-year Flood Zones, ArcGIS map service, accessed October 2015), and counties with FIRM products frequently do not have complete coverage, with rural areas and lower-order streams frequently — if not typically — lacking in floodplain assessment (Ntelekos et al., 2010; Sangwan and Merwade, 2015). Thus, using FEMA FIRMs to assess the extent of floodplains and integrated wetland systems is significantly hampered by the lack of available data.

Extending FEMA methods more broadly is currently cost-prohibitive, with official FEMA floodplain delineation estimates ranging from \$3,000 to \$6,000 per river kilometer in the U.S. (FEMA, 2006; Merwade et al., 2008). Recently, Sangwan and Merwade (2015) developed an approach to rapidly and inexpensively map floodplains, using widely available soil survey data (Soil Survey Geographic Database [SSURGO], National Resources Conservation Service, U.S. Department of Agriculture), thereby expanding floodplain mapping to low-order systems and agricultural regions not covered by FIRMs. Others have suggested additional approaches to identify floodplains, using geomorphic characterization of river basins and valley bottoms (*e.g.*, Wolman, 1971; Tate et al., 2002; Gallant and Dowling, 2003; Hicks and Peacock, 2005; Dodov and Fofoula-Georgiou, 2005; Nardi *et al.*, 2006) or satellite imagery of inundation extent (*e.g.*, Chen et al., 2015). Researchers have also employed geospatial (or Euclidean) distance from river networks as a floodplain proxy (*e.g.*, Tiner et al., 2002; Tiner, 2003; Lane et al., 2012; Dahl, 2014; Lane and D’Amico, 2016) to quantify the abundance of wetlands potentially integrated into river networks. However, a systemic comparison of the accuracy of these approaches to determine floodplain and integrated wetland extents remains a critical research need.

Accordingly, we contrasted available FEMA FIRMs with three additional measures of floodplain extent based on geospatial distance from the river network (*e.g.*, Lane and D’Amico, 2016), SSURGO soil characteristics (*e.g.*, Sangwan and Merwade, 2015), and geomorphic characteristics (*e.g.*, De Reu et al., 2013; Lindsay et al., 2015), in a large mixed-land use watershed in central Indiana, U.S. We sought to understand which of the methods best estimated floodplain areas at the watershed scale and could form the basis to indicate wetland spatial connectivity or integration with lotic systems. For purposes of this article, we define wetlands partially or wholly located within a mapped floodplain as spatially “connected” and *a priori* integrated into the river network. In a literature review of over 1,300 peer-reviewed articles, the USEPA (2015) determined that wetlands in floodplain areas were physically, chemically, and biologically integrated into riverine networks. However, we underscore that wetlands spatially located outside of the floodplain are also functionally connected or integrated into the river network through hydrological, biogeochemical, and habitat processes (*e.g.*, Golden *et al.*, 2016; Cohen *et al.*, 2016). These

functionally connected but spatially discrete wetlands may be hydrologically connected by swales, channels, streams, and near-surface groundwater to the river network (Rains *et al.*, 2015), functionally connected via biogeochemical processing (Marton *et al.*, 2015), or functionally connected via biological processes (*e.g.*, Subalusky *et al.*, 2009).

Herein, we spatially contrasted the multiple floodplain extent methods with independently collected field-based observations of floodplain inundation resulting from high return period storm events (ranging from 25 to >100 years; Morlock *et al.*, 2008). We expected that the geospatial-based floodplain characterization as currently assessed (*c.f.*, Lane *et al.*, 2012; Lane and D'Amico, 2016) would, as a distance-based proxy, underestimate floodplain extent (especially in larger stream orders; Strahler, 1952) and thus overestimate the abundance of wetlands outside the floodplain areas (*i.e.*, not spatially connected to river networks). Geomorphic- and SSURGO-based floodplain assessments were expected to vary in accuracy due to scale issues associated with topography, soil mapping, and spatial data (Thorp *et al.*, 2010). FEMA FIRMs, due to their focus on communities and urban areas, were expected to be most limited in their large-scale application.

METHODS

Study Site Descriptions

We analyzed the White River basin in south-central Indiana, U.S., which flows through three separate (Omernik, 1987) ecoregions from northeast to southwest: Eastern Corn Belt Plains, Interior Plateau, and the Interior River Valleys and Hills (Figures 1a–1c). The White River basin is a 6-digit Hydrologic Unit Code (HUC) system composed of nine 8-digit HUCs (USDA NRCS, 2015a). We conducted our analyses on six of these nine 8-digit HUCs (hereafter the modified White River [MWR] watershed). The six HUCs included in our analysis were dissolved to create a single study area. The remaining three nonanalyzed HUCs showed over-densification errors in the high-resolution National Hydrography Dataset (NHD) (Jeffrey Simley, USGS, 2015, personal communication; see Figures 1a–1c). Over-densified NHD Flowline errors occurred when the upper reaches of stream systems were delineated as extending further, and with greater spatial density, throughout the subwatershed than appropriate for the data resolution. The MWR, which discharges into the Wabash River, covers 24,082 km² and is drained by two main rivers that cumulatively flow approximately 887 km (White River — 582 km; East Fork of the White — 305 km) from the northeast to southwest. Approximately, half of the MWR basin is involved in agricultural production (*e.g.*, soy, corn) and 34% is herbaceous, deciduous forest, evergreen forest, and mixed forest land cover (Multi-Resolution Land Characteristics Consortium, 2015; Homer *et al.*, 2015). A substantial portion (12%) of the basin has developed land use, including Indianapolis, located in the northern portion of the watershed. Soils are loamy or clayey and somewhat poorly drained in the level glacial till plain in the northern portion of the watershed, and well drained with steeper slopes in the central and southwest portions of the watershed (USDA NRCS, 2015b). The 1981–2010 normal precipitation ranges from 983 to 1,231 mm per year (Oregon State University, 2015).

Floodplain Definition

We note that there are many floodplain definitions in the literature based on hydrology, geomorphology, and vegetation composition. Estimates of floodplain extent differ from estimates of wetland extent, as wetlands are ecologically defined by the soils, hydrology, and vegetation (Cowardin et al., 1979). FEMA defines a floodplain as, “any land area susceptible to being inundated by floodwaters from any source” (FEMA, 2016). Geomorphologists may define a floodplain as the “largely horizontally-bedded alluvial landform adjacent to a channel, separated from the channel by banks, and built of sediment transported by the present flow-regime” (Nanson and Croke, 1992). The geomorphic approach focuses on landforms bordering channels and delineates floodplains based on local relief (Wilson and Gallant, 2000; De Reu et al., 2013; Stout and Belmont, 2014; Lindsay et al., 2015). Belmont (2011) incorporated hydrology and defined floodplain as the area bordering a channel that is inundated with a specified frequency regardless of its alluvial nature (Hydraulic Engineer Center, 1976; Nanson and Croke, 1992). We used the FEMA floodplain definition, qualified by incorporating the frequency of inundation, due to the cross-discipline familiarity of the “100-year floodplain” and its broad inclusion of many similar ecotype definitions (*e.g.*, Fennessy and Cronk, 1997). The FEMA floodplain may, but need not, coincide with the geomorphic floodplain.

Integrated Floodplain and Wetland Mapping

We applied four different methods to identify integrated floodplain and wetland system areas in our study watershed based on the following: (1) Geospatial Distance; (2) SSURGO Soil Data; (3) Geomorphic Characteristics; and (4) FEMA Floodplain Maps (*i.e.*, FIRMs). As noted, wetland systems outside floodplain areas derived in this study may be considered spatially discrete systems (*e.g.*, not spatially connected) but are functionally connected with river networks (*c.f.*, Golden *et al.*, 2016; Cohen *et al.*, 2016).

We identified wetland location and extent for this study using the National Wetlands Inventory (NWI) (Cowardin et al., 1979). The NWI is the finest resolution national dataset for wetlands covering the coterminous U.S. though it does not map all wetlands. Furthermore, the NWI or Cowardin et al. (1979) definition of wetlands requires only one of three wetland indicators (soils, hydrology, or plants), whereas regulatory wetland delineation requires all three [33 Code of Federal Regulations 328.3(b)]. We used ArcGIS (version 10.x, ESRI, Redlands, California) for all geographic information system analyses. Following Lane et al. (2012) and Lane and D’Amico (2016), we acquired palustrine and lacustrine wetland system NWI data (USFWS, various dates, 2013-2015) for the MWR. NWI identifies both wetlands and deepwater habitats, categorizing freshwaters as riverine, palustrine, or lacustrine systems (Cowardin et al., 1979). The NWI is based on aerial imagery dating within the White River basin from 2000-2010. Imagery scale for the NWI data is >1:40,000 (USFWS, various dates, 2013-2015). The targeted mapping unit with NWI varies with the scale of the imagery from 0.4 to 2.0 ha (Tiner, 1997). Multipart NWI wetland polygons, those with more than one wetland type within a spatially connected wetland polygon (*e.g.*, palustrine open water polygon surrounded by or abutting a palustrine emergent marsh) were merged. The resulting 68,002 spatially discrete post-processed NWI wetlands in the MWR

basin comprise approximately 4% of the basin's cumulative area, totaling 955 km² of wetland habitat.

Geospatial Distance Floodplain Extent

Floodplain areas, using three different spatial distance-based floodplain proxies were defined in this approach as lands within a 10-, 30-, or 300-m buffer of National Hydrography Dataset (NHD) features (Figure 2). NHD is the best nationally available dataset depicting the location of most surface waters of the U.S. We acquired available statewide 1:24,000 NHD from the USGS website (USGS, various dates, 2013-2015). The NHD typically maps lotic features that are >1.6 km and lentic features that are >0.024 km² (2.4 ha), though that is not consistently followed throughout the country. Aerial data used in delineating the NHD vary in age from the 1950s to the present. High resolution NHD was created for the study area by the USGS during 2003-2007 from revised digital line graph data supplemented by aerial photographs. We extracted NHD components, including flowline, water body, and area. Polyline NHD components such as streams and rivers (including perennial, intermittent, and ephemeral), canals and ditches and named artificial paths were used in the buffering process. We also selected lakes, ponds, and reservoirs from the water-body dataset, and polygons of streams and rivers from the area dataset to be buffered at three buffer distances (see Lane et al., 2012; Lane and D'Amico, 2016 for additional methodology). The 10-m floodplain width approximates the lateral positioning error (~12 m) of NHD 1:24,000 data (USGS, various dates, 2013-2015) and could be further considered an approach to quantify wetlands directly connected (*e.g.*, a 10-m buffer) or adjoining the river network (*e.g.*, 30- and 300-m buffers). In addition, the initial buffer selection builds from the body of literature, using 10-m (*e.g.*, Reif et al., 2009; Frohn et al., 2009; Lane et al., 2012; Frohn et al., 2012) and acknowledges horizontal limitations in the accuracy of the NHD data layer (Lang et al., 2012). We selected 30-m and 300-m as additional exploratory buffer distances (*i.e.*, distance-based proxies for floodplain ecotypes) that states or other entities may choose to use to define potential floodplain extent (see also Lane and D'Amico, 2016). Wetlands were identified as within the geospatial floodplain area if any portion of the post-processed NWI wetland polygons intersected the geospatial floodplain map.

SSURGO Soil Survey Floodplain Extent

The SSURGO soil data for the study watershed was collected and compiled over various dates at a scale of 1:12,000 to 1:24,000 (USDA NRCS, 2005; USDA Web Soil Survey, 2015). Following Sangwan and Merwade (2015), we selected the map units with the following SSURGO attributes: (1) All Water Bodies; (2) Flood Frequency >100 years (*i.e.*, flooding probability is at least 1% annually); (3) Fluvial Soil Origins; and (4) Fluvial Geomorphology. This was conducted using the following attribute query of the SSURGO dataset fields and combining the resulting polygons to a single, basin-based map: `[muname] = "water" OR [geomdescr] = "% flood%" OR [taxsubgrp] = "% fluv%" OR [floodfreqdcd] in ("Rare," "Occasional," "Frequent," "Very Frequent")`. While early analyses of this method appeared to successfully delineate floodplain areas based on visual analyses, we found it also selected soils associated with wetland features spatially isolated from fluvial influence (*i.e.*, obviously upland-embedded wetland features spatially discrete from the river network). These artifacts not associated with floodplain areas were removed from the data layer by

first aggregating the post-query SSURGO polygons that were within a 1-m buffer of each other. Next, a count of the number of aggregated [muname] “water” polygons were attributed to each feature. Finally, any potential artifact polygon that contained only one water feature and was <8.1 ha (the size threshold for lacustrine, or lake systems) (Cowardin et al., 1979) was removed, which resulted in spatially appropriate (*i.e.*, within a likely flood-prone area) SSURGO-based floodplain delineation. Wetlands were identified as within the SSURGO-based floodplain area if any portion of the post-processed NWI wetland polygons intersected the SSURGO-based floodplain map.

Geomorphic-Based Floodplain Extent

Valley floor landforms (Gallant and Dowling, 2003), a surrogate for floodplain areas, were delineated through the use of the deviation from mean center (DEV), a digital elevation model (DEM) filtering algorithm. The DEM was acquired from the National Elevation Dataset, $\frac{1}{3}$ arc-second raster assembled by the USGS (USGS, various dates, 2013-2015). DEV is an established approach in digital terrain analysis for classifying landforms in heterogeneous topography (De Reu et al., 2013; Lindsay et al., 2015). The DEV (Equation 1) describes relative topographic position as a fraction of terrain ruggedness (Wilson and Gallant, 2000):

$$\text{DEV}(D) = \frac{z_0 - \bar{z}}{\sqrt{\frac{1}{n_r - 1} \sum_{i=1}^{n_r} (z_i - \bar{z})^2}} \quad (\text{Equation 1})$$

where D is the focal window size, z_0 is elevation, $\bar{z}$ is mean elevation, and the denominator is the elevation standard deviation.

The roving or focal window size in which the DEV is calculated is an important factor in geomorphic floodplain characterization. To determine the scale-dependent topographic character of each pixel, multiple roving window sizes were explored to determine the absolute maximum topographic deviation ($|\text{DEV}_{\text{max}}|$) relative to scale for every DEM pixel. For example, a DEM pixel in the middle of a wide valley is not topographically distinct if the roving window only captures other valley floor pixels. However, if the roving window is expanded to include ridge features then the pixel in question would appropriately be assigned a negative DEV (relatively depressed feature), indicating a valley landform. Whitebox Geospatial Analysis Tools (GAT) (Lindsay, 2014), an open source GIS (geographic information systems) software which includes an efficient integral image approach for $|\text{DEV}_{\text{max}}|$ calculations was used for this analysis. The Maximum Elevation Deviation tool in Whitebox GAT calculates the DEV for a user-defined roving window step size, stores the DEV value at each window size to memory and returns the $|\text{DEV}_{\text{max}}|$ for each pixel to a final DEV grid (Lindsay, 2014; Lindsay et al., 2015). The DEV calculation was completed on the MWR, using a 10-m DEM (USGS National Elevation Dataset, various dates, 2013-2015). We resampled the DEM to 12-m as our analyses were limited by available processing memory with the native 10-m DEM resolution. Iterative $|\text{DEV}_{\text{max}}|$ rasters were created at local ($n = 100$, minimum window of 36 m, maximum of 6,000 m), meso ($n = 200$, window size 6,001-18,000 m), and broad scales ($n = 200$, window size 18,001-36,000 m), using a 60-m window step size. The creation of the local-, meso-, and

broad-scale $|\text{DEV}_{\text{max}}|$ rasters provides unique details about the topographic position of each pixel location at each of the three scale ranges. The $|\text{DEV}_{\text{max}}|$ of each pixel from the total number of iterations was calculated for $|\text{DEV}_{\text{max}}|$ local-, meso-, and broad-scale rasters. After the three $|\text{DEV}_{\text{max}}|$ files for the study area were calculated, a minimum overlay analysis was performed to transform the lowest pixel value from the three $|\text{DEV}_{\text{max}}|$ grids into a single grid. This process selected the most topographically depressed pixels from the three scale ranges. Supervised classification of the minimum overlay grid was performed to delimit the valley floors. Binary thresholds identifying potential valley floors were iteratively analyzed to determine a “best fit” to the DEM hillshade for each study area. After the threshold was determined, the DEV binary raster was converted to a polygon feature, thereby defining the valley floors. Valley floor areas not containing NHD flowlines were removed, providing a final polygon feature of DEV-based (or geomorphic) floodplains. Wetlands were identified as within the geomorphic-based floodplain area if any portion of the post-processed NWI wetland polygons intersected the geomorphic-based floodplain map.

FEMA FIRM Floodplain Extent

FIRMs were downloaded from FEMA’s Map Service Center (FEMA, 2015) for the MWR watershed. The following FIRM flood zone (A) categories were used to delineate the floodplain area: Zone A (*i.e.*, 1% annual chance of flooding, no base flood elevation); Zone AE (*i.e.*, 1% annual chance of flooding, with base flood elevation); Zone AE Floodway (*i.e.*, floodway, regulatory floodway); and Zone AO (*i.e.*, 1% annual chance of 0.3-0.91 m sheet flow flooding). As with all methods described above, wetlands were identified as within the FEMA floodplain area if any portion of the post-processed NWI wetland polygons intersected the FEMA FIRM floodplain map. FIRMS were available for 32% of the MWR watershed.

Accuracy Assessment of Floodplain and Integrated Wetland Systems

We used observed flooding events (OFE) in the White River watershed independently collected via field-based measures throughout the watershed by Morlock et al. (2008) to evaluate our integrated floodplain and wetland system delineations. During an approximately 16-h period during 06-07 June, 2008, 5.0-26.4 cm of rain fell across the White River watershed, which had saturated antecedent soil conditions from March to May 2008 precipitation indexing from 1.2 to 1.8 times greater than historical normals (Indiana State Climate Office, 2008). Morlock et al. (2008) analyzed flooding effects on communities within the White River basin from this storm, using both permanent stream gage data and field-based high-water marks along >80 km of stream reaches. These data were referenced by Morlock et al. (2008) to the North American Vertical Datum of 1988 and flood-peak inundation maps were created for 17 stream reaches, 8 of which were in our study area (see Figures 1a–1c). The inundation process used DEMs coupled with the high-water marks and geoprocessing software to create a water surface map across the floodplain area at the height of the flood (see Morlock et al., 2008 for additional methodological information). Flooding events across the Morlock et al. (2008) stream reaches used in this study had recurrence intervals (USDA NRCS, 2012) from 25 to 50 years to >100 years (Table 1).

We included one additional source of OFE from Fowler et al. (2010) for the White River at Edwardsport, Indiana (see Figure 1a). Fowler et al. (2010) derived flood-inundation maps for this community, using permanent stream gage and stage-discharge rating curve data; the available GIS file from Fowler et al. (2010) is for inundated areas with a stage height of 9.1 m, the maximum value of the current stage-discharge curve, with estimated discharge of 3,199.8 m³/s. This estimated discharge value is 3.7% greater than the estimated 100-year recurrence interval discharge for Edwardsport (3,086.5 m³/s with an approximate stage height of between 8.8 and 9.1 m; see Fowler et al. 2010 for additional information).

Comparisons between the extent of flood events listed in Table 1 and our derived floodplain areas were conducted, using three methods. First, we assessed the simple areal overlap between our calculated floodplain areas and the OFE. We then applied equations for correctness (C-index, Equation 2) and fit (F-index, Equation 3), both of which are commonly used measures to assess the overlap and goodness-of-fit between mapping products (*e.g.*, Bates and De Roo, 2000; Horritt and Bates, 2002; Tayefi et al., 2007; Alfieri et al., 2014):

$$\text{Correctt}(\%), C = 100 \times (A_{ab}/A_b) \quad \text{Equation 2}$$

$$\text{Fit}(\%), F = 100 \times [A_{ab}/(A_a + A_b - A_{ab})] \quad \text{Equation 3}$$

where A_a and A_b are floodplain areas observed or predicted by methods A and B, respectively, and A_{ab} is the area of overlap between maps produced by methods A and B. Unlike the F-index, the C-index does not penalize for overprediction (or commission) errors, making the F-index the more conservative comparative approach (Sangwan and Merwade, 2015).

RESULTS

We derived integrated floodplain and wetland system areas in the MWR, using four different methods: (1) Geospatial Distance; (2) SSURGO Soil Survey Data; (3) Geomorphic Data; and (4) FEMA FIRM data.

Delineating Integrated Floodplain and Wetland System Extent: Contrasting Methods

Geospatial distance measures of 10-, 30-, and 300-m were used to delineate integrated floodplain and wetland systems extent (Figure 3). Using a 10-m distance-based measure delineated 3.4% of the watershed as floodplain area, spatially intersecting 73.7% of the post-processed NWI wetland area (approximately 704 km²; Figure 4). A 30-m buffer covered 8.1% of the watershed area and slightly increased the extent of wetlands within the floodplain proxy slightly, to 75.7% (approximately 723 km²). Increasing the buffer to 300 m substantially increased the watershed area covered (to 60.6%; *e.g.* Figure 2); this increased the extent of wetlands integrated into the floodplain to 89.6% (approximately 856 km²). Assessing the number (instead of NWI wetland area) of wetlands in geospatially derived metrics using the 10-m, 30-m, and 300-m buffers resulted in 17.6, 21.5, and 67.2% of MWR wetlands located within the floodplain, respectively.

We analyzed integrated floodplain and wetland system extent, using three additional approaches based on SSURGO soil data, geomorphic data, and FEMA FIRMs (Figure 5). SSURGO soil-based floodplain analyses delineated 16.4% of the MWR basin area as floodplain (see Figure 4) intersecting 77.4% of the wetlands (approximately 739 km²) with the river network. Geomorphic mapping (*i.e.*, DEV) delineated 31.7% of the White River as floodplain area, which intersected 85.7% or approximately 818 km² of the wetlands. The FEMA FIRM delineated 11.2% of MWR as floodplain, spatially intersecting 57.8% (approximately 552 km²) of the wetlands to the river system. As with the areal extent, the geomorphic mapping method intersected the greatest number of wetlands (44.1%) compared with 24.9% using SSURGO soil-based floodplain delineation and 14.1% using FEMA FIRMs.

Contrasting Floodplain Area Extent with Observed Flooding Events

We contrasted the overlap in floodplain areas delineated by the different methods and observed flooding events in nine communities along the MWR; representative examples for three communities are provided (Columbus, Indiana; Figure 6), (Seymour, Indiana; Figure 7), and (Worthington, Indiana; Figure 8). Geospatial distance-based measures of floodplain extent, including the 300-m buffer, consistently underestimated the flooded area (Table 2), on average covering 8.1% ($\pm 3.3\%$) of the observed flooded area using 10-m, 13.6% ($\pm 3.9\%$) at 30-m, and 82.1% ($\pm 11.8\%$) at 300-m. SSURGO soil-based floodplain area delineation averaged 102.4% ($\pm 35.1\%$) of the OFEs (Table 3). FEMA FIRMs underestimated the flooded areas, covering 89.9% ($\pm 26.7\%$). FEMA FIRM data were not available at the Edwardsport study site. In contrast, geomorphic measures substantially overestimated the OFEs, averaging 161.2% ($\pm 69.0\%$).

In addition to analyzing the simple percent overlap, we used the C and F indices to analyze the overlap of floodplain area delineation with nine observed 25-year to >100-year recurrence interval OFEs across the MWR (see Table 1). Geospatial distance-based measures performed poorly, with only the 300-m floodplain area delineation achieving mean C- and F-index values >45% (C-index $56.9\% \pm 9.8$, F-index $45.9\% \pm 10.0$), with the C-index and F-index averaging <10% for 10-m and <13% for 30-m across all sites (Table 2). Floodplain area extents calculated using SSURGO soil, geomorphic data, and FEMA FIRMs best approximated the OFEs, with geomorphic-based measures having the best percent correct (C-index, $91.9 \pm 14.4\%$) and FEMA FIRMs the second best C-index ($84.1 \pm 25.2\%$). We calculated F-index values, which penalizes the overprediction (or commission) error, and FEMA FIRMs had the best fit (F-index, $79.4 \pm 24.1\%$) and SSURGO soil-based methods the second best F-index ($63.3 \pm 26.5\%$), though not far from the geomorphic values ($59.4 \pm 19.5\%$; see Table 3).

DISCUSSION

Identifying floodplain extent and integrated wetland area is a timely research need to effectively manage aquatic resources. Additionally, this information is important for understanding potential CWA jurisdiction (*e.g.*, to determine whether a given aquatic system such as a wetland is, "...'adjacent' (bordering, contiguous, neighboring) to other clearly

defined ‘Waters of the United States,’ such as a traditional navigable water, interstate water, impoundment, tributary, or territorial sea (40 CFR §122.2)’; Mushet et al., 2015, p. 7). The literature is conclusive: wetlands in floodplains are physically, chemically, and biologically integrated into — or directly connected to — downstream waters through functions which improve or affect the quality of the receiving, or downstream, water body (Alexander, 2015; USEPA, 2015). While we determined a wetland to be “connected” if spatially colocated within a floodplain as derived in these analyses, we readily acknowledge that wetlands in a floodplain, as well as those outside of floodplains, are functionally connected through biogeochemical, hydrological, and biological processes (see Marton *et al.*, 2015; Rains *et al.*, 2015; Mushet et al., 2015; Cohen *et al.*, 2016).

To better understand alternative nationally applicable methods, we compared geospatial distance-based measures as proxies of floodplain extent with geomorphic and SSURGO soil-based floodplain maps, as well as with the current FEMA FIRMs. We expected that geospatial distance-based measures would underestimate floodplain area extent and thus underestimate the abundance of wetlands integrated into the river network, and that FEMA maps would be limited in their application, especially in nonurban areas. Although all but the FEMA floodplain extent measures intersected >73% of the wetlands of the MWR watershed (see Figure 4), the 10-m buffer required 3.4% of the watershed area to do so, whereas the geomorphic method (see Equation 1) required 31.7%. FEMA FIRMs identified 58% of the MWR wetlands as within floodplain areas, while covering 11% of the watershed with FIRM-delineated flood zones. Overall, the concordance between these results in the abundance of wetlands intersected suggests that the majority of the MWR watershed wetlands occur in floodplain portions of the system. While these multiple approaches resulted in generally similar findings, there are substantial caveats associated with each of them.

Deriving Floodplain Extent Using Geospatial Distance as a Proxy

When analyzed through fit and correctness measures of OFE, the geospatial distance measures (especially the 10- and 30-m measures) performed poorly in the study watershed (see Table 2). These results suggest that while geospatial distance-based measures designated an abundance of MWR wetlands as colocated within the floodplain proxy, these measures might be including wetlands that are substantially spatially removed from the actual active floodplain. The extent of the integrated floodplain and wetland system, using the geospatial distance-based method, is determined by buffering both areal and linear NHD features. We therefore buffered NHD flowlines including ephemeral and intermittent stream systems at the upper reaches of the MWR. These low Strahler (1952) stream order systems likely did not have substantial floodplains associated with them, and generally did not have NHD area features associated with them, either. In a typical setting, a stream transitions from confined valley (with no floodplains) to a laterally unconfined valley (with continuous floodplains) via an intermediate, partially confined valley (with discontinuous floodplains; Brierley and Fryirs, 2005; Thorp et al., 2010). The relative rates of different geomorphic processes such as erosion, sediment transfer and deposition, which in turn are determined by the total stream power and longitudinal profile form, essentially govern the existence and spread of floodplains along the river course (Jain *et al.*, 2008). Supporting this, Dodov and

Foufoula-Georgiou (2005) reported that streams draining $<100 \text{ km}^2$ had narrow and poorly developed floodplains resulting from frequent yet ephemeral flooding events. Nardi *et al.* (2006) found that floodplain width followed a power law distribution and suggested that contributing area is a good predictor of floodplain width. Thus, as headwater streams have the smallest contributing areas, they would have the smallest floodplain widths. Using geospatial distance as a floodplain proxy throughout the entire course of a river network may incorrectly imply the existence of floodplains throughout the entirety of the corresponding NHD network. However, we make no claim on actually quantifying hydrologic connectivity throughout the network. Though headwaters may not have actual floodplains in some cases, they may yet have a dynamic riparian area wherein the headwater system overflows bed and bank and hydrologically connects proximal wetland systems (*e.g.*, Vanderhoof *et al.*, 2015; White and Crisman, 2016).

We further explored our results by analyzing the abundance of NHD stream orders (SO) that intersected the different methods (Figure 9). Low SO numbers are indicative of headwater systems and smaller, wadeable streams; as streams merge SO numbers increase to nonwadeable systems and eventually to great rivers (Strahler, 1952). As noted above, we buffered NHD flowlines, using a geospatial distance approach. However, $<16\%$ of NHD SO1 reaches (*i.e.*, headwaters) were contained by FEMA FIRMs; this increased to approximately 40% with SO2. Geomorphic and SSURGO soil-based methods intersected approximately 89% and 48% of SO1 and 96% and 78% of SO2, respectively (see Figure 9). The FIRM data on average intersected 33% of all stream reaches in the MWR *vs.* 65% for SSURGO soil-based and 92% for geomorphic methods. FIRMs focused on larger-order systems and urban areas, intersecting up to 93% of SO6. This is logical considering that larger SO have greater contributing areas likely resulting in less frequent, but longer-lasting and more impactful flooding events (Dodov and Foufoula-Georgiou, 2005).

Deriving floodplain areas to quantify the abundance of wetland systems integrated into the river network provides estimates of potential floodplains at large scales, something that is lacking across the conterminous U.S. and can be useful in protecting human health and well-being (Jonkman, 2005). Understanding floodplain extent may also inform the potential jurisdiction of the aquatic resource under local, state, or federal regulations. Selecting a geospatial distance for the buffer to apply to existing aquatic network maps is a simple approach, yet one that may inaccurately extend floodplain areas to a network's furthest reaches. For instance, while we used geospatial distance-based proxies in all headwater systems, the alternative methods suggest a wide variation in possible floodplain extent with as few as 14% of SO1 and 37% of SO2 headwaters having floodplain areas based on FIRMs and as much as 90% of SO1 and 96% of SO2 based on geomorphic approaches (see Figure 9). The error propagation from geospatial distance buffers can be substantial when considering that $\sim 50\%$ of the stream lengths throughout the conterminous U.S. are headwaters (Nadeau and Rains, 2007), conceivably without extensive floodplain areas (Dodov and Foufoula-Georgiou, 2005; Nardi *et al.*, 2006). However, in some systems, such as regions of the U.S. with low slope like the Atlantic and Gulf Coast plains (Omernik, 1987), the existence of floodplain areas in headwaters is appropriate and hence the accuracy from use of geospatial distance buffers to derive integrated floodplain and wetland areas would increase. For instance, White and Crisman (2016) reported that the majority of

Florida's headwaters emanate from wetlands; these wetland systems would likely be within a geospatial buffer and therefore within an existing floodplain area. However, parts of the country with higher slopes would be expected to lack discernible floodplain areas outside of the active channel, excepting valley floors (Gregory et al., 1991). While wetlands spatially proximal to stream systems across all stream orders will more likely be hydrologically connected than those further away (USEPA, 2015), lower-order stream systems may not have ecologically or hydrologically defined floodplains. Therefore, while wetlands proximal to the river network (in particular) may be functionally integrated into the river networks they may not be within an actual floodplain, creating commission errors in our analyses.

SSURGO Soil-Based Floodplain Derivation and Integrated Wetland System Extent

The OFE F-index values for FIRMs (79.4%) and SSURGO soil-based floodplain areas (63.3%) in this study are similar to the findings of Sangwan and Merwade (2015). In a study of Washington, Wisconsin, and Minnesota floodplains, Sangwan and Merwade (2015) reported FIRM F-index values were 11-20.3% higher than SSURGO soil-based methods. SSURGO soil-based methods have the utility of being based on nationally available SSURGO data and on being a very rapid and inexpensive approach to integrated floodplain and wetland system mapping, albeit with somewhat lower accuracy than FEMA FIRMs (when the latter are available). The SSURGO soil-based method also appears to be regionally adaptable to improve performance. For instance, Sangwan and Merwade (2015) improved floodplain mapping in certain ecoregions of northern Indiana when an additional criterion was included specific to soils of that region, increasing their F-index values markedly. As with other mapping products, the utility of the SSURGO soil-based method is dependent on the quality of the input data. SSURGO map data across the U.S. were collected at scales ranging from 1:12,000 to 1:63,360 and include map unit data collected over the past 100 years (USDA Web Soil Survey, 2015). Though the base layer may be correct, the landform may have undergone substantive change in the ensuing years, resulting in changes that may, or may not, affect the characteristics of the soil unit as mapped in SSURGO (*e.g.*, the frequency of flooding may have markedly changed since the data were collected due to changes in upstream impervious surface abundance; Caldwell et al., 2012).

Geomorphic Floodplain Derivation and Integrated Wetland System Extent

Using geomorphic characteristics to derive floodplain areas requires substantial topographic difference to demarcate the existence of a valley bottom (*vs.* the valley walls). Thus, its use in parts of the U.S. lacking substantive topographic deviation (or sufficiently resolved topographical/elevation data) is questionable. Furthermore, the presence of a substantial variance in the slope of a transverse line does not necessarily mean a floodplain area is present, though it may identify and bound the extent of the area prone to flood-based geomorphic changes and impacts. Thus, defining floodplain areas by geomorphology would likely result in commission errors wherein an overabundance of the watershed would be considered a flood-prone area, and wetlands therein considered spatially integrated into the river network. This was borne out by our analyses, with the average F-index value (which penalizes overprediction or commission errors) for the geomorphic method ($59.4 \pm 19.5\%$) lower than both the SSURGO soil-based and FIRM methods. However, when contrasted

with OFEs in the MWR, the geomorphic approach had the highest average C-index of the methods ($91.9 \pm 14.4\%$ fit, see Table 3).

Developing the geomorphic floodplain area extent also requires parameter selection that can greatly affect the results. In this study, we selected parameters through a trial- and-error approach, attempting to cover the fullest extent of the NHD network, while simultaneously not overextending the DEV-derived floodplain area up the “valley walls” of the MWR. This required substantial operator expertise and time, decreasing the likelihood that this method could be applied efficiently at larger scales. Should scale- or geomorphic approaches be established such that operator time and/or subjectivity could be reduced, the geomorphic approach may be increasingly useful. Furthermore, with increased efficiency, the geomorphic approach may be successfully married with other methods to couple topographic relief with landscape and/or hydrological modeling approaches to establish integrated floodplain and wetland system area extent.

FIRM Floodplains and Integrated Wetland System Extent

Wherever FEMA FIRMs exist, their utility in risk-management is manifest. However, their usefulness in determining the extent of integrated floodplain and wetland system areas is an area of active research, especially in light of the recent CWA regulation (the Clean Water Rule; currently stayed) which clarifies that wetlands within 100-year floodplains may be jurisdictional (80 *Federal Register*, p. 37,081, 37,104 *et seq.*). FIRM maps currently do not comprehensively map floodplain areas in our study area for use in identifying watershed-scale floodplains and integrated wetland systems, suggesting their use elsewhere is suspect. FIRMs are typically developed through the application of hydraulic simulation and terrain analyses to model the estimated inundated area following 100-year storm flow events (Anderson, 2000; Knebl et al., 2005). As previously noted, the development and release of FIRMs by FEMA is an expensive endeavor, costing \$3,000-6,000 per stream km (FEMA, 2006), and as a result a large expanse of the nation’s aquatic network — typically the more rural areas — remains unmapped by FEMA. In addition, many of the FIRMs are out of date, a problem that is inherent to many large spatial datasets. Approximately 33% are at least 15 years old, and an additional 30% are from 10 to 15 years old such that floodplain areas may now be “built out” or hydrologic changes, such as those borne by global climate change — in the watershed may result in dramatically different inundation frequencies (Caldwell et al., 2012; Highfield et al., 2013). The spatial coverage of FIRMs throughout the MWR watershed network was generally poor, with only 32% of NHD reaches covered. However, where we had both FIRMs and OFE, the FIRMs had the highest F-index in 88% our study areas (seven of eight sites with OFEs; see Table 3). This may reflect the focus of Morlock et al. (2008) and Fowler et al. (2010) on quantifying flooding events for impacted communities, and communities and urban settings is where FEMA has similarly (and logically) focused their attention.

Summary and Conclusions

We compared four methods to map the potential extent of integrated floodplain and NWI-mapped wetland systems for a large portion of the White River of Indiana, U.S. We evaluated the accuracy of the floodplain mapping methods with independently collected

observed flooding events. Our methodology to quantify floodplain extent included analyses of geospatial distance, SSURGO soil, and geomorphic characteristics, and was contrasted with painstakingly and expensively collected FEMA FIRM data. Where the FIRM data existed, it was of high-quality and appeared to more accurately reflect flooding events than the other methods, as determined by comparison to ground-based flood mapping with recurrence intervals of 25-50 to >100 years. However, an important caveat to that conclusion is that FIRMs only covered 32% of the stream reaches of the MWR, limiting their use in quantifying the extent of floodplains and the wetland systems therein. Floodplain extent in lower-order stream systems and those in nonurban areas were particularly underestimated with FIRMs. Geomorphic-based floodplain extent measures were moderately effective, but require substantive expertise to avoid valley-floor overreach and suffered from commission errors. The geomorphic approach used in this study, however, did provide the most comprehensive coverage of the river network (~93%) when contrasted with the SSURGO soil-based and FIRM methods. Geospatial distance-based measures identified wetlands integrated into floodplain proxies with buffer widths of 10-, 30- and 300-m buffers throughout the full NHD network. This method had likely commission errors in the upper reaches and omission errors in the lower reaches (*i.e.*, the higher stream order values) when flooding extent and integrated wetland area was substantially greater than the buffer-delineated floodplain areas. We conclude that SSURGO soil-based integrated floodplain and wetland system mapping appears to have the highest potential for management application at large scales due to its use of the nationally available SSURGO database and ability to be modified by the end-user to reflect regionally specific soil parameters associated with floodplains. We note in closing that our definition of floodplain area does not reflect a CWA jurisdictional assessment and that the recurrence interval for the observed inundation data used ranged from 25 to 50 to >100-year flooding events. An ideal assessment of floodplain areal extent to inform wetland and river-network integration would include field-based data from a “100-year storm” measured throughout the full drainage network. In the absence of such data, we suggest stream gage data coupled with both SSURGO soils (*e.g.*, Sangwan and Merwade, 2015) and geomorphic-based assessments (*e.g.*, Hicks and Peacock, 2005) may provide the most accurate measures of integrated floodplain and wetland area extent.

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LITERATURE CITED

- Alexander LC 2015 Science at the boundaries: scientific support for the Clean Water Rule. *Freshwater Science* 34(4): 1588–1594.
- Alfieri L, Salamon P, Bianchi A, Neal J, Bates P, and Feyen L, 2014 Advances in Pan-European Flood Hazard Mapping. *Hydrological Processes* 2813:4067–4077.
- Anderson DJ 2000 GIS-Based Hydrologic and Hydraulic Modeling for Flood Delineation at Highway River Crossings. Masters' Thesis, University of Texas at Austin, Austin, Texas.

- Association of State Wetland Managers (ASWM). 2001 Consistent Methods for Identifying Waters That May No Longer Be Regulated Under the Clean Water Act Following the SWANCC Decision. Berne, NY, Association of State Wetland Managers.
- Bates PD and De Roo APJ, 2000 A Simple Raster-Based Model for Flood Inundation Simulation. *Journal of Hydrology* 236:54–77.
- Caldwell P, Sun G, McNulty SG, Cohen EC, and Moore JA. 2012 Impacts of impervious cover, water withdrawals, and climate change on river flows in the conterminous US. *Hydrology and Earth System Sciences* 168: 2839–2857.
- Chen N, Zhou L, Chen Z. 2015 A Sharable and Efficient Metadata Model for Heterogeneous Earth Observation Data Retrieval in Multi-Scale Flood Mapping. *Remote Sensing* 78: 9610.
- Cowardin LM, Carter V, Goulet FC, and LaRoe ET. 1979 Classification of Wetlands and Deepwater Habitats of the United States. Washington D.C., U.S. Fish and Wildlife Service.
- Dahl TE 2014 Status and trends of prairie wetlands of the United States 1997 to 2009. U.S. Department of the Interior, Fish and Wildlife Service, Ecological Services, Washington DC.
- De Reu J, Bourgeois J, Bats M, Zwervaegher A, Gelorini V, De Smedt P, Chu W, Antrop M, De Maeyer P, Finke P, Van Meirvenne M, Verniers J, Crombé P. 2013 Application of the topographic position index to heterogeneous landscapes. *Geomorphology* 1860: 39–49.
- Dodov B and Foufoula-Georgiou E 2005 Fluvial processes and streamflow variability: Interplay in the scale-frequency continuum and implications for scaling. *Water Resources Research* 415:W05005.
- Federal Emergency Management Agency (FEMA). 2006 Floodplain Management Requirements: A Study Guide and Desk Reference for Local Officials. http://www.fema.gov/media-library-data/20130726-1539-20490-0241/nfip_sg_unit_3.pdf, accessed October 2013.
- Fowler KK, Kim MH, Menke CD, and Arvin DV, 2010, Flood of September 2008 in Northwestern Indiana: U.S. Geological Survey Open File Report 2010–1098, 20 p.
- Frohn RC, Reif M, Lane CR, and Autrey B 2009 Satellite remote sensing of isolated wetlands using object-oriented classification of Landsat-7 data. *Wetlands* 293: 931–941.
- Frohn R, D'Amico E, Lane CR, Autrey B, Rhodus J, and Liu H 2012 Multi-temporal Sub-pixel Landsat ETM+ Classification of Isolated Wetlands in Cuyahoga County, Ohio, USA. *Wetlands* 322: 289–299.
- Gallant JC and Dowling TI 2003 A multiresolution index of valley bottom flatness for mapping depositional areas. *Water Resources Research* 3912: 1347–1361.
- Gregory SV, Swanson FJ, McKee WA, Cummins KW 1991 An Ecosystem Perspective of Riparian Zones. *Bioscience* 418: 540–552.
- Hey DL, Kostel JA, Crumpton WG, Mitsch WJ, and Scott B. 2012 The roles and benefits of wetlands in managing reactive nitrogen. *Journal of Soil and Water Conservation* 672: 47A–53A.
- Hicks FE and Peacock T 2005 Suitability of HEC-RAS for Flood Forecasting. *Canadian Water Resources Journal / Revue canadienne des ressources hydriques* 302: 159–174.
- Highfield WE, Norman SA, and Brody SD. 2013 Examining the 100-Year Floodplain as a Metric of Risk, Loss, and Household Adjustment. *Risk Analysis* 332: 186–191.
- Homer CG, Dewitz JA, Yang L, Jin S, Danielson P, Xian G, Coulston J, Herold ND, Wickham JD, and Megown K. 2015, Completion of the 2011 National Land Cover Database for the conterminous United States-Representing a decade of land cover change information. *Photogrammetric Engineering and Remote Sensing*, v. 81, no. 5, p. 345–354
- Horritt MS, and Bates PD, 2002 Evaluation of 1D and 2D Numerical Models for Predicting River Flood Inundation. *Journal of Hydrology* 268:87–99.
- Indiana State Climate Office 2008 May 2008 Climate Report. 13 p, www.iclimate.org/summary.asp, accessed February 2016
- Jonkman SN 2005 Global Perspectives on Loss of Human Life Caused by Floods. *Natural Hazards* 342: 151–175.
- Knebl MR, Yang Z-L, Hutchison K, and Maidment DR, 2005 Regional Scale Flood Modeling Using NEXRAD Rainfall, GIS, and HEC-HMS/RAS: A Case Study for the San Antonio River Basin Summer 2002 Storm Event. *Journal of Environmental Management* 754:325–336.

- Lane CR, D'Amico E, and Autrey B 2012 Isolated Wetlands of the Southeastern United States: Abundance and Expected Condition. *Wetlands* 324: 753–767.
- Lane CR and D'Amico E. Accepted Identification of putative geographically isolated wetlands of the conterminous United States. *Journal of the American Water Resources Association*.
- Lang M, McDonough O, McCarty G, Oesterling R, and Wilen B. 2012 Enhanced Detection of Wetland-Stream Connectivity Using LiDAR. *Wetlands* 32: 461–479.
- Leibowitz S 2015 Geographically Isolated Wetlands: Why We Should Keep the Term. *Wetlands* 355: 997–1003.
- Lindsay JB. The Whitebox Geospatial Analysis Tools project and open-access GIS; Proceedings of the GIS Research UK 22nd Annual Conference; 16–18 April; The University of Glasgow; 2014. .
- Lindsay JB, Cockburn JMH, and Russell HAJ 2015 An integral image approach to performing multi-scale topographic position analysis. *Geomorphology* 245: 51–61.
- Merwade V, Olivera F, Arabi M, and Edleman S. 2008 Uncertainty in Flood Inundation Mapping: Current Issues and Future Directions. *Journal of Hydrologic Engineering* 137: 608–620.
- Miranda LE 2005 Fish Assemblages in Oxbow Lakes Relative to Connectivity with the Mississippi River. *Transactions of the American Fisheries Society* 1346: 1480–1489.
- Morlock SE, Menke CD, Arvin DV, Kim MH 2008 Flood of June 7–9, 2008, in Central and Southern Indiana: U.S. Geological Survey Open File Report 2008–1322: 15 pp.
- Mushet D, Calhoun AJK, Alexander LC, Cohen MJ, DeKeyser ES, Fowler L, Lane CR, Lang MW, Rains MC, and Walls SC. 2015 Geographically Isolated Wetlands: Rethinking a Misnomer. *Wetlands* 35: 423–431.
- Nadeau T-L and Rains MC 2007 Hydrological Connectivity Between Headwater Streams and Downstream Waters: How Science Can Inform Policy1. *JAWRA Journal of the American Water Resources Association* 431: 118–133.
- Ntelekos AA, Oppenheimer M, Smith JA, Miller AJ 2010 Urbanization, climate change and flood policy in the United States. *Climatic Change* 1033: 597–616.
- Omernik JM 1987 Ecoregions of the Conterminous United States. *Annals of the Association of American Geographers* 771: 118–125.
- Reif M, Frohn RC, Lane CR, Autrey B 2009 Mapping isolated wetlands in a karst landscape: GIS and remote sensing methods. *GIScience and Remote Sensing* 462: 187–211.
- Sangwan N and Merwade V 2015 A Faster and Economical Approach to Floodplain Mapping Using Soil Information. *JAWRA Journal of the American Water Resources Association*: n/a–n/a.
- Smith LM Euliss NH, Wilcox DA, and Brinson MM. 2008 Application of a geomorphic and temporal perspective to wetland management in North America. *Wetlands* 283: 563–577.
- Strahler AN 1952, Hypsometric area-altitude analysis of erosional topology, *Geological Society of America Bulletin* 63 11: 1117–1142
- Tate EC, Maidment DR, Olivera F, and Anderson DJ. 2002 Creating a Terrain Model for Floodplain Mapping. *Journal of Hydrologic Engineering* 72: 100–108.
- Tayefi V, Lane SN, Hardy RJ, and Yu D. 2007 A Comparison of One- and Two-Dimensional Approaches to Modelling Flood Inundation Over Complex Upland Floodplains. *Hydrological Processes* 21:3190–3202.
- Thorp JH, Flotemersch JE, Delong MD, Casper AF, Thoms MC, Ballantyne F, Williams BS, O'Neil BJ, and Haase CS. 2010 Linking ecosystem services, rehabilitation, and river hydrogeomorphology. *Bioscience* 601: 67–74.
- Tiner RW 1997 NWI Maps: what they tell us. *National Wetlands Newsletter* 192: 5–12.
- Tiner RW 2003a Estimated extent of geographically isolated wetlands in selected areas of the United States. *Wetlands* 233: 636–652.
- Tiner RW 2003b Geographically isolated wetlands of the United States. *Wetlands* 233: 494–516.
- Tiner RW, Bergquist HC, DeAlessio GP, and Starr MJ 2002 Geographically Isolated Wetlands: A Preliminary Assessment of Their Characteristics and Status in Selected Areas of the United States. Hadley, MA, U.S. Department of the Interior, Fish and Wildlife Service, Northeast Region.

- U.S. Department of Agriculture, National Resources Conservation Service (USDA NRCS), 2005 National Soil Survey Handbook. <http://soils.usda.gov/technical/handbook/>, accessed October 2013.
- 2012 National Engineering Handbook Part 630 Hydrology. Available at <http://www.nrcs.usda.gov/wps/portal/nrcs/detailfull/?cid=stelprdb1043063>, accessed February 2016.
- U.S. Environmental Protection Agency (U.S. EPA). 2015 Connectivity of Streams and Wetlands to Downstream Waters: A Review and Synthesis of the Scientific Evidence EPA/600/R-14/475F. US EPA Office of Research and Development, Washington, DC.
- Wharton CH, Kitchens WM, Pendleton EC, and Sipe TW. 1982 The Ecology of Bottomland Hardwood Swamps of the Southeast: A Community Profile Washington. FWS/OBS-81/37. DC, US Department of the Interior Washington, DC.
- White WR and Crisman TL in press Headwater streams of Florida: Types, distribution, and a framework for conservation. River Research and Applications.
- Wilson JP and Gallant JC 2000 Terrain Analysis: Principles and applications. Wiley, New York, NY.
- Wolman MG, 1971 Evaluating Alternative Techniques Floodplain Mapping. Water Resources Research 76:1383–1392.

(a-c) White River Watershed, Indiana, United States Selected for This Study. (a) Includes nine communities with observed flooding events for assessing the different integrated floodplain and wetland area delineation methods, (b) covers various land uses and land covers, (c) includes three different ecoregions. Note that portions of watershed that are cross-hatched were not included in the study due to errors in the National Hydrography Dataset (NHD). NLCD, National Land Cover Database.

Figure 2. Schematic displaying the progressively larger buffer sizes that were used to characterize the riparian and floodplain areas of the White River, Indiana.

Figure 3.

An Example from the Study Watershed Contrasting the Extent of Three Different Floodplain Proxy Geospatial Buffer Widths, Characterizing the Increased Spatial Integration of the Wetland Areas Therein. Due to the scale of the figure, the 10- and 30-m geospatial buffers appear as linear systems whereas the 300-m buffer appears as a polygon encompassing a well-defined area.

Figure 4.

Percent of the Modified White River (MWR) Watershed Intersected by the Floodplain Area Analyses, Showing Both the Abundance of the Watershed Covered by the Various Methods as well as the Extent of the Wetland Area Intersecting the Derived Floodplain Areas. Note the following abbreviations for the approaches used: geomorphic (GEO), SSURGO soils-based floodplain mapping (SFM), and FEMA Flood Insurance Rate Maps (FIRM).

Figure 5.
An Example Showing the Various Integrated Floodplain and Wetland Areas Derived Through the Use of FEMA Flood Insurance Rate Maps (FIRM), SSURGO Soil-Based Floodplain Mapping (SFM), and Geomorphic (GEO) Methodologies.

Figure 6.

An Observed Flooding Event on the East Fork of the White River Affecting the Columbus, Indiana, Community Showing Overlap with Geomorphic (GEO), SSURGO Soil-Based (SFM), and FEMA FIRM Floodplain Area Mapping. FIRM, Flood Insurance Rate Maps; NHD, National Hydrography Dataset.

Figure 7.

An Observed Flooding Event on the East Fork of the White River Affecting the Seymour, Indiana, Community Showing Overlap with Geomorphic (GEO), SSURGO Soil-Based (SFM), and FEMA FIRM Floodplain Area Mapping. FIRM, Flood Insurance Rate Maps; NHD, National Hydrography Dataset.

Figure 8.
An Observed Flooding Event on the Eel Creek Tributary to the White River Affecting the Worthington, Indiana, Community Showing Overlap with Geomorphic (GEO), SSURGO Soil-Based (SFM), and FEMA FIRM Floodplain Area Mapping. FIRM, Flood Insurance Rate Maps; NHD, National Hydrography Dataset.

Figure 9.

The Abundance of National Hydrography Dataset Stream Kilometers for Each Strahler (1952) Stream Order Intersecting Geomorphic (GEO), SSURGO Soil-Based (SFM), and FEMA FIRM Approaches to Delineating Integrated Floodplain and Wetland Extents. FIRM, Flood Insurance Rate Maps.

Table 1.

Communities with Observed Flooding Events (OFEs) from storms in the White River watershed (Indian) in June 2008 that were used to estimate the accuracy of the riparian and floodplain areas delineated in this study (Morlock et al. 2010).

Location	Estimated Flood Recurrence Interval, T (years)	Area of Observed Flooding Event (ha)
White River at Worthington	Est. 50-100	57.65
White River at Spencer	25-50	185.81
East Fork White River at Seymour	50-100	2,179.71
White River at Paragon	Est. 50-100	112.90
White River at Newberry	> 100	107.93
White River at Martinsville	Est. 50-100	163.48
Eel Creek at Worthington	Est. 50-100	27.16
East Fork White River at Columbus	25-50	208.55
White River at Edwardsport	>100	835.65 ^A

^AThis data point was calculated, not observed (see Fowler et al. [2010]).

Table 2.

Comparisons between riparian and floodplain areas mapped using the three geospatial distance (10-m, 30-m, and 300-m) methods and the observed flooding event (OFE).

Location	10-m Geospatial Extent				30-m Geospatial Extent				300-m Geospatial Extent			
	10-m/Obs. (%)	C-Index (%)	F-Index (%)	F-Index (%)	30-m/Obs. (%)	C-Index (%)	F-Index (%)	F-Index (%)	300-m/Obs. (%)	C-Index (%)	F-Index (%)	F-Index (%)
White River at Worthington	11.4	10.2	10.2	10.0	16.3	14.6	14.4	14.4	91.3	59.7	59.7	45.4
White River at Spencer	13.0	12.9	12.9	12.9	20.8	20.0	19.9	19.9	99.4	77.6	77.6	63.7
East Fork White River at Seymour	6.6	0.1	0.1	0.1	11.4	11.1	11.1	11.1	67.7	62.9	62.9	60.0
White River at Paragon	2.5	1.7	1.7	1.7	7.2	5.2	5.1	5.1	79.0	44.3	44.3	32.9
White River at Newberry	11.4	10.9	10.9	10.8	15.8	15.1	15.0	15.0	75.5	47.8	47.8	37.4
White River at Martinsville	8.0	7.3	7.3	7.3	14.3	12.7	12.5	12.5	86.7	57.1	57.1	44.0
Eel Creek at Worthington	7.5	5.7	5.7	5.6	13.9	9.5	9.1	9.1	84.9	53.2	53.2	40.4
East Fork White River at Columbus	5.8	5.8	5.8	5.7	11.9	11.5	11.4	11.4	91.3	58.6	58.6	44.1
White River at Edwardsport	6.4	6.3	6.3	6.3	10.5	10.0	10.0	10.0	63.2	50.6	50.6	45.0
Average	8.1	6.8	6.8	6.7	13.6	12.2	12.1	12.1	82.1	56.9	56.9	45.9
Standard Deviation	3.3	4.2	4.2	4.2	3.9	4.2	4.2	4.2	11.8	9.8	9.8	10.0

Table 3.

Comparisons between riparian and floodplain areas delineated with soil, geomorphic, and FEMA FIRM approaches and the observed flooding event (OFE).

Location	Soil Floodplain Mapping (SFM)				Geomorphic Based Mapping (GBM)				FEMA FIRM Based Mapping			
	SFM/Obs. (%)	C-Index (%)	F-Index (%)	GBM/Obs. (%)	C-Index (%)	F-Index (%)	FIRM/Obs. (%)	C-Index (%)	F-Index (%)	FIRM/Obs. (%)	C-Index (%)	F-Index (%)
White River at Worthington	104.2	96.8	90.1	107.2	98.6	90.8	106.4	100.0	93.9	100.0	100.0	93.9
White River at Spencer	94.2	89.8	86.1	198.6	100.0	50.4	101.4	99.2	97.0	101.4	99.2	97.0
East Fork White River at Seymour	89.6	88.2	87.0	108.9	99.6	91.2	101.5	98.2	95.0	101.5	98.2	95.0
White River at Paragon	136.7	38.9	19.7	268.7	100.0	37.2	26.3	26.0	25.9	26.3	26.0	25.9
White River at Newberry	103.1	97.5	92.3	64.8	62.9	61.8	101.0	97.4	94.0	101.0	97.4	94.0
White River at Martinsville	81.2	55.8	44.5	173.8	100.0	57.5	105.9	96.0	87.4	105.9	96.0	87.4
Eel Creek at Worthington	68.2	47.7	39.5	99.9	70.9	54.9	89.3	77.8	69.8	89.3	77.8	69.8
East Fork White River at Columbus	66.8	62.0	59.2	197.7	99.7	50.4	87.3	78.5	72.1	87.3	78.5	72.1
White River at Edwardsport	177.1	93.6	51.0	231.6	95.4	40.4	NA	NA	NA	NA	NA	NA
Average	102.3	74.5	63.3	161.2	91.9	59.4	89.9	84.1	79.4	89.9	84.1	79.4
Standard Deviation	35.1	23.2	26.5	69.0	14.4	19.5	26.7	25.2	24.1	26.7	25.2	24.1

Note: NA = data not available