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Quantitative assessment of floodplain functionality using an index of integrity

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ABSTRACT

Floodplain integrity can be defined as the ability of a floodplain to support essential geomorphic, hydrologic, and ecological functions that maintain biodiversity and ecosystem services. Humans alter floodplain functionality by changing the physical landscape of the floodplain or by altering river flow regimes and subsequent floodplain inundation dynamics. This research evaluates floodplain integrity by assessing the prevalence of anthropogenic modifications to hydrology and landscape. Specifically, the objectives of this research are to: 1) develop a methodology to assess floodplain integrity using geospatial datasets available for large spatial scales; and 2) use the methodology to evaluate spatial patterns of floodplain integrity in the state of Colorado. To accomplish these objectives, we evaluated the critical floodplain functions of attenuating floods, storing groundwater, regulating sediment, providing habitat, and regulating organics and solutes. At present, this work is the first to quantify the integrity of specific floodplain functions instead of measuring floodplain health solely by ecological integrity. We applied the index of floodplain integrity methodology in the state of Colorado to analyze the integrity of each of the five floodplain functions and the aggregated overall integrity. In Colorado, overall floodplain integrity decreased as stream order increased above third order streams. Floodplain integrity was also lower in floodplains that intersected urban areas than those that did not, which indicates the index of floodplain integrity captured the adverse relationship between development and floodplain health established in literature. By quantifying anthropogenic reductions to floodplain functionality at broad spatial scales, the index of floodplain integrity can help target restoration efforts towards the most affected functions and areas.

1. Introduction

1.1. Floodplain functions

Floodplains are unique and vital ecosystems. They support unparalleled levels of biodiversity (Tockner and Stanford, 2002; Ward et al., 1999), are among the most productive landscape types (Tockner and Stanford, 2002), and are second only to estuaries in terms of global value of ecosystem services (Costanza et al., 1997). The characteristic intermittent wetting and drying of floodplains allows them to serve a multitude of purposes to support a healthy ecosystem. Generally, there are five main functions provided by floodplains: 1) *flood reduction* through attenuation by storing water and reducing peak flows (Burt, 1997; Helton et al., 2014); 2) *groundwater storage* by increasing hydraulic residence time and groundwater recharge through increasing vertical hydraulic connectivity (Brunke and Gonser, 1997; Helton et al., 2014; Stanford and Ward, 1993); 3) *sediment regulation* by providing a buffer between the zones of sediment creation and transport, serving as either a sediment source or a sink depending on the sediment and flow regime present (Fryirs, 2013; Fryirs et al., 2007; Nanson and Croke, 1992; Wohl et al., 2015); 4) *organics and solutes regulation* as floodplain heterogeneity and intermittent wetting makes them well suited to retaining and transforming various forms of carbon and nutrients (Brunke and Gonser, 1997; Noe and Hupp, 2009; Sutfin et al., 2016; Wollheim et al., 2014); and 5) *habitat provisioning* by supporting high biodiversity and providing habitat crucial to the life cycle of many aquatic species due to their heterogeneity and high productivity (Brunke and Gonser, 1997; Junk et al., 1989; Tockner and Stanford, 2002; Ward et al., 1999).

Despite the variety of important functions they perform, floodplains are among the most threatened ecosystems and are disappearing at a faster rate than other landscapes due to human alteration (Tockner and Stanford, 2002). In a summary of the current state and future of floodplains, Tockner and Stanford (2002) arrived at the alarming

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conclusion that the only hope for sustaining floodplains long term is through "highly enlightened management and restoration efforts". A useful first step in improving or protecting floodplains using management and restoration efforts includes assessing overall floodplain health or integrity.

1.2. Integrity of environmental systems

The concept of integrity in an environmental context was first discussed by Leopold in his landmark 1949 essay that introduced his Golden Rule of Ecology that, "A thing is right when it tends to preserve the integrity, stability, and beauty of the biotic community. It is wrong otherwise." (Leopold, 1949). In the following decades, various works explored and clarified the definitions of ecological and biological integrity and their use in environmental management (Angermeier and Karr, 1994; Karr, 1996, 1992; Karr and Dudley, 1981). Importantly, these explorations clarified that reductions to integrity were defined explicitly to be caused by human alterations as opposed to natural disturbances (Karr, 1981).

Further work applied the concept of environmental integrity to guide watershed management perspectives (Novotny et al., 2005; USEPA, 2012, 1998). The definition of high watershed integrity ranged from a watershed that sustains ecosystem services for humans (USEPA, 1998) to a watershed completely free of human influence (Novotny et al., 2005; USEPA, 2012). Flotemersch et al. (2016) attempted to resolve this ambiguity and create an operable definition of environmental integrity as "the capacity of a system (and its sub-components) to support and maintain the full range of ecosystem processes and functions essential to the long-term sustainability of its it is [*sic*] diversity and natural resources" (Flotemersch et al., 2016).

The definition of integrity proposed by Flotemersch et al. (2016) can be applied to ecological units besides watersheds, such as floodplains. At present, studies of integrity in floodplains are predominantly focused on ecological integrity in the floodplains rather than assessing integrity of the floodplains themselves (Chovanec et al., 2003; Chovanec and Waringer, 2001; Funk et al., 2017; Petts, 1996). The key difference between assessing ecologic integrity in floodplains and assessing floodplain integrity is that ecologic integrity focuses solely on habitat quality, therefore providing little or no information about the other four functions of healthy floodplains listed in Section 1.1. In contrast, Konrad (2015) performed a holistic assessment of floodplain functions for major rivers in the Puget Sound. Though not explicitly stated as a study of floodplain integrity, this assessment of the anthropogenic changes to a variety of floodplain functions fits the definition of integrity proposed by Flotemersch et al. (2016). Our assessment provides a more explicit examination of mechanistic alterations to floodplains caused by human activities.

1.3. Quantifying floodplain integrity

Although a consistent definition of floodplain integrity is a necessary first step, the usefulness of the concept of floodplain integrity from a management perspective is in being able to measure it. Konrad (2015) provides an example of a method for assessing floodplain integrity at a broad spatial scale using GIS analysis of spatial data. However, one limitation of this study is that the resulting evaluations are categorical; for each floodplain function, the floodplain in question is assigned to a category. The categories provide specific information about the functions but have no hierarchy of integrity. This method of categorical assessment provides substantial information about floodplain condition at a given location but limits comparisons and analysis of spatial trends. Brinson (1996) emphasizes the importance of numerical assessments while proposing a method to evaluate wetland functionality, noting that identifying which functions are impacted and by how much moves restoration efforts from "fuzzy generalities" to specific goals.

Congruent to this focus on quantifiable evaluations, Flotemersch et al. (2016) and Thornbrugh et al. (2018) develop and then employ a methodology to quantitatively assess watershed integrity, which we use as the basis for this methodology to quantify floodplain integrity presented in this paper. Remarking that unaltered reference watersheds are practically non-existent (Stoddard et al., 2006), Flotemersch et al. (2016) instead propose studying the presence of anthropogenic stressors to measure changes to watershed function. Thornbrugh et al. (2018) implemented this methodology to assess watershed integrity for the continental United States using broadly available datasets. The result was an Index of Watershed Integrity (IWI) and Index of Catchment Integrity (ICI) ranging from zero to one (lowest to highest integrity) for all catchments and watersheds associated with the National Hydrography Dataset Version 2 stream segments. Although the ICI and IWI were calculated for six watershed functions and an aggregated overall value, Thornbrugh et al. (2018) conclude that the index representing hydrologic alteration could be used to represent overall watershed integrity more efficiently and with minimal loss of information compared to calculating and combining all six functional metrics.

Not only does the methodological framework to assess watershed integrity developed by Thornbrugh et al. (2018) provide a valuable starting point for this study, but by adopting a similar approach for assessing floodplain health we can explore the links between watershed and floodplain health. Hydrologic processes within a watershed occur at various nested spatial and temporal scales (Covino, 2017), and floodplains, because of their unique placement within a catchment, often serve as mitigating landscapes between upslope watershed conditions and stream conditions. Measurements of stream conditions have commonly been used to assess watershed health (e.g. Bunn et al., 1999) assuming that unhealthy watersheds would lead to degraded stream conditions (Norris and Thoms, 1999). However, some floodplain functions, such as transformation of nutrients and storage of sediment, can buffer the impact of poor watershed health before runoff enters a stream, making overall river health more resilient to watershed degradation (Flotemersch et al., 2016). Of course, hydrologic connections and processes that link watershed, floodplain, and river systems are complex and depend on attributes of the river system, such as geomorphic setting, position in the river network, and river geometry. Thus, we do not expect a clear linear relationship between watershed health and floodplain health. Trends or thresholds may exist, however, such that very poor watershed health may also be reflected as poor floodplain health, and vice versa.

This study builds off the advances made in both the qualitative assessment of floodplains in the Puget Sound region of Konrad (2015) and the quantitative assessment of watershed integrity in Thornbrugh et al. (2018) by developing a novel methodology to quantitatively assess floodplain integrity and applying the methodology to floodplains in the state of Colorado.

1.4. Index of floodplain integrity

For the purpose of this study, floodplain integrity is defined as the ability of a floodplain to support essential geomorphic, hydrologic, and ecological functions that maintain biodiversity and ecosystem services provided to society. Similar to Thornbrugh et al. (2018), we aim to address the limitations of inefficient small-scale field studies and the lack of a truly unaltered reference environment by using available datasets to assess the level of alteration to floodplains. However, as floodplains are unique hydrogeomorphic features, the functions they provide and the human alterations that inhibit these functions are unique from those of entire watersheds. In particular, floodplain functionality is dependent not only on the physical landscape of the floodplain, but also driven by the frequency and duration of overbank flooding (Opperman et al., 2010). Because of the tight link between floodplain inundation and floodplain function, we chose to explicitly include human alterations to river hydrology, which were absent from Thornbrugh et al. (2018), as a stressor variable in the assessment of floodplain integrity.

The objectives of this research are to: 1) develop a methodology to assess floodplain integrity using geospatial datasets available for large spatial scales; and 2) use the methodology to evaluate spatial patterns of floodplain integrity in the state of Colorado. Colorado is large enough to ensure our proposed approach can be applied to a large spatial extent, while still providing a refined spatial extent for iterating on the methodology. Additionally, Colorado contains varied geomorphology, climate, hydrology, and levels of human alteration, which ensures a robust evaluation of the methodology. Through quantifying the abundance of anthropogenic alterations to floodplains in the state of Colorado, this research produces and analyzes an index of floodplain integrity (IFI) for each of the five floodplain functions and an aggregated overall IFI.

2. Links between floodplain functions and human stressors

In order to quantify the effects of humans on floodplains, we first identified specific anthropogenic alterations that reduce floodplain functionality. As the intent of this research is to measure anthropogenic disturbance we did not consider the impact of natural disturbances, such as fires or landslides, on floodplain functions. We conducted an in-depth literature search to identify relevant stressors and their effect for the five floodplain functions, and we have summarized our findings in Fig. 1 pertaining to human stressors that we included in this study. We later used these identified stressors to choose relevant datasets, which are discussed in Section 3.2 and illustrated in Table 3.

2.1. Flood reduction stressors

Floodplains' potential to reduce peak flows and provide transient surface water storage is stressed by human developments in the floodplain that lower the floodplain storage capacity and therefore increase flood stage for the same volume of water (Konrad, 2003; Larson and Plasencia, 2001; Wheater and Evans, 2009). Levees are a particularly important stressor, as they can completely cut off connection with the floodplain (Criss and Shock, 2001; Tobin, 1995; Wheater and Evans, 2009). Roads and railroads also hinder flood attenuation by being a barrier that isolates segments of the floodplain (Beevers et al., 2012; Kumar et al., 2014; Tarolli and Sofia, 2016), intercepting and diverting subsurface flow (Wemple and Jones, 2003), or increasing runoff by collecting and channelizing surface flow, which increases flood peaks (Tarolli and Sofia, 2016). Flood attenuation is also sensitive to changes in land cover, as vegetation helps to slow and store floodwater (Nicholson et al., 2012; Sholtes and Doyle, 2011; Zell et al., 2015) and urbanization increases conveyance and therefore flood peaks (Wheater and Evans, 2009).

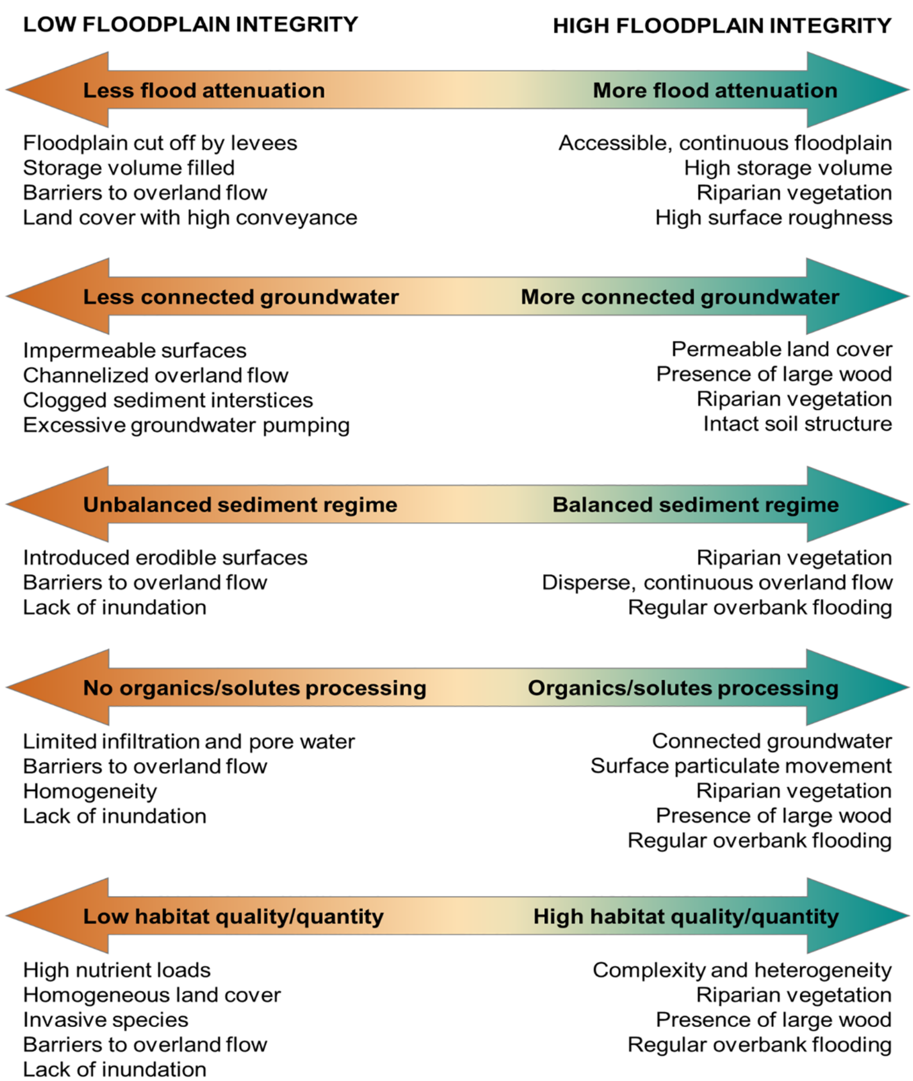

Fig. 1. Conceptual diagram of floodplain functional integrity and the variables that change each function. This figure only illustrates the anthropogenic stressors that are represented in this study.

2.2. Groundwater storage stressors

The ability of floodplains to store and regulate groundwater is primarily stressed by reductions in vertical connectivity. These reductions can be driven by increased area of impermeable surface in floodplains, which reduces infiltration (Brunke and Gonser, 1997; Wheater and Evans, 2009). Infiltration can also be limited by channelization of overland flow as this decreases the contact time and area by hastening the movement of surface flows from the floodplain to the river (Brunke and Gonser, 1997; Hancock, 2002; Wheater and Evans, 2009). Colmation, or clogging of interstitial spaces in alluvial sediments, also reduces infiltration in floodplains. Colmation can be caused by increased fine sediment loading, increased algal growth, and degradation of soil structure, which are often responses to changes in land cover (Brunke and Gonser, 1997; Hancock, 2002; Wheater and Evans, 2009). Excessive pumping of groundwater can also contribute to colmation (Brunke and Gonser, 1997). In the short term, pumping of groundwater can lower the water table and provide increased groundwater storage. However, in the long term, lowering the groundwater table endangers riparian vegetation, which harms soil structure and increases erosion and therefore reduces groundwater connectivity (Brunke and Gonser, 1997). Finally, vertical connectivity can be enhanced riparian vegetation, large wood, and beaver dams, which serve to improve soil structure, increase ponding, and increase time for infiltration (Boulton, 2007; Hancock, 2002; Harper et al., 1999; Wheater and Evans, 2009).

2.3. Sediment regulation stressors

Floodplains' ability to serve as sediment buffer zones is dependent on the floodplain landscape and floodplain inundation dynamics. Unaltered floodplains help to moderate the sediment regime by switching roles between being a sediment source or sediment sink, but anthropogenic land cover change can shift this balance (Lecce, 1997; Wohl et al., 2015). In particular, agriculture in floodplains has increased sediment supply and erodibility, causing floodplains to be a greater sediment source (Knox, 2006; Walling and Fang, 2003; Wheater and Evans, 2009). Removal of riparian vegetation also shifts the role of floodplains in the sediment regime because riparian vegetation helps filter suspended sediment and reduce sediment yield to rivers (Brunke and Gonser, 1997; Wheater and Evans, 2009), and reductions in riparian vegetation make flows much more effective at mobilizing sediment (Fryirs, 2013). Sediment connectivity and residence time are also affected by roads and railroads, which can increase sediment production in floodplains by intercepting and channelizing surface flows, which increases their erosive power (Persichillo et al., 2018; Tarolli and Sofia, 2016). Additionally, the natural cycle of sediment deposition and erosion in floodplains is disproportionately dependent on large overbank flows (Florsheim and Mount, 2003; Wohl et al., 2015), and therefore is severely limited by reductions in the magnitude or frequency of peak flows (Fryirs, 2013; Nanson, 1986).

2.4. Organics and solutes regulation stressors

The storage of organics and the chemical processing that occurs in floodplains are also dependent on both the landscape and the inundation of the floodplain. Regular overbank flooding is beneficial for accumulation of organic matter and enhancing denitrification (Craig et al., 2008; Sgouridis et al., 2011; Tockner et al., 1999), and thus hydrologic alteration can change the processing of organics and solutes in floodplains. Connectivity of groundwater is also important for nutrient processing and filtration (Brunke and Gonser, 1997; Burt, 1997; Stanford and Ward, 1993) therefore impermeable areas that limit vertical connectivity in floodplains reduce floodplain solute regulation. Reductions in lateral overland connectivity are also a stressor, as connected surface flow is responsible for particulate movement (Tockner et al., 1999). Vegetation and large wood contribute to retention of organic matter and nutrient loads and carbon storage in floodplains (Craig et al., 2008; Hanberry et al., 2015; Harper et al., 1999; Pinay and Decamps, 1988; Stanford and Ward, 1993; Sutfin et al., 2016). Floodplains can also be a significant source of organics and solutes due to autochthonous production (Junk et al., 1989; Roach et al., 2014). Consequently, the loss of riparian vegetation and associated loss of complexity can reduce mediation and change the production of organics and solutes in floodplains. Although we do not consider changes in floodplain topography in this work, the spatial complexity and patterns of floodplain topography can also influence hydrological connectivity and biogeochemical processing (e.g. Scown et al., 2016).

2.5. Habitat stressors

Many anthropogenic modifications to floodplains degrade habitat and result in loss of biodiversity. For instance, changes in land use towards urbanization and agriculture reduce biodiversity and increase nutrient pollution (Harper et al., 1999; Tockner et al., 1999). Floodplain habitat is also highly vulnerable to species invasion, which can harm fitness of native species and reduce aquatic biodiversity (Tockner et al., 1999). Lateral connectivity of floodplain habitat is an important contributor to floodplain heterogeneity (Ward and Stanford, 1995), and therefore development that blocks the movement of water and aquatic species in the floodplain reduces habitat area and quality (Beevers et al., 2012; King et al., 2003). Additionally, loss of trees and large wood in floodplains leads to less complex and diverse habitat and reduces channel movement, producing a cyclic effect that can lead to further loss of native riparian vegetation (Collins et al., 2012; Harper et al., 1999). Finally, floodplain habitat can be detrimentally impacted by hydrologic alteration, as regular overbank flows are vital to maintain biodiversity, habitat heterogeneity, and ecosystem dynamism (Amoros and Bornette, 2002; Brunke and Gonser, 1997; Galat et al., 1998; Harper et al., 1999; Higgisson et al., 2019; Junk et al., 1989; Tockner et al., 1999; Ward et al., 1999). Although we do not consider spatial variations of floodplain topography in this study, metrics of topographic complexity, such as those described by Scown et al., (2016), may be useful for identifying loss of habitat since high topographic diversity is often correlated with high habitat diversity (e.g. Ward et al., 1999).

3. Methods

In order to assess floodplain integrity, we first identified datasets that represent the anthropogenic stressors to floodplain functions described in Section 2. Next, we calculated the prevalence of these stressors in discretized floodplain elements. From the relative densities of these stressors in the floodplain, we calculated an IFI for each of the five floodplain functions. Then, we combined these functional IFI values to make an overall IFI metric. The functional and overall IFI values range from zero to one, representing floodplains where functionality is most to least altered, respectively. This process is represented graphically in Fig. 2 and each step is described in detail in the following sections, with a sample calculation provided in the Supplemental information.

3.1. Discretization of floodplain elements

Assessing the integrity of floodplains across Colorado requires a floodplain delineation for the entire state. Floodplain boundaries used in the project were adapted from results of flood hazard mapping performed for the conterminous United States at a 30-m resolution using a 2D hydrodynamic model and regionalized flood frequency estimates (Wing et al., 2017). The floodplain delineation used in this research is associated with the 100-year flood in an "undefended" (without levees) condition. We chose to use the flood hazard maps provided by Wing et al. (2017) because they were the most current and extensive estimate

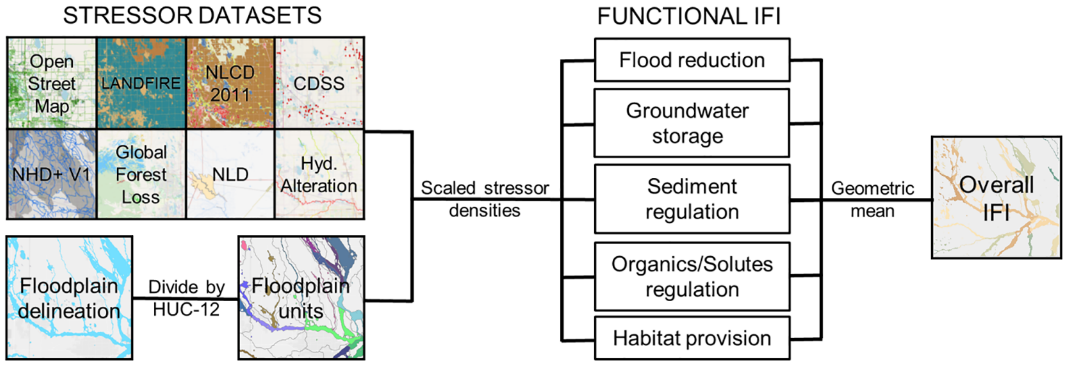

Fig. 2. Overview of IFI methodology.

of floodplain extents at the time of this study and did not require us to develop new floodplain delineations for Colorado. However, other methods of floodplain estimation, such as hydrogeomorphic techniques (e.g. Jafarzadegan and Merwade, 2017; Nardi et al., 2018; Scheel et al., 2019), may also be applicable and more relevant for fluvial processes than the inundation extents associated with a given return interval.

From the floodplain delineation for the entire US, we extracted a floodplain shapefile for the state of Colorado. We performed minor cleaning of the delineated floodplains by filling gaps and removing disconnected islands in the shapefile that were smaller than 3 raster grid cells (< 2700 m^2). This minor cleaning changed the overall area of the delineated floodplain in Colorado from 14,202 km^2 to 14,214 km^2 (+0.0008%).

To create smaller floodplain elements to compare across the state, we divided floodplains along the boundaries of sub-watersheds delineated by 12-digit hydrologic unit codes (HUC-12s) from the Watershed Boundary Dataset (Seaber, 1987). This resulted in 3,025 floodplain elements in the state with an average of 4.70 km^2 per floodplain element (Fig. 3).

We associated each floodplain element with a stream order using the National Hydrography Dataset Version 1 (NHDPlus V1) streamlines (McKay et al., 2010). Each floodplain element was attributed the maximum stream order in the associated HUC-12 based on the assumption that the majority of the floodplain area will be preferentially associated with the largest streams in a given HUC-12. Of the HUC-12 sub-basins used to divide the floodplain, 100 HUC-12s do not contain an NHDPlus V1 streamline with a reported stream order, and therefore there is no stream order attributed to 100 floodplain elements. Floodplain elements were also associated with a physiographic division (Fenneman, 1917) based on the region in which the majority of the floodplain area was contained. Summaries of floodplain area by stream order and physiographic region can be found in Tables 1 and 2, respectively.

3.2. Identification of stressor datasets

Once we determined the relevant stressors for each floodplain function, we identified datasets that could be used to measure the amount of each stressor across Colorado floodplains. We selected datasets based on the following criteria: 1) information contained in the dataset was available for the entire state; 2) the datasets were the same or finer spatial scale than the floodplain delineation; and 3) the datasets were publicly available or soon to be publicly available. Our intention in focusing on publicly available datasets was to create a methodology

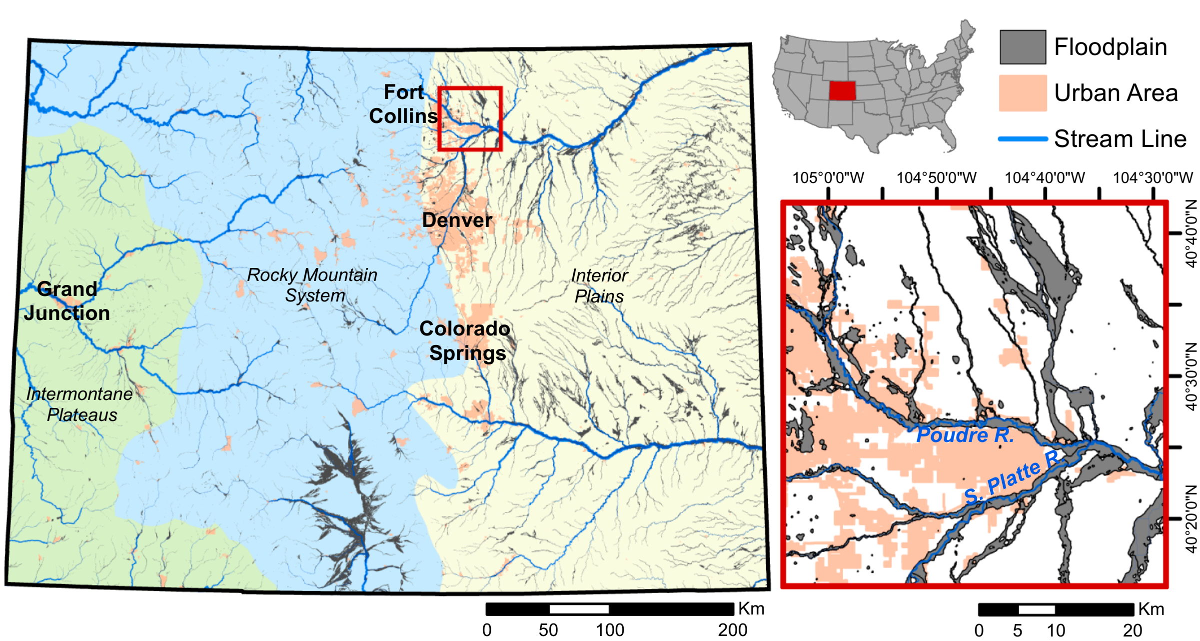

Fig. 3. Floodplain study location map. The state of Colorado (red on US map) is shown with fourth order and larger rivers (blue), census-designated and incorporated areas (orange), physiographic regions (green, blue, and yellow shading), and floodplain areas (grey). The red inset map shows a close-up view of the floodplain elements divided by HUC-12 boundary. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table 1
Floodplain area by stream order.

Stream Order	Floodplain Area (km^2)
1	486
2	1507
3	2817
4	3788
5	2284
6	932
7	1136
8	5
N/A	1258
Total	14,214

Table 2
Floodplain area by physiographic region.

Physiographic Division	Floodplain Area (km^2)
Intermontane Plateaus	1063
Rocky Mountain System	4495
Interior Plains	8656
Total	14,214

that could easily be replicated and updated without needing to contact individuals or organizations for access to data.

The datasets we selected vary in their representativeness of the stressors. In some cases, datasets that directly measured the stressor were available, such as the National Landcover Database (NLCD) percent impervious surface raster data to quantify impervious surface coverage. For other stressors, we were unable to identify a large-scale measurement and reporting effort, so we instead used proxy indicators of the stressor for which data were available. For instance, since measurements of groundwater depletion in Colorado are not currently available at the scale and coverage required, we estimated this stressor with the density of groundwater wells in the floodplain. The datasets used to represent each stressor and important characteristics of the datasets, such as data type (e.g. point or raster) and resolution, are shown in Table 3. Note that the same stressor may be represented by a different dataset for a different function, or that the same dataset may be used to represent several stressors. These links between the datasets and the stressors were informed by the function-specific review presented in Section 2.

One unique dataset used in this study is an estimate of the magnitude of change for a variety of indicators of hydrologic alteration for NHDPlus V1 stream lines. This dataset was created following the method described in McManamay et al. (2017) and extended to additional hydrologic alteration metrics (see Olden and Poff (2003) for definitions of the indicators of hydrologic alteration). To create this dataset, hydrologic alterations at USGS gages across the U.S. were calculated by comparing observed values (i.e., “altered” conditions) to modeled estimates of natural flows (i.e., “expected” conditions) from USGS reference gage sites (McManamay, 2014). Hydrologic alteration values were then extrapolated from gages to stream reaches using random forest models based on fifty-two variables describing anthropogenic stressors to the water cycle (e.g., urban land cover, dam regulation, water withdrawals) (McManamay et al., 2017). This novel data-driven modeling of hydrologic alteration represents a notable advancement over representing hydrologic alteration using proxies such as the presence of dams and irrigation canals. This dataset provides estimates for several relevant indicators of hydrologic alteration that represent changes in the magnitude, duration, frequency, and timing of flows of various return intervals. However, because all of the relevant indicators were highly correlated (see Supplemental information), we chose to use a single indicator to represent all types of change to hydrology. We selected alterations to M_H20, or mean annual maximum flow divided by catchment area, as the metric to represent

Table 3
Summary of datasets used to represent floodplain function stressor.

Floodplain function	Stressor	Dataset	Units	Data attributes
Flood reduction	Reduced storage volume	Buildings[1]	km^2/km^2	Polygon, July 17, 2018 version
	Floodplain disconnection	Leveed area[2]	km^2/km^2	Polygon, April 2015
	Overland flow interception	Roads and Railroads[1]	km/km^2	Polyline, July 17, 2018 version
	Land cover change	Forest cover loss events[3]	km^2/km^2	Raster, 30 m resolution, loss 2000–2018
		Developed area[4]	km^2/km^2	Raster, 30 m resolution, 2011 version
Groundwater storage	Impermeable surface	Percent imperviousness[4]	km^2/km^2	Raster, 30 m resolution, 2011 version
	Channelized overland flow	Ditches and canals[5]	km/km^2	Polyline, 1:100,000 scale, 2006 release
	Colmation	Agricultural area[4]	km^2/km^2	Raster, 30 m resolution, 2011 version
	Loss of wood and vegetation	Forest cover loss events[3]	km^2/km^2	Raster, 30 m resolution, loss 2000–2018
	Lowered water table	Groundwater wells[6]	$count/km^2$	Points, October 2018
Sediment regulation	Land cover change	Agricultural area[4]	km^2/km^2	Raster, 30 m resolution, 2011 version
	Loss of wood and vegetation	Forest cover loss events[3]	km^2/km^2	Raster, 30 m resolution, loss 2000–2018
	Overland flow interception	Roads and Railroads[1]	km/km^2	Polyline, July 17, 2018 version
	Hydrologic alteration	Change in M_H20[7]		Data for NHD + V1 polylines, 2018 hydrology data
Organics and solutes regulation	Hydrologic alteration	Change in M_H20[7]		Data for NHD + V1 polylines, 2018 hydrology data
	Vertical connectivity	Percent imperviousness[4]	km^2/km^2	Raster, 30 m resolution, 2011 version
	Overland flow interception	Roads and Railroads[1]	km/km^2	Polyline, July 17, 2018 version
	Loss of wood and vegetation	Forest cover loss events[3]	km^2/km^2	Raster, 30 m resolution, loss 2000–2018
Habitat provision	Land cover change	Developed area[4]	km^2/km^2	Raster, 30 m resolution, 2011 version
		Agricultural area[4]	km^2/km^2	Raster, 30 m resolution, 2011 version
	Loss of wood and vegetation	Forest cover loss events[3]	km^2/km^2	Raster, 30 m resolution, loss 2000–2018
	Species invasion	Non-native introduced vegetation[8]	km^2/km^2	Raster, 30 m resolution, 2014 release
	Overland flow interception	Roads and Railroads[1]	km/km^2	Polyline, July 17, 2018 version
	Hydrologic alteration	Change in M_H20[7]		Data for NHD + V1 polylines, 2018 hydrology data

1. OpenStreetMap Contributors (2018).
2. National Levee Database; USACE (2015).
3. Global Forest Loss Dataset; Hansen et al. (2013).
4. National Landcover Database; Homer et al. (2012).
5. National Hydrography Dataset, Version 1; McKay et al. (2010).
6. Colorado Decision Support System; CWCB/DNR (2018).
7. Hydrologic Alteration Data; McManamay et al., 2017 and personal communication
8. LANDFIRE Existing Vegetation Type; Rollins (2009).

hydrologic alteration, as its physical meaning is simple to understand and the mean annual maximum flow is likely to activate the floodplain. Although this hydrologic alteration dataset is not currently available to the public, we chose to include the dataset in this investigation as the data will be published and available in the near future.

3.3. Calculation of stressor density

After we identified a dataset to represent each stressor, we were able to quantify the level of each stressor within the floodplain. The method we used to compute the stressor density was dependent on the data type. Polygon, polyline, and point type stressor datasets all represented binary stressor presence or absence, such that prevalence of the shape features indicated the prevalence of the stressor. As such, we calculated the stressor level as the density of the polygons, polylines, and points in the floodplain element in km^2/km^2, km/km^2, and $count/km^2$, respectively. For the forest cover loss dataset, the percentage of cells in the floodplain that reported forest loss events between 2000 and 2018 was computed. Prevalence of developed area was considered the percentage of cells in the floodplain reported as high, medium, or low intensity development (NLCD classes 21–24). We computed the level of agriculture as the percentage of cells in the floodplain reported as pasture/hay or cultivated crops (NLCD classes 81 and 82). To quantify impervious surface, we averaged the percent imperviousness values reported for each 30 m cell for all cells in the floodplain. We computed the percentage of non-native introduced vegetation as the percentage of cells in the LANDFIRE Existing Vegetation Type raster reported as groups 701–709, 711, and 731, which represent various types of invasive, non-agricultural plant species. The hydrologic alteration dataset reports the change to the indicator M_H20, or specific mean annual maximum flow, for each connected NHDPlus V1 segment. To aggregate these stream segment values to one number for each floodplain element, we averaged the values for the streamlines of the maximum order in the floodplain element. This aggregation method is based on the assumption that the floodplain area is preferentially associated with higher order streams (refer to Supplemental information for an investigation of alternate streamline-to-floodplain hydrologic alteration value aggregation methods). We computed all stressor densities in the floodplain elements using ArcGIS tools written in Python.

3.4. Stressor rescaling

Using the methods described in Section 3.3, we calculated the quantity of each stressor in each floodplain element. Stressors datasets that were raster or polygon type measured stressor density in area, and therefore have a theoretical maximum value of one. However, polyline and point type datasets have no theoretical maximum. Additionally, most of the stressor area densities observed in Colorado are much lower than one as the likelihood of a single stressor occupying the entire floodplain area is very low. Accordingly, we rescaled quantities of each stressor from zero to one, with a zero-value indicating absence of stressor in the floodplain and value of one being the 90th percentile of the stressor levels in the floodplain observed in Colorado. All stressor levels over the 90th percentile were assigned a value of one. However, for the two datasets for which 90 percent or greater of the floodplain elements still had no stressor present (leveed area and wells), a value of one instead corresponded to the maximum observed value.

We performed this rescaling for two main reasons. First, it provided a more consistent method to quantify the prevalence of stressors on a zero to one scale when using several different data types (i.e., areas, lines, and points). Secondly, it provided much more spread amongst the observed levels of the stressors compared to unscaled stressor densities. As the purpose of the IFI is to provide a comparison between floodplains across the state, this increased spread makes comparisons between floodplain elements more meaningful, rather than a comparison to a theoretical worst-case scenario. One limitation of this rescaling of the datasets is that the scaling now depends on the observed data, which makes comparisons between separate computations of the IFI more difficult. Plots of the rescaled data and a more in-depth discussion of the scaling rationale can be found in Supplemental information.

3.5. Calculation of IFI for functions

Using the scaled quantities of each stressor in each floodplain element, we calculated the IFI values for the five floodplain functions. First, we performed a Pearson correlation analysis for the scaled stressor data for the floodplain elements (see Supplemental information). For any two stressor datasets with correlation coefficients greater than 0.7, only one of the stressors was included in the calculation of each function to avoid over-weighting one stressor type. With the remaining stressor datasets, we calculated the function IFI for each of the five functions as:

$$IFI_{i,k} = 1 - \frac{\sum_{j=1}^{n_{j,k}} S_{i,j}}{n_{j,k}}$$

where $IFI_{i,k}$ is the integrity of the *ith* floodplain element for the *kth* function; $S_{i,j}$ is the scaled stressor value for the *jth* stressor in the *ith* floodplain element; and $n_{j.k}$ is the number of stressors, j, that impact floodplain function k. This function assumes a negative linear response to the abundance of stressors where higher values of scaled stressors in the floodplain equate to lower function IFI and vice versa. It also implies an equal weighting of all stressors that contribute to a given function. The assumptions of equal weighting and negative linear response to stressors are necessary simplifications due to the current lack of understanding of the complex functional responses in floodplains. We performed a sensitivity analysis on using non-linear equations to relate stressor density to IFI. We tested the linear relation (shown in the equation above) versus a positive and negative quadratic relationship. All three relationships were chosen such that they produce an IFI value of zero with a stressor density of one and vice versa. We found that changing the function relating stressor density to IFI resulted in a significantly different average overall IFI ($p < 0.0001$), with the positive quadratic producing the highest average overall IFI and the negative quadratic producing the lowest (Fig. 4). Non-linear relationships or weighting of the functions could easily be incorporated into this methodology at this step should future research clarify the expected changes in functionality due to floodplain modifications.

3.6. Calculation of overall IFI

The overall IFI for each floodplain element was calculated as the geometric mean of the five function IFI values, such that:

$$IFI_i = \left(\prod_{k=1}^{5} w_k IFI_{i,k}\right)^{\frac{1}{5}}$$

where IFI_i is the overall index of integrity for the *ith* floodplain element; w_k is an optional weighting factor for the *kth* function; and $IFI_{i,k}$ is the index of integrity for the *kth* function in the *ith* floodplain element. In this work, we used a weighting factor equal to one for each function. Because values of $IFI_{i,k}$ are not normally distributed (see Fig. S6 in Supplemental information), we chose to use the geometric mean to calculate the overall index of integrity. As described by Sandoval-Solis et al. (2011), this approach also allows us to assume that each floodplain function is critical to floodplain function. Accordingly, if one function is evaluated at zero integrity, the overall integrity of the floodplain element is also zero, thus combining several essential and non-substitutional metrics into one index.

After computing the functional and overall IFI, we summarized the results based on spatial attributes. These attributes included the physiographic region and stream order of the floodplain (as described in

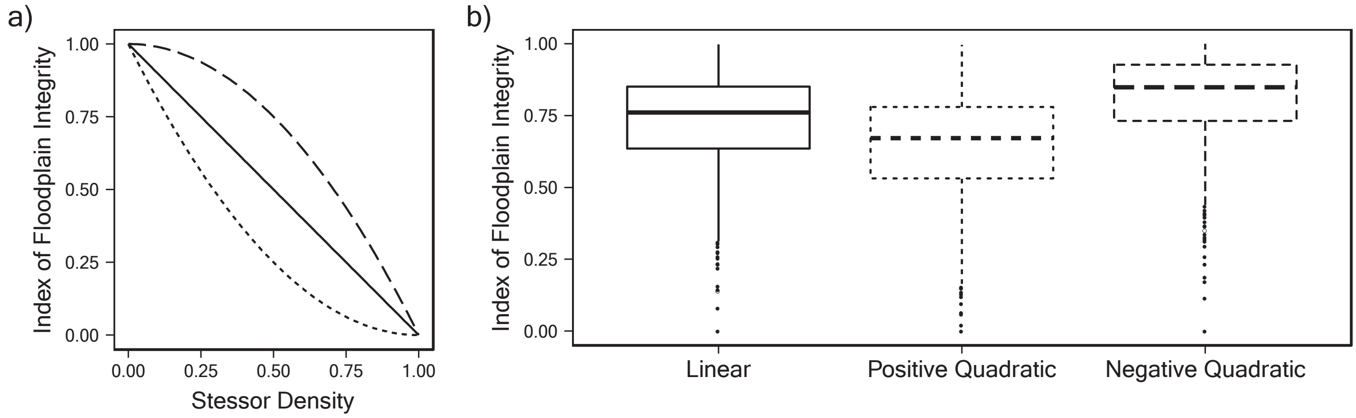

Fig. 4. Sensitivity of overall IFI to relationship used to calculate IFI from stressor density, showing a) the three stressor density vs. IFI relationships tested and b) the resultant overall IFI calculated using each of the three relationships shown in a).

Section 3.1), and also whether or not the floodplain element intersected the TIGER2010 City Boundaries shapefile, which includes incorporated places and census designated places (2010 TIGER/Line Shapefiles, 2011).

3.7. Comparison with other datasets

The overall IFI values for the entire state were compared to the Index of Catchment Integrity (ICI) values computed in Thornbrugh et al. (2018). To allow a one-to-one comparison, we calculated the mean ICI of the catchments that intersected each floodplain element. This produced a single ICI value for each floodplain element.

Additionally, we compared the overall IFI values to the density of wetlands in the floodplains. Wetlands were considered to be areas of the classes "Freshwater Emergent Wetland" and "Freshwater Forested/ Shrub Wetland" from the National Wetland Inventory (USFWS, 2018). The justification behind comparing IFI to wetland density is that wetlands are more likely to be supported in floodplains that have little human alteration as compared to floodplains that are highly modified.

Finally, the results for the floodplain element in HUC-12 101900070805 were compared to the results of the State of the Poudre assessment, which used field investigations and aerial imagery to determine the health of a 39 km reach of the Poudre River in northeast Colorado (State of the Poudre: A River Health Assessment, 2017). Although the reach assessed for the State of the Poudre is contained within a single floodplain element, the State of the Poudre is the most comprehensive assessment of riparian function in Colorado. The State of the Poudre quantifies a variety of river health metrics and then summarizes them using a letter grading scale. In particular, the scores for floodplain connectivity and riparian conditions from the State of the Poudre were compared to the flood reduction and habitat provision functional IFI from our study.

4. Results

The computed function and overall IFI values were mapped to the floodplain across the state of Colorado at the HUC-12 spatial resolution (see Fig. 5 and https://doi.org/10.4211/hs.419f2564a43c4f639066edb9594fd0d3 for full IFI results by HUC-12).

Fig. 6 shows the distribution of the computed IFI values by area of floodplain for each of the five floodplain functions and the overall IFI. IFI values for all functions and overall are left skewed, with the highest skew occurring for flood reduction and groundwater storage. Statistics of the computed overall and function IFI values are summarized in Table 4. The functional IFI values are generally highly correlated, with correlation coefficients ranging from 0.65 to 0.89 (see Supplemental information). Knowing that the median overall IFI value is 0.76 (Table 4), a value less than the median can be selected to represent an impaired floodplain. For instance, when we chose a value of 0.5 as the IFI threshold for determining an impaired floodplain, we found that 14 percent of floodplain area in Colorado shows impaired functionality.

Fig. 7 shows a sample of the mapped IFI results at a 1:1,000,000 scale for the region of Colorado shown in the red box on Fig. 3. In Fig. 7, there are visible gradients in integrity present. Similar spatial patterns are present for the overall IFI and functional IFI values, although magnitudes of IFI differ.

IFI values were analyzed by physiographic region, urban versus rural area, and stream order, with results shown in Fig. 8. Using the Tukey Honestly Significant Difference (HSD) test (Tukey, 1953), floodplains in the Interior Plains region (median = 0.81, mean = 0.78) have a significantly different average IFI ($p < 0.01$) than the Intermontane Plateau (median = 0.72, mean = 0.70) or Rocky Mountain System regions (median = 0.71, mean = 0.69), between which there is no significant difference ($p = 0.61$). Fig. 8b shows that the average overall IFI of floodplain elements that intersect urban areas is lower (median = 0.53, mean = 0.55) than that of floodplain elements that do not (median = 0.79, mean = 0.77), which are considered rural. The difference in average overall IFI between rural and urban floodplains is significant using the Student's *t*-test ($p < 0.01$). Fig. 8c shows overall IFI decreasing with stream order for streams above third order (except for eighth order, which only includes two floodplain elements). The differences between average IFI as stream order increases are significant between third and fourth ($p < 0.01$), fourth and fifth ($p < 0.01$), and fifth and sixth ($p < 0.01$) order streams using Tukey HSD. The relationship between overall IFI and the area of the floodplain element was also investigated to check for an area bias, but no meaningful relationship existed ($R^2 = 0.02$) (see Supplemental information).

We also analyzed the functional and overall IFI data to determine the importance of each function to the overall IFI for each floodplain element. Fig. 9 shows the ratio between the functional IFI and the overall IFI value for each of the floodplain elements. Ratios greater than one indicate that the function IFI is increasing the overall IFI, while ratios less than one indicate that the function IFI is reducing the overall IFI for that floodplain element. On average, flood reduction and groundwater storage functional IFI are slightly higher than overall IFI, while sediment regulation, organics/solutes regulation, and habitat provision functional IFI are lower than overall IFI. Differences between the average ratios for all functions are significant except for sediment regulation and organics/solutes regulation using Tukey HSD (p values in Supplemental information). We also investigated the standard deviation of the five function IFI values and the frequency and spatial distribution of the function with the minimum IFI value of the five functions (see Supplemental information).

In comparing the computed overall IFI to ICI and density of

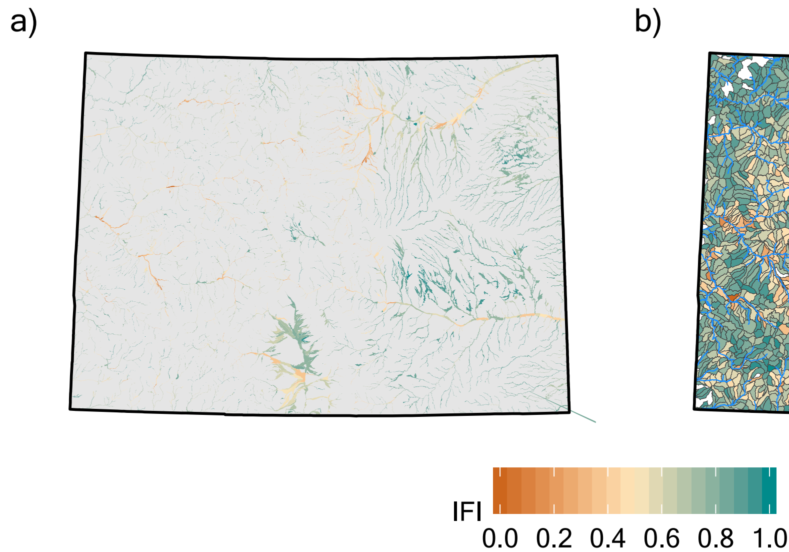

Fig. 5. Overall floodplain integrity in Colorado shown a) mapped to the floodplain only; and b) with the entire HUC-12 colored according to the IFI of the floodplain contained within. IFI by HUC-12 is included because the floodplains are small relative to the area of the state.

wetlands, no meaningful linear relationships were found, as shown in Fig. 10. Coefficients of determination were 0.05 for IFI versus ICI and 0.01 for IFI versus wetland density. However, despite the absence of a predictive relationship, the correlations of overall IFI to ICI and wetland density were both statistically significant ($p < 0.01$). The regression of IFI and wetland density was also performed with floodplains separated by stream order, with no meaningful relationships found (see Supplemental information).

For the comparison to the State of the Poudre assessment, the overall grade for the Poudre was a C, or 76 out of 100, whereas the overall IFI for floodplain element 101900070805 was 0.318. The floodplain element had a flood reduction IFI of 0.330, while the floodplain connectivity score from the Poudre report card was a C. For Riparian condition in the Poudre report card, the grades for the reaches assessed ranged from B to D, with the average score being a C, while the habitat provision IFI was 0.318. The grade of C in the State of the Poudre indicates that "stressors…substantially impair functionality" but "basic natural river functions are still sustained" (State of the Poudre: A River Health Assessment, 2017).

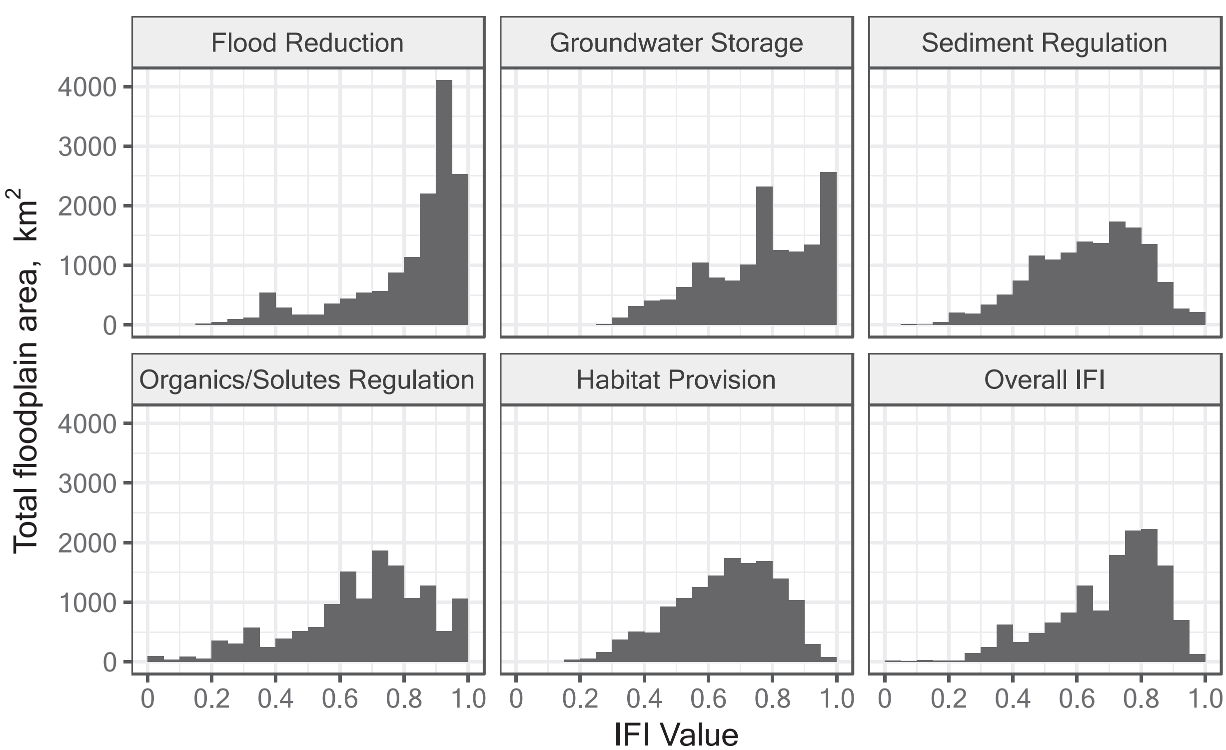

Fig. 6. Prevalence of IFI value by total floodplain area for each of the five floodplain functions and the aggregated overall IFI. Note that all functions and overall IFI show a left skew.

Table 4
Summary statistics of computed IFI for overall integrity and floodplain functional integrity.

	Overall IFI	Flood reduction	Groundwater storage	Sediment regulation	Organics/solutes regulation	Habitat provision
Minimum	0.00	0.20	0.25	0.05	0.00	0.16
Median	0.76	0.89	0.85	0.68	0.73	0.71
Mean	0.73	0.82	0.83	0.67	0.68	0.69
Maximum	1.00	1.00	1.00	1.00	1.00	1.00
Standard deviation	0.16	0.18	0.15	0.17	0.20	0.15

5. Discussion

The methodology developed to compute IFI was successfully applied to the state of Colorado. With functional and overall IFI mapped for Colorado's floodplains, it is possible to visualize the anthropogenic effect on floodplain integrity across the state. At present, this work is the first to quantify the integrity of specific floodplain functions instead of measuring floodplain health solely by ecological integrity. Because the IFI is numeric, it is possible to use the IFI values computed here for a broad range of analyses. The examples of IFI by physiographic region, stream order, and city versus rural represent analyses that can be performed, but any other spatial division or pattern could be investigated without recalculating IFI.

Similarly, because this methodology focuses on broadly available datasets, the computation of IFI can be repeated in a different area. The only Colorado-specific dataset used in this implementation of the IFI calculation was the groundwater well locations from the Colorado Decision Support System. All other datasets are available for the continental US. If alternate stressor datasets were identified for a new region, it would be straightforward to substitute these datasets into the IFI computational framework.

Regarding the results for Colorado, it is unsurprising that functional IFI values for the five floodplain functions are highly correlated (see Supplemental information). Many of the same stressors inhibit several functions (see Table 3), even though the specific manner in which the stressor affects the floodplain may vary between functions. The highly correlated functional IFI values are an inherent result of the interconnectedness of floodplain functions. A similar interdependence of stressors and indicators of functionality in floodplains has been noted in previous studies. For instance, Bouska et al. (2019) developed

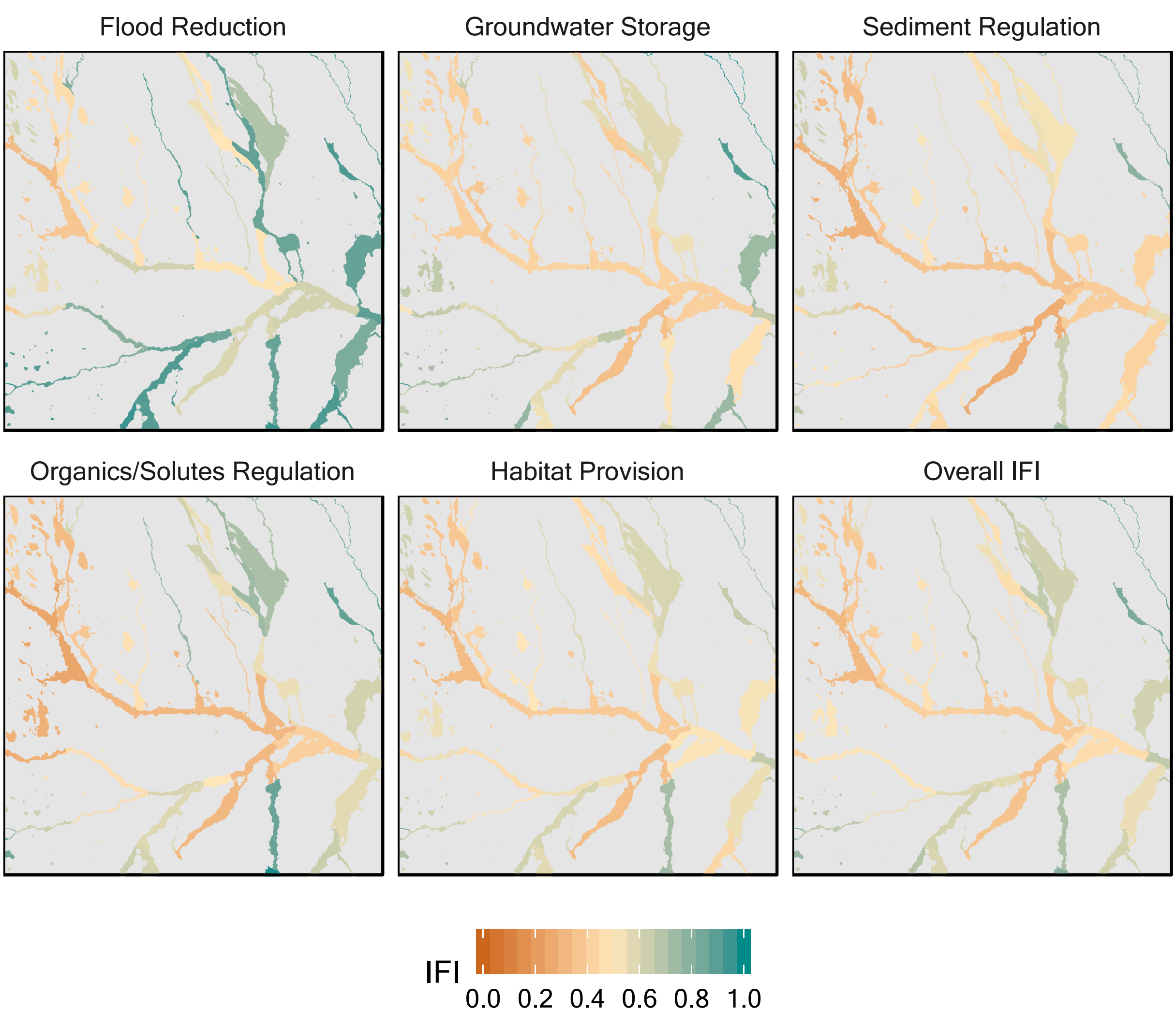

Fig. 7. Close up view of mapped IFI values for each of the five floodplain functions and overall IFI. The region of Colorado shown in this figure is the same close-up region shown in Fig. 3. Gradients of color representing gradients in floodplain integrity are present.

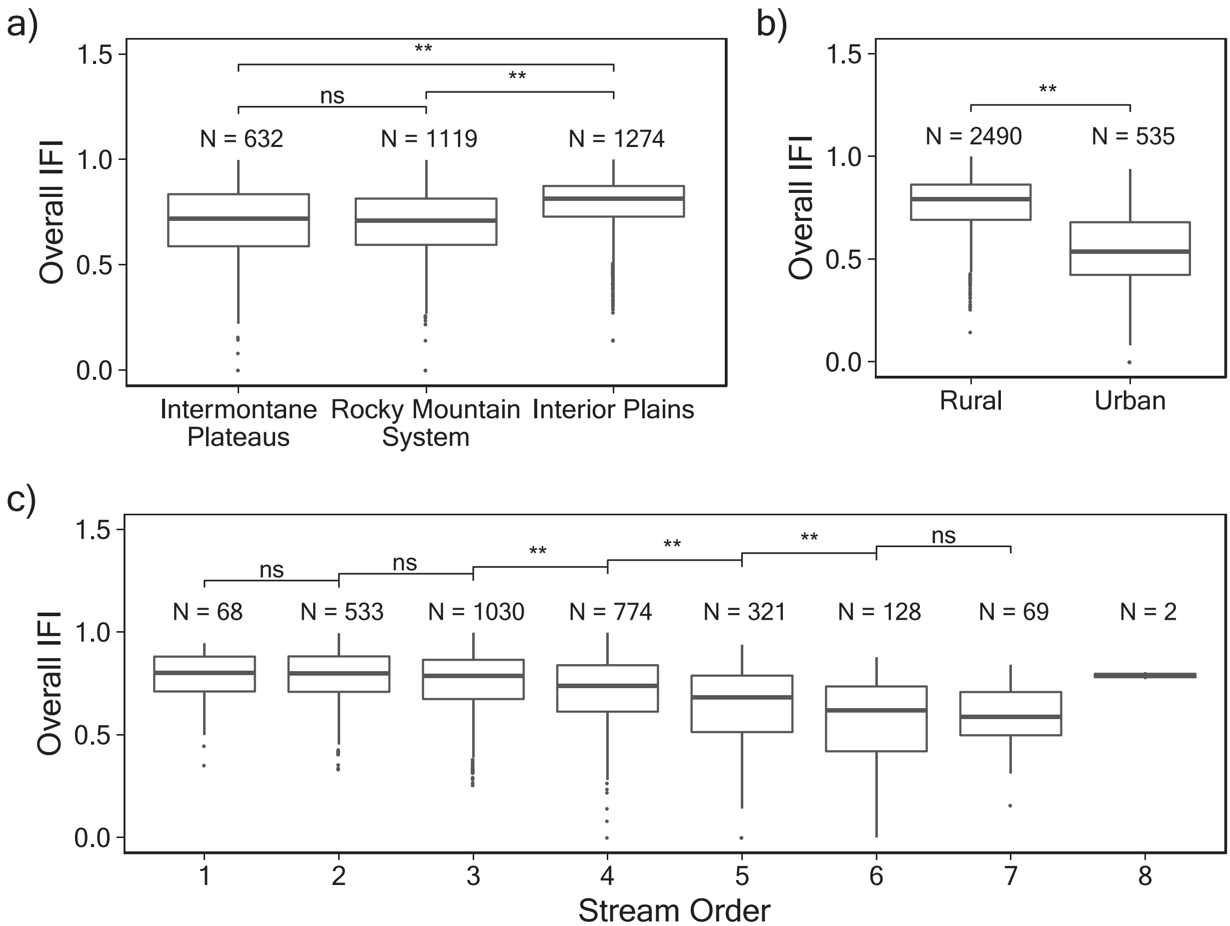

Fig. 8. Analysis of IFI by a) physiographic region, b) rural vs urban, and c) stream order. Physiographic regions and urban areas are shown shaded in Fig. 3. Statistical significance between means is indicated by ns (not significant) and **, indicating the p value is > 0.05 and < 0.01, respectively.

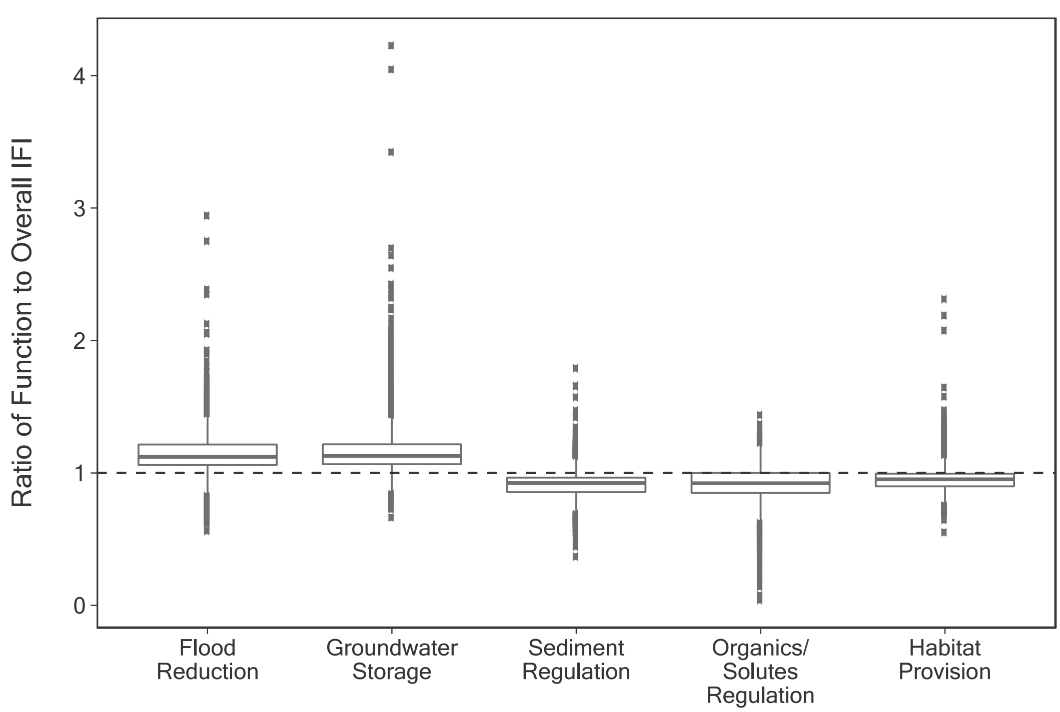

Fig. 9. Ratio of functional IFI to overall IFI for the five floodplain functions. Ratios greater than one indicate that the function is increasing the overall IFI, while ratios less than one mean that the function is reducing the overall IFI.

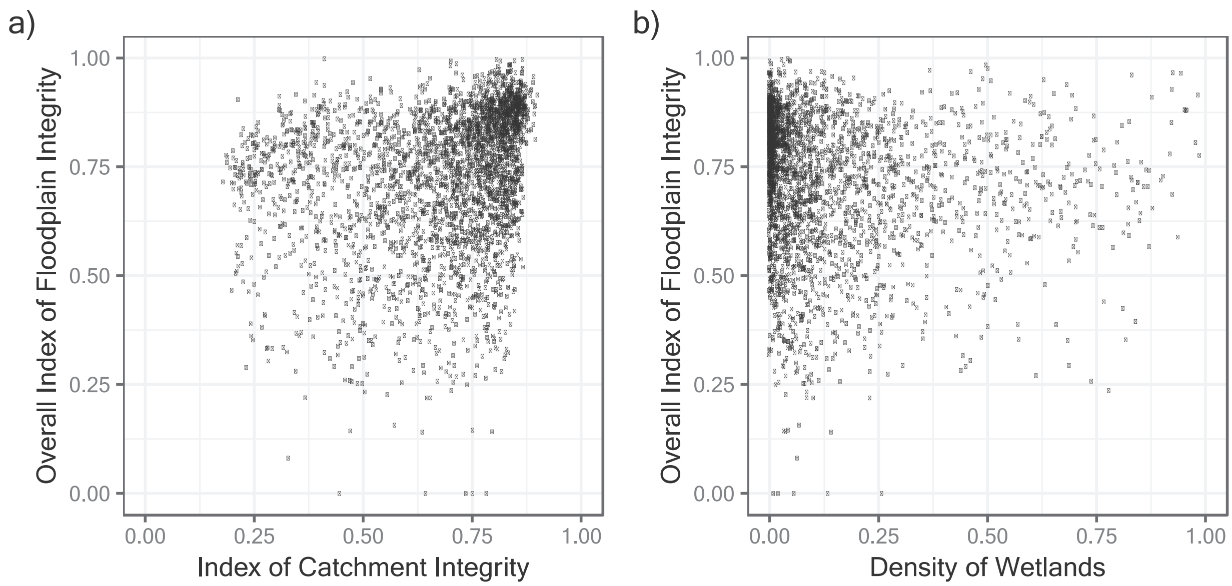

Fig. 10. Comparison of overall IFI to a) ICI and b) wetland density. The relationships are not predictive ($R^2 < 0.1$), although they are statistically significant ($p < 0.01$).

indicators of adaptive capacity for the Upper Mississippi River System and concluded that the indicators were often interdependent but that no single indicator appropriately described floodplain resilience. Furthermore, a review of the impact of altered flow regime on river and floodplain ecosystems by Bunn and Arthington (2002) noted the difficulty of distinguishing the impacts of flow alterations “from those of a myriad of other factors and interactions,” highlighting the complexity of stressor responses in floodplains. Because many of the functional IFI values are correlated, management actions to improve a specific floodplain function could result in the improvement of other functions as well. For instance, if agricultural areas are removed from floodplains to improve habitat conditions, this action could also improve groundwater connectivity and sediment regulation functions by reducing substrate colmation, limiting sediment loads, and promoting a more balanced sediment regime (Table 3).

5.1. IFI in Colorado

Using an overall IFI threshold of lower than 0.5 to indicate impaired floodplains, 14 percent of floodplain area in Colorado is impaired. However, as the IFI is a relative metric, there is no physical basis for setting a threshold of 0.5 to designate impaired functionality. The IFI threshold for impaired floodplains can be adjusted according to the desired level of conservativism in identifying floodplains with reduced functionality. The low percentage of floodplains with an IFI lower than 0.5 is due to the left skew of the functional and overall IFI values (Fig. 6), which is an inherent result of the distributions of the scaled stressor data used in their computation. As shown in Supplemental information, the stressor density data are all skewed right, and thus the negative linear relationship between stressor density and IFI results in left skew of the IFI values. The two stressors that were not present in greater than 90 percent of the floodplain elements were leveed area and groundwater wells, which were included in the calculation of the flood reduction and groundwater storage IFI, respectively. As a result, flood reduction and groundwater storage IFI show the highest skew and also have the most tendency to raise the overall IFI of the five functions (Fig. 9). However, despite the relatively higher average IFI of flood reduction and groundwater storage, all five functions report a ratio of functional IFI to overall IFI above and below one for some floodplain elements, showing that there was variability in the relative integrity of the functions despite their high correlation. This inter-function variability is quantified by the histogram of the standard deviation of the functional IFI values shown in Supplemental information.

When mapped to the floodplain elements, the computed IFI shows gradients in integrity (Fig. 7). One conclusion to draw from these visible gradients is that the scale at which the floodplains were divided is appropriate. If a random distribution of IFI values were observed, it could imply that the division of the floodplains was too fine relative to the stressor data scale and average trends in stressor level were not captured. However, if the IFI changed minimally between floodplain elements, it could signal that spatial trends in stressor density were masked by averaging over too large of an area. As neither a random nor uniform distribution of IFI values was produced, the HUC-12 division of the floodplains appears to be an acceptable scale for this methodology.

The analyses of IFI by physiographic region, urban versus rural, and stream order present an overview of spatial variations in floodplain integrity in Colorado. The analysis by stream order provides information about the effect on integrity of a floodplain’s position within a watershed. Higher integrity is generally observed in the headwaters than in larger order streams, which makes sense considering that human activity tends to be focused around larger rivers and that headwater streams are often in less populated (and therefore less modified) areas. Also, floodplains that intersect urban areas have a significantly lower average integrity than those that do not, which also is supported by the fact that humans disturb floodplain function (Wohl, 2019), and humans are preferentially concentrated in urban areas. When considering the regional trends in floodplain integrity, we were surprised to see higher integrity in the plains than the other physiographic regions, especially considering that the largest cities in Colorado are also in the plains region. One possible explanation for this is relative recentness of development in the mountainous regions relative to the plains, which feeds into a time bias described further in Section 5.3. Additionally, different regions have different primary stressors. For the interior plains, the primary stressors are likely surface flow regulation and lowered groundwater table, which are both stressors that do not have a directly measured dataset. Accordingly, the regional differences in overall IFI may reflect more on regional changes in primary stressors and representativeness of the associated dataset than actual differences in integrity.

5.2. IFI validation

As IFI is intended as a comparative metric and has no physical meaning, it is difficult to validate the IFI results. We attempted to find datasets to use for comparison to the Colorado IFI results, but were unable to identify an appropriate measure of floodplain functionality. Most riverine integrity studies focus on watershed level or in-stream metrics with a strong emphasis on ecological integrity, which complicates the comparison with a multi-function floodplain specific metric like the IFI.

Future work could help identify large-scale datasets, developed through field efforts or other assessment methods, which could be used to validate IFI results based on our methodology. Such datasets will likely be regionally specific and focus on watershed health but would be helpful in determining the suitability of both overall and functional IFI results. For example, The Healthy Rivers Assessment of Colorado (White et al. 2007), developed by The Nature Conservancy, identifies watershed-scale indices to evaluate river and watershed health but may correlate with our IFI results. Though not always specific to floodplain landscapes, indices in The Healthy Rivers Assessment that focus on the physical settings of watersheds, such as riparian cover, agricultural land use, and total water diversions, could serve as independent validation data. Unfortunately, spatial data from The Health Rivers Assessment was not readily available for comparison in this study.

Furthermore, since human stressors are often removed during floodplain restorations, data collected following restoration activities might be especially valuable in validating IFI results because they would describe floodplain conditions in the absence of stressors. For instance, recent floodplain restoration work on the Danube River (Funk et al. 2018) prioritizes metrics that overlap with stressors or functions we used to calculate IFI values, including floodplain connectivity, presence of dykes, and degree of flood attenuation.

Nonetheless, we compared our results to multiple datasets, both regional and local, to assess correlations to our IFI results. First, we compared our IFI results for Colorado to ICI from Thornbrugh et al. (2018) and wetland density to see if similar spatial patterns existed.

We found very little correlation between IFI and ICI or wetland density, which was somewhat surprising since floodplains are intermediate-scale landscapes nested within larger catchments. One implication of this is that catchment health is not an appropriate indicator of floodplain health, as their differing processes and forms make them distinct ecological units that must be evaluated individually. One notable difference between the ICI and IFI computation is that many catchment stressors are water quality related, which were not included as floodplain stressors. For instance, one of the six watershed functions (Thornbrugh et al., 2018) identified was regulation of water chemistry, which included mines, superfund sites, fertilizer application, industrial facilities, and wastewater treatment plants as stressors. The importance of water quality to the watershed integrity evaluation is reflected in the fact that IWI explained more than 25 percent of the variability in a water quality metric derived from the EPA's National Rivers and Streams Assessment (Thornbrugh et al., 2018; USEPA, 2016). Furthermore, the lack of correlation between IFI and ICI values highlights that hydrologic connections and processes that link watershed, floodplain, and river systems are complex and not easily discernible at large scales.

When considering the relationship between overall IFI and wetland density, there is no predictive linear relationship. However, there does appear to be a threshold relationship, where high densities of wetlands are not observed in floodplains with low overall IFI. This is evidenced by the absence of points in the lower right corner of Fig. 10b and indicates that a floodplain element with a high density of wetlands is also likely to have high overall IFI values. Not all floodplain landscapes are hydrogeomorphically suited for wetland ecosystems (Dvorett et al., 2012), but our analysis supports the notion that floodplains that currently contain a large density of wetlands are also likely to maintain high levels of functionality and overall integrity (e.g. McAllister et al., 2000; Jacobson et al., 2011; Ameli and Creed, 2019).

One final note on the comparison of overall IFI to ICI and wetland density is that the relationships were statistically significant, which means that there is evidence to support that the data are not entirely random. However, the low coefficients of determination for both comparisons demonstrate that, though significant, the linear relationships have negligible predictive power.

When comparing of the State of the Poudre report findings to the relevant floodplain element, both assessments show degraded but existent floodplain function. According to our functional IFI analyses, there is limited variability within the flood reduction, habitat provision, and overall IFI values. These results qualitatively agree with the State of the Poudre grading for floodplain connectivity (lowest score of 68/100), riparian condition (lowest score of 68/100), and overall river health (score of 74/100). Although the extent of the comparison is limited and the floodplain scales are not the same, the IFI metric is qualitatively supported by this field-based floodplain assessment on the Cache la Poudre River. Still, the validation of our results would benefit from additional field data collected in floodplain regions throughout Colorado.

5.3. Limitations of the IFI method

Although the IFI approach presented in this paper is novel in its assessment of specific floodplain functions, there are also limitations that reduce the usefulness of this methodology. Likely the most impactful of these limitations is that the datasets available to quantify the stressors of floodplain functions vary in their representativeness. For instance, density of groundwater wells does not necessarily correspond directly to groundwater depletion, especially considering that no withdrawal volume is included in the dataset. This introduces uncertainty into the integrity estimate for groundwater storage.

One other stressor that is poorly represented by available data is the presence of large wood and forest stands. The Hansen et al. (2013) global forest loss dataset only contains forest loss occurring after 2000 and therefore does not represent the bulk of the deforestation in the state. This limited date range also serves to introduce a bias into the integrity assessment as forest loss is preferentially shown in regions of new development as opposed to areas where forest may have been cleared for development historically. A final note on the forest loss dataset is that it is also used to represent loss of large wood in the floodplain system as no other datasets quantify this at a broad enough scale. However, prevalence of large wood has been reduced through active log jam removal in Colorado (Wohl, 2019), not only deforestation, and therefore the forest loss dataset provides an incomplete quantification of this stressor. This limitation of poor stressor representativeness could be addressed with identification or creation of additional datasets that measure these human landscape alterations for large spatial extents. To support modeling and restoration efforts consistent statewide data are needed, such as measurements of groundwater levels, or log jam and beaver dam removals. As more tools are developed for large scale assessments, datasets with statewide or larger extents are crucial.

Another notable limitation of this methodology is the assumption that the responses of functions to stressors are all equal and negatively linear (Thornbrugh et al., 2018). It is probable that certain stressors are more influential to given functions. Additionally, certain relationships between stressors and functionality may be non-linear and have thresholds where functionality changes drastically. The sensitivity analysis performed on a linear versus quadratic relationship between stressor density and function showed significantly different IFI values, which demonstrates the importance of correctly representing these response curves for the IFI results to be representative of floodplain function. Although there are currently few studies that specifically explore the responses of floodplain functions to stressors, there is ample evidence that thresholds exist in floodplain morphology (Livers et al., 2018; Meyer, 2001; Wohl, 2019), so it is probable that they exist in floodplain functionality as well. As new research elucidates more complex functional responses, substituting these relationships into the IFI computation is a minor process modification that can improve the credibility of the IFI metric. Specifically, studies that measure floodplain functionality at a variety of stressor levels would provide useful insight. For instance, an investigation could be performed to identify if a threshold density of impervious surface exists below which groundwater recharge is no longer impaired.

Functional responses to stressors may also be time-dependent, which we do not consider in our IFI methodology. Our current approach assesses functional and overall floodplain health as a snapshot in time according to the most recent stressor data available, but studies have shown that some floodplain processes are temporally dynamic. For instance, the recruitment, growth, and forest stand dynamics of floodplain vegetation is dependent on temporal interactions of hydrologic and physiologic conditions, including the timing of seed dispersal, floodplain inundation, flood recession rates, and overall hydroclimatic conditions (e.g. Lytle and Merritt, 2004; Rood et al., 2005; Thapa et al., 2019). Other floodplain functions show temporal dependencies, including sediment regulation (e.g. Wohl et al., 2015) and biogeochemical processing (e.g. Valett et al., 2005). Although we do not consider temporal scales of floodplain functions in this study, the incorporation of data and functions which are time-dependent would be an important, yet challenging, next step in our approach.

One additional limitation of the IFI methodology is that the computed IFI is scaled relative to the datasets included, which complicates comparisons between different implementations of the methodology. Because the stressor data are rescaled relative to the 90th percentile of the data included in the analysis, the IFI calculated for Colorado in this investigation are not directly comparable to results calculated for other locations. Although insight could still be gained in comparing the distributions or spatial patterns of IFI calculated with two different datasets, the best practice would be to rescale the stressor data using datasets that cover the entire area of interest before calculating IFI.

A final consideration for the results of the IFI calculation is that the floodplain delineation we used in this study is a hydraulically modeled 100-year floodplain based on a 30-m resolution elevation raster. If the floodplain was delineated for a different return interval or delineated hydrogeomorphically, the results would change as they are dependent on the precise floodplain delineation. However, we would expect changes in the results with floodplain delineation to be small as stressors tend to have gradual spatial changes, so slight floodplain boundary shifts will not drastically change the stressor levels observed in the floodplain. Also, because Wing et al. (2017) used a 30-m resolution elevation raster to delineate floodplains, narrower floodplains that tend to exist in confined headwater rivers in Colorado are likely underrepresented in our results. If a finer resolution elevation raster is used when estimating the floodplain extent, the total area of floodplains in Colorado may increase, and our results would better reflect floodplain integrity in mountainous regions of the state.

5.4. Future work

As mentioned in the discussion of limitations of the IFI method, there are opportunities to expand upon the methodology and implementation presented in this paper. First, incorporation of new or more representative stressor datasets will contribute to the trustworthiness of the IFI assessment. Secondly, the relationships between floodplain functions and their stressors should be updated as new research provides additional information into the complexities of floodplain response. Finally, this methodology can be applied to additional and potentially larger areas, such as the continental United States, to both serve as a test of the methodology's robustness and to provide useful information about the integrity of floodplain functions across a larger region.

6. Conclusion

This study presents a novel methodology to assess the integrity of floodplains and their functions over broad spatial scales and then demonstrates the methodology in the state of Colorado. The IFI methodology is based upon identifying and quantifying anthropogenic stressors that inhibit critical floodplain functions. The prevalence of these stressors is used to evaluate the relative integrity of five floodplain functions: flood reduction, groundwater storage, sediment retention, organics and solutes retention, and habitat provision, as well as evaluating overall integrity. For Colorado, overall floodplain integrity decreased with stream order above third order streams. Overall integrity was also lower for floodplains that intersected urban areas. Finally, regional differences in IFI were identified, with the Interior Plains having higher integrity than the Intermontane Plateaus or Rocky Mountain System. The IFI methodology as presented in this study provides an important first step towards quantifying changes to floodplain integrity and the results of this study can provide a useful management tool for agencies that perform floodplain restoration projects. By highlighting the functions and the areas with the highest reductions in functionality, the IFI can enable more efficient restoration efforts by targeting the areas of greatest need early in the restoration planning process. The trustworthiness of the IFI is currently limited by the datasets available and the state of knowledge of floodplain functional response. Progress in either of these areas could easily be incorporated into the IFI methodology to create a more informative metric. Despite this potential for improvement, we believe the IFI methodology can be applied to additional areas to provide key high-level guidance to floodplain restoration projects. Understanding the extent of human influence on floodplain functionality is a crucial step towards preserving floodplains and their associated benefits.

7. Data statement

Data created in this study are available at https://doi.org/10.4211/hs.419f2564a43c4f639066edb9594fd0d3.

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CRediT authorship contribution statement

Marissa N. Karpack: Methodology, Investigation, Writing - original draft. **Ryan R. Morrison:** Supervision, Conceptualization, Writing - review & editing. **Ryan A. McManamay:** Investigation, Writing - review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecolind.2019.106051.

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