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Mapping valley bottom inundation patterns from beaver dam activity: A potential proxy for hydrologic inefficiency

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Data availability statement: All data are available in the Riverscapes Data Exchange: https://data.riverscapes.net/c/d059fa0f-bbe5-4704-8b82-5007c7564e5e/.

Abstract

For centuries, streams and rivers have been altered and degraded such that the conveyance of water downstream is unnaturally efficient, often to the detriment of other biophysical processes that maintain healthy riverscapes. Structural elements, such as beaver dams, can impact hydraulics and alter downstream water conveyance. While the hydraulic, hydrologic, geomorphic, and ecological effects of beaver dams have been quantified at individual study sites, study methods are often cost-prohibitive and complicated, making them less practical for monitoring at large spatial scales and in diverse settings. We mapped inundation extent and type (free flowing, ponded, and overflowing) in beaver dam complexes in diverse hydrogeomorphic settings as a simple method to monitor beaver-influenced riverscapes based on delineating inundation patterns. Our mapping of over 75 inundation events at 37 sites suggests that, on average, under undammed conditions valley bottom inundation ranged from 2.7% - 17.4% (mean 6.8%) whereas under dammed conditions the same sites had valley bottom inundation that ranged from 9.5% - 47.5% (mean 23.2%). We observed that, when beaver dams are present, roughly half of surface water inundation is converted from a free-flowing type to ponded and overflow types. This research also reveals that the focus of most previous beaver dam studies on low gradients and low stream orders is unnecessarily restrictive. We report similar magnitudes of influence in steeper gradient riverscapes as well as in beaver-modified floodplains and anabranches of higher-order rivers that are typically considered to be too large for beaver dams. While the quantification of inundated area and type presented here is valuable as a simple metric, we postulate that delineation of inundation type and extent can be used as a practical proxy for physical processes and indicators of riverscape health such as longer and more varied water residence times (i.e., hydrologic inefficiency).

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1 Introduction

For centuries, streams and rivers were managed both intentionally and inadvertently to increase the conveyance and drainage of water [1–3]. Widespread harvest of beaver and removal of beaver dams are among many anthropogenic activities that perpetuated the channelization and simplification of rivers [4–7]. Removal of wood accumulations and beaver dams has "structurally-starved" (sensu [8–10]) degraded stream channels such that water often moves through with artificially high efficiency. In the context of water conveyance, efficiency can be characterized by shorter water residence times and travel distances and higher, more homogeneous velocity distributions. Historically, there has been a negative connotation with inefficient water conveyance in both the flood control and water resources communities, particularly in the context of downstream diversions or irrigation withdrawals [e.g., 11]. However, there has been a recent paradigm shift in what characterizes a naturally functioning, healthy riverscape that challenges the prioritization of efficiency over other attributes [10,12–14] and recognizes the important role that structural forcing by large wood and beaver dams often plays in river processes [15,16]. An "efficiency" focus with regards to water conveyance has now been widely recognized as insufficient in terms of meeting longer-term flood management and water resources goals, and focus has largely shifted to attenuation and the importance of lateral and vertical connectivity of the river and its floodplain.

Wheaton et al. [8] introduced the term "hydrologic inefficiency" and asserted that it "is a hallmark of a healthy system" because it indicates longer and more varied residence times, increased attenuation, and decreased longitudinal connectivity. However, the extreme of this interpretation of hydrologic inefficiency is a reservoir with little to no conveyance downstream. When thinking about increased hydrologic inefficiency as a "positive" attribute, it is important to simultaneously consider other principles of riverscape health. More varied and an overall increase in water residence times (i.e., increased hydrologic inefficiency) is beneficial when achieved in conjunction with dynamic and complex riverscapes [10,17]. This concept is similarly described as having increased retention [e.g., 18,19].

The mechanisms by which beaver dams increase hydrologic inefficiency and improve riverscape health have been well captured by existing literature at the local scale of dams and dam complexes (i.e., 10^1 m to 10^2 m extents). Beaver dams force upstream ponding and cause a decrease in velocity, increase in depth, and increase in water residence time in these ponded areas [20]. Downstream, dams often force complex and multithreaded overflow paths onto floodplain surfaces and otherwise dry in-channel surfaces like bars, benches and ledges [21–23]. Flooding of riverscapes is typically assumed to be associated with high flows. However, when beaver dam crest elevations are higher than the adjacent floodplain, floodplain surfaces both upstream (ponding) and downstream (overflow) of dams are often inundated even at low flows [22]. This flooding at baseflow phenomenon was pervasive historically and yet has been so systematically managed against by efficiently draining riverscapes that it represents a significant example of a shifted baseline in our understanding of rivers [16,24,25]. The increase in surface water inundation

with “structurally-forced” flooding on the landscape reflects local changes to water conveyance and hydrologic pathways [26]. Increased duration of water flowing over active channel (e.g., otherwise exposed bars) and floodplain surfaces influences surface-groundwater interactions and increases infiltration, hyporheic exchange, groundwater recharge, and water table elevations [22,26,27]. These effects likely contribute to an increase in water residence time within portions of a beaver dam complex [20,28] as surface and subsurface transient water storage increases [28–30]. Previous studies have captured increased transient water storage volume reflected in a buffered hydrograph in which flood peaks can be attenuated, and baseflow increased [31–34]. A portion of transient storage is suggested to be lost to increased evapotranspiration [34,35].

Hydrologic inefficiency can be quantified as a relative increase (when compared to undammed conditions) in water residence time or transient water storage with the use of hydraulic models derived from bathymetric data [e.g., 20], tracer tests [e.g., 28,30], and mass balance approaches that rely on discharge measurements [31,33,36,37]. However, these data require extensive instrumentation, laborious in-person data collection, and can be time consuming to collect [36,38]. Moreover, riverscapes modified by beaver dams are inherently complex and take even more time to survey and traverse than undammed streams. These complications are likely why few studies exist at spatial scales larger than the beaver dam complex or short reach scales and why we do not have a tractable way to approximate hydrologic inefficiency across many different physiographic and riverscape settings.

Existing literature on beaver dam activity tends to focus on dams located in low to moderate gradient (<6%), wadeable, 1st through 4th order streams [6,21,39,40]. This focus was informed by early dam census studies [e.g., 41–44]. Despite an early dam census study by Retzer [45] that found that over 30% of complexes were observed in gradients steeper than 6%, subsequent studies have almost entirely focused, through selective sampling bias, on gradients of less than 6% [e.g., 46,47]. Some recent studies have addressed beaver dams in gradients over 6% [e.g., 48] and on floodplains of larger rivers [e.g., 39,40,49], but the importance that beaver dams play in these settings is less known.

The objective of this paper is to report an initial quantification of how beaver dams influence surface water inundation extent and type across a diverse array of riverscapes in the Montane Western United States of America (USA). Inundation is one of the more visibly obvious response variables to structural forcing, and changes to the extent and nature of inundation reflect many of the beaver dam influences quantified in previous studies. The inundation mapping results presented here provide a quantifiable reference condition for beaver-influenced riverscapes.

2 Methods

2.1 Study design and site selection

We conducted a relatively rapid, but manual digitization of features from readily available (e.g., Google Earth) and/or easily acquirable (e.g., with consumer-grade drones) high-resolution satellite and/or aerial imagery. The manual digitization of visible features from high-resolution ortho-photos is a widely used method [38,50–53]. We used this approach to map inundation patterns across the Intermountain West, USA. We conducted 77 surveys at 37 sites in 11 US Geological Survey (USGS) eight-digit Hydrologic Unit Code (HUC; Seaber [54]) watersheds (Fig 1).

We surveyed sites from each of the settings described in Fig 2, which highlights an example of the “classic” setting typically covered in the literature as well as examples from floodplain and steep settings in which beavers also build dams. For each site, at least two surveys were conducted: a dammed survey, and an approximated undammed condition survey. The undammed condition surveys were based on pre-existing satellite and/or aerial imagery and evidence from undammed portions of the riverscape located upstream or downstream of the site. Surveys targeted baseflow conditions. In cases where it was not possible to conduct the dammed survey at low flow, we used imagery of the undammed condition from a similar flow to which the dammed survey was collected. See S2 Appendix for an example of inundation extent at three different flows.

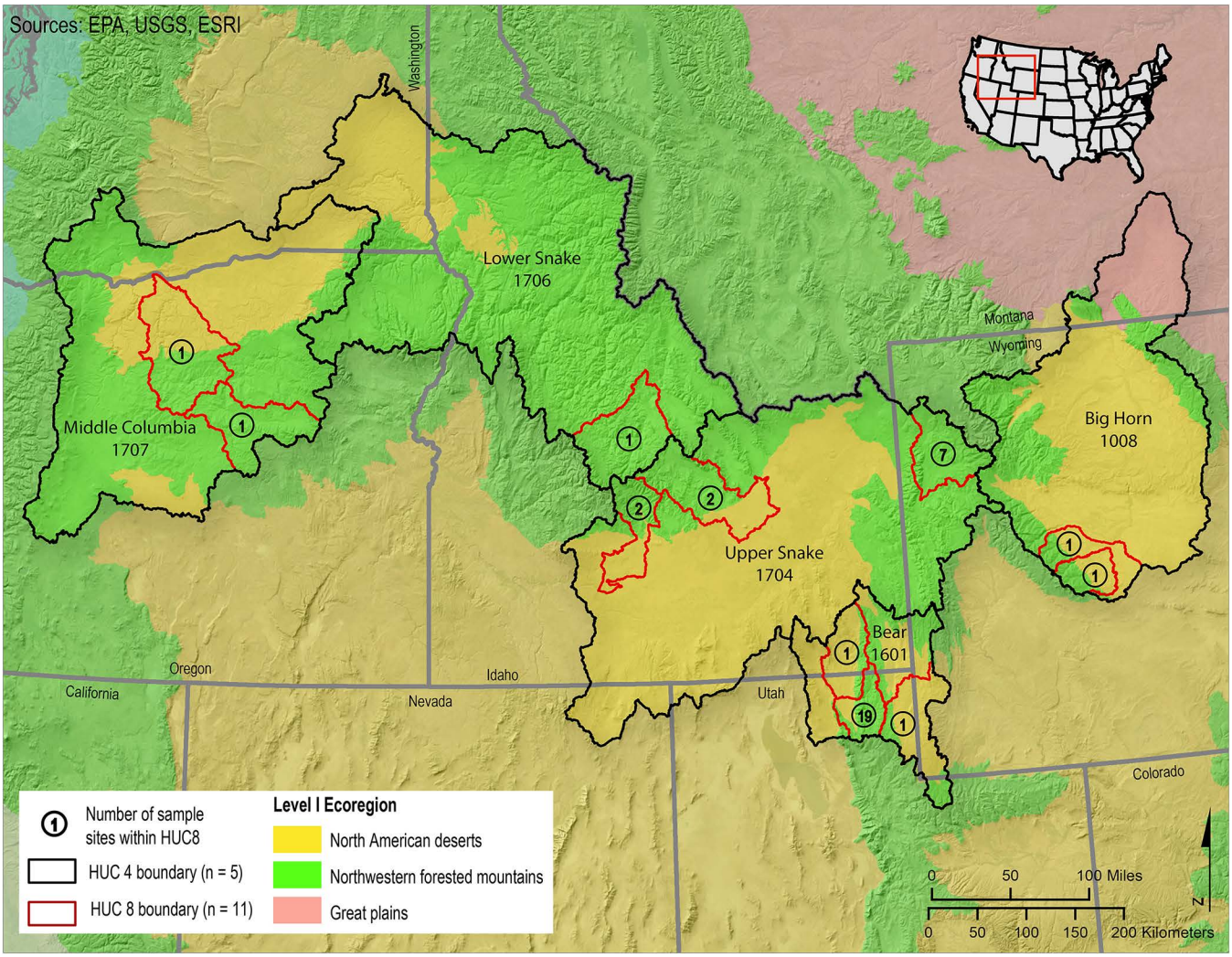


Fig 1. Location of USGS HUC 4 (black) and USGS HUC 8 (red) watersheds with the number of study sites (black circles) located in each. In total we conducted surveys at 37 sites in 11 different watersheds. Base layers: EPA Level I Ecoregions (U.S. Environmental Protection Agency, public domain, https://www.epa.gov/eco-research/ecoregions) and USGS Watershed Boundary Dataset (U.S. Geological Survey, public domain, https://www.usgs.gov/national-hydrography/watershed-boundary-dataset).

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2.2 Inundation mapping - sample design

Each site was chosen to represent a riverscape segment, defined laterally by the valley bottom extent [15,55], and longitudinally by the upstream and downstream zone of influence of a beaver dam complex or multiple complexes with overlapping zones of influence (typically spanning between 100 m and 800 m). Fig 3 provides a workflow of the three-step process taken at each site; 1) acquiring basemap imagery, 2) digitizing features that represented a) riverscape context, b) degree of structural forcing, and c) inundation and thalweg responses, and 3) quantification of metrics from the mapping.

2.2.1 Imagery acquisition. Basemap imagery for digitization for all surveys was acquired with an Uncrewed Aerial Vehicle (UAV), or from available satellite and/or aerial imagery. For sites in which we acquired imagery during field visits, we used a DJI Phantom 4 or Mavic 2 drone at flight heights ranging from 50 to 80 m. Imagery was post-processed in either Agisoft Metashape or DroneDeploy to produce a 2 cm resolution orthomosaic image [e.g., 50,56]. Imagery used

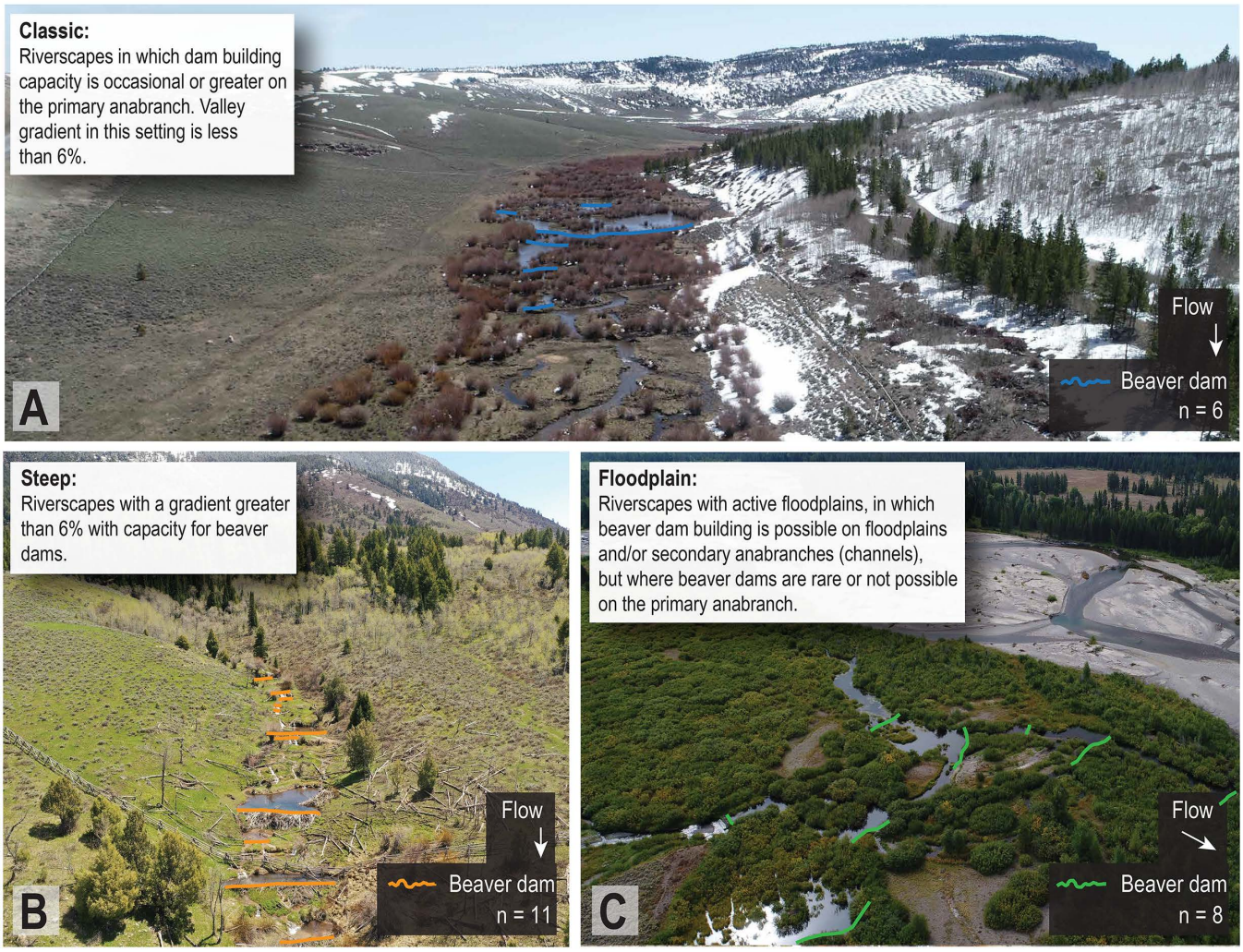


Fig 2. Dominant riverscape dam building opportunities for beaver (also referred in this paper as settings). A) The classic setting in the top panel represents the typical setting in which beaver dam building is studied. B) Even though beaver dams in steep riverscapes with gradients over 6% represent over 1/3 of early reported observations in the literature, they are often ignored. C) The floodplain settings along typically larger rivers where beaver dam building is concentrated on the floodplains. This figure was inspired by Bush and Wissinger [49]. Photos by Karen Bartelt and Joe Wheaton.

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to assess the undammed inundation extent spanned from 1930 to 2019 and was sourced from Google Earth or National Agriculture Imagery Program (NAIP) (20–500 cm resolution).

2.2.2 Site characterization. To contextualize the relative impact of beaver dam activity on different riverscapes, we mapped valley bottom extents [55], which provided a basis for normalization. Next, we interpolated a valley bottom centerline and used this to characterize site length. We calculated integrated valley bottom width for each site by dividing valley bottom area by site length. To approximate valley gradient we took the difference in the extracted minimum elevations within a 30 m buffer of the upstream and downstream end of the valley bottom centerline from 10 m USGS National Elevation Database (NED) Digital Elevation Models (DEMs) [48,57]. To characterize site hydrology, we used baseflow and 2-year recurrence interval discharge, and stream power estimates from the Macfarlane et al. [48] Beaver Restoration Assessment Tool (BRAT v3.1.00; http://brat.riverscapes.net). These attributes were derived from channel position from USGS National Hydrography Dataset (NHD)+HR, NED, and USGS regional curves (Fig 3).

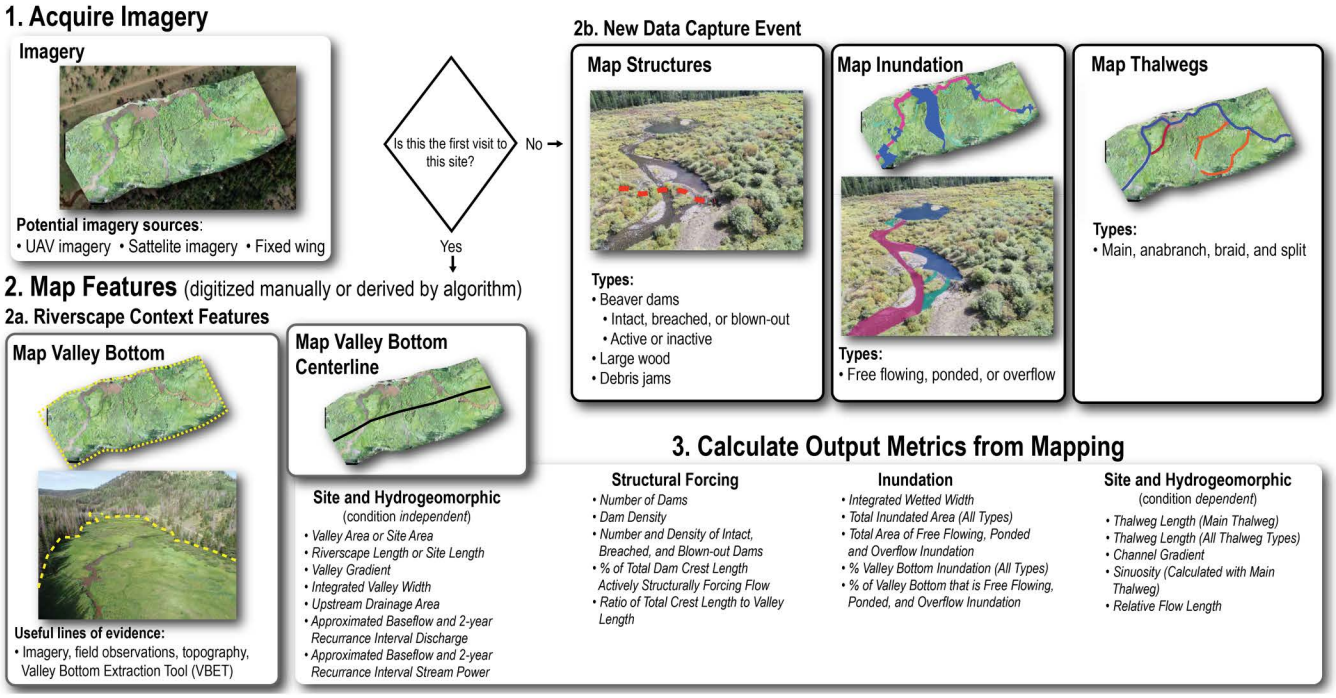


Fig 3. The sample design at each site can be broken into three steps: 1) imagery acquisition, 2) feature mapping, and 3) metric calculation. Riverscape context features such as valley bottom extent and centerline (step 2a) are generally mapped once as they should not change appreciably between surveys. For any subsequent surveys, we proceed to map structures, inundation, and thalwegs (step 2b). Finally, summary metrics were calculated from the mapped features (step 3). Photos by Karen Bartelt.

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2.2.3 Mapping and attributing structurally-forced features. For each survey, we digitized beaver dam crests, channel thalwegs, and inundation extent and type as defined by Hafen et al. [58]. Below is a description of the features mapped, which were all digitized in ArcGIS version 10.7 at a map panel zoom of 1:250 for consistency. Additionally, UAV imagery acquisition provided an opportunity for direct field observations to inform the subsequent mapping and desktop delineation of features.

2.2.3.1 Mapping dam crests. Beaver dam crests represent the top of the dam, and beavers tend to construct them at a constant elevation such that when the dam is maintained and full, water spills over the contour of the dam crest evenly. We digitized the beaver dam crest for each beaver dam by tracing the polyline representing a contour at the crest elevation of the dam.

For each digitized dam crest, we determined attributes that together help characterize dam condition and beaver dam activity: dam state and the length of the dam crest that was actively ponding flow at the time of the survey. An active dam crest length less than the total dam crest indicates water levels in the pond that are lower than the crest elevation. Dam state refers to the condition of the dam and whether it was intact, breached, or blown out at the time of the survey based on definitions by Hafen et al [58].

2.2.3.2 Mapping thalwegs. The hydrogeomorphic attributes of the riverscape we described in section 2.2.2 are assumed to be constant across multiple surveys at each site. To characterize more dynamic hydrogeomorphic attributes such as planform changes (e.g., multi-threadedness and sinuosity) that potentially occur between survey dates, we mapped the location and type of thalwegs in the riverscape at the time of each survey. We mapped the main channel thalweg and three additional thalweg types adapted from the Kramer-Anderson et al. [59] Geomorphic Unit Tool and defined by Bartelt [17]: main, anabranch, split, and braid.

We used the main thalweg to calculate channel gradient with the same method used to calculate valley gradient in section 2.2.2 [48]. We calculated "relative flow length" to characterize planform changes like multi-threadedness by dividing the total length of all thalweg types by the valley bottom length. We also calculated the sinuosity of the main thalweg and percentage of total thalweg length that is the main thalweg.

2.2.3.3 Mapping inundation. For each survey, we mapped inundation by digitizing a polygon around the wetted edge visible in the aerial imagery following the method described by Weber et al. [60] and Bartelt [17]. The relatively high zoom level of 1:250 was chosen because the resolution of the imagery was high enough to support mapping at this scale, and it also was broad enough to visualize most of the wetted width or ponds. We inferred between visible boundaries where vegetation or shadows obscured the water's edge.

Each inundation survey polygon was then broken into three flow type classes on a continuum from more lotic (free flowing) to more lentic (ponded, but still flowing), selected based on previous literature described in Section 1. We defined these classes as follows:

- Free flowing – not obstructed by a channel-spanning structural element.
- Overflow – structurally forced flow onto floodplain or otherwise exposed in channel surfaces (e.g., bars, benches and/or ledges).
- Ponded – structurally forced backwater ponding upstream of a channel-spanning structural element.

We consider this simple classification a first tier of flow types to discriminate large differences in flow characteristics. Similar classifications have been previously used to describe beaver-modified streams [e.g., 39,61].

Once the inundation types were classified, we calculated the total area of each first-tier inundation type. We then divided the inundated area by the valley bottom area to derive the percentage of total inundation for each inundation type, providing a normalized measure of inundation to facilitate inter-site comparison.

To account for uncertainty, we derived two buffered uncertainty polygons (buffer width equal to three times the image resolution) to represent an upper and lower bound on the maximum and minimum proportion of the total valley bottom that was inundated for each site. Uncertainty polygons were also derived for each individual inundation type to quantify uncertainty specific to each type. We estimated the integrated wetted width by dividing the total inundated area by the valley bottom length.

When high quality historical imagery was available, inundation mapping for the undammed condition relied on the method described above. However, when high quality historical imagery was not available, we relied on the poorer quality historic imagery as much as possible to infer undammed planform characteristics of the site such as the path of the channel, whether there were likely any side channels present, and the rough channel width. Then, higher resolution imagery of free flowing portions of the site and adjacent, undammed portions of the riverscape upstream and/or downstream of the site was used as further evidence to check and refine the estimation of the undammed inundation boundary and wetted width of the undammed channel. When upstream and/or downstream reaches were included in the assessment of undammed conditions, we verified that the adjacent reaches used were geomorphically consistent with the site (e.g., no substantial changes in valley slope, width, or confinement).

2.3 Algorithms, tools, & data management

The workflow and algorithms described above were packaged into an open-source tool called the Riverscape Inundation Mapper (RIM v0.1.0; written in Python 3.8.0; http://rim.riverscapes.net) [62]. The RIM tool includes Python scripts used to calculate the summary metrics described above, in Fig 3, as well as additional metrics. Site mapping data can be viewed or downloaded online from the Riverscapes Data Exchange (https://data.riverscapes.net/c/d059fa0f-bbe5-4704-8b82-5007c7564e5e/).

No permits were required for this study as field work was conducted on publicly accessible U.S. Forest Service and Bureau of Land Management lands using non-invasive measurement techniques, supplemented by remote sensing data and publicly available datasets that required no special permits or restricted area access.

3 Results and interpretation

For all sites surveyed, Table 1 highlights site characteristics including valley widths, valley gradients, locations within the drainage network, and varying degrees of beaver dam activity observed during the dammed condition survey (Table 1). In general, the floodplain sites had wider valley bottoms on average (μ = 220 m) than classic (μ = 74 m) and steep (μ = 41 m) sites (Table 1). There was no significant difference ($p = 0.16$) between valley gradients in classic and floodplain sites. By definition, steep sites were greater than or equal to 6% valley gradient, and also tended to have smaller upstream drainage areas (μ = 9.9 km2) than classic sites (μ = 49.4 km2; Table 1).

Inundation mapping results are shown first at an individual site to illustrate a typical example of the impacts of structural forcing on inundation patterns. We then report and discuss the summary results across all sites.

3.1 Example of site-specific results

Fig 4 shows the undammed (4A) and dammed surveys (4B) of Mill Creek, a ~ 260 m long classic setting (Fig 2) riverscape segment in the Uinta Mountains of Utah. Mill Creek is a 2nd order stream with a valley gradient of 0.015 and an integrated valley width of 105 m. Throughout the valley bottom of Mill Creek there was evidence of beaver dams, with some dams actively ponding water at the time of the survey and others that were not. In addition to sometimes backing up water, old dams left physical imprints to the valley bottom such as lines of willow extending across the valley bottom along the crests of abandoned dams, a stepped floodplain topography (indicative of structurally forced floodplain formation) and grade breaks marking the crest of relic dams. Old dams supported secondary channels that began both downstream and upstream of the relic dam crests. The extent of old ponds appeared to have either filled in with sediment or breached and subsequently revegetated throughout the pond except for in these anabranches. Apart from beaver dams, no other sources of structural forcing (e.g., large wood recruitment, boulders, etc.) were observed within this site.

The undammed survey (Fig 4A) shows that at low flow without dams, Mill Creek's inundation is contained within a single free flowing channel (integrated wetted width = 3.5 m). The inundated area was measured to be 1281 ± 455 m^2, or 4.7% of the valley bottom (Fig 4A & D). In the dammed survey (Fig 4B & C) that was conducted using imagery acquired in August 2019, there were twenty beaver dams (dam density = 76.3 dams/km of riverscape; or 54.6 dams/km of channel) and 471 total meters of dam crest length present within the site. Of that total dam crest length, 61% (289 m of 471 m) was actively ponding water at the time of the survey. The dam dimensions (width and height) relative to the channel dimensions throughout the site were large enough (generally a ratio of dam width to channel width greater than 1) to force water out of the channel and onto the floodplain. The total low flow inundation increased from ~5% to ~19% of the valley bottom. Of that total inundated area, almost 66% was ponded, 24% was overflow, and 11% was free flowing (Fig 4D). In the dammed survey, total thalweg length doubled relative to the undammed survey because of the addition of anabranches and areas of split flow.

In Mill Creek, a single valley bottom-wide dam forced multiple areas of overflow as sheetflow and secondary channels (Fig 4). This dam resulted in at least eight subsequent downstream dams on overflow channels creating an additional 2392 m^2 of ponded and overflow inundation. Inundation ultimately caused by this one dam represented almost 46% of the total inundated area at that snapshot in time. These and additional metrics of structural forcing and riverscape inundation patterns are provided for the other 36 sites in S1 Table.

3.2 Summary inundation results

We used the Mill Creek site (Fig 4) as an example of the impacts of structural forcing with imagery provided as context. In Fig 5, we present riverscape inundation schematics across 30 of the sites by portraying the inundation extent and type

Table 1. The USGS HUC8 watershed and mean and range of valley widths, gradients, upstream drainage area, estimated 2-year flood magnitude, estimated stream power magnitude at 2-year flood, and dam densities covered by sites (note at least 2 surveys at all sites; n = 77 surveys). Note all sites were surveyed for a "dammed" and "undammed" condition, hence dam density was only recorded for the dammed condition.

Dominant dam building opportunity	HUC 8	Number of sites	Valley width (m)			Valley gradient			Upstream drainage area (km²)			Q2 flow magnitude in cfs (cms in parentheses)			SP2 stream power magnitude (watts)			Dam density (dams/km)	
			Mean	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean	Max
Classic	10080002	1	84	84	84	0.010	0.010	0.010	21.3	21.3	21.3	38.3 (1.1)	38.3 (1.1)	38.3 (1.1)	54	54	54	26	26
	10080003	1	89	89	89	0.049	0.049	0.049	2.6	2.6	2.6	8.7 (.25)	8.7 (.25)	8.7 (.25)	149	149	149	60	60
	16010101	1	105	105	105	0.015	0.015	0.015	5.0	5.0	5.0	17.1 (.48)	17.1 (.48)	17.1 (.48)	0	0	0	76	76
	16010203	10	44	26	67	0.034	0.014	0.059	29.6	2.2	61.0	68.7 (1.95)	12.5 (.35)	117.2 (3.32)	677	250	1251	56	98
	17040218	2	165	145	185	0.021	0.017	0.025	22.2	14.0	30.4	41.1 (1.16)	25.9 (.73)	56.2 (1.59)	154	138	170	64	90
	17060201	1	155	155	155	0.006	0.006	0.006	35.6	35.6	35.6	55.4 (1.57)	55.4 (1.57)	55.4 (1.57)	15	15	15	64	64
	17070201	1	53	53	53	0.005	0.005	0.005	327.1	327.1	327.1	433.7 (12.28)	433.7 (12.28)	433.7 (12.28)	724	724	724	39	39
	17070204	1	81	81	81	0.013	0.013	0.013	157.8	157.8	157.8	72.6 (2.06)	72.6 (2.06)	72.6 (2.06)	214	214	214	78	78
Summary		∑ = 18	μ = 74			μ = .027			μ = 49.4			μ = 77.5 (2.19)			μ = 457.5			μ = 57.0	
Steep	16010202	1	59	59	59	0.063	0.063	0.063	3.8	3.8	3.8	10.1 (.29)	10.1 (.29)	10.1 (.29)	283	283	283	71	71
	16010203	8	39	16	72	0.085	0.061	0.142	10.7	0.9	30.3	32.9 (.93)	6.7 (.19)	72.9 (2.06)	634	107	1184	71	141
Summary		∑ = 9	μ = 41			μ = .083			μ = 9.9			μ = 30.3 (.86)			μ = 595.4			μ = 71.4	
Floodplain	16010203	1	114	114	114	0.035	0.035	0.035	83.9	83.9	83.9	145.5 (4.12)	145.5 (4.12)	145.5 (4.12)	1318	1318	1318	60	60
	17040101	7	208	129	485	0.016	0.005	0.021	81.4	28.3	274.5	231.3 (6.55)	96.2 (2.72)	688.7 (19.5)	682	202	1245	35	63
	17040219	2	315	233	396	0.015	0.013	0.017	183.7	63.5	303.9	129.8 (3.68)	72 (2.04)	187.5 (5.31)	384	304	463	40	40
Summary		∑ = 10	μ = 220			μ = .017			μ = 102.1			μ = 202.4 (5.73)			μ = 686.0			μ = 38.6	
Summary	n = 11	37	106	16	485	0.038	0.005	0.142	54.0	0.9	327.1	99.8 (2.83)	6.7 (.19)	688.7 (19.5)	553	0	1318	56	141

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without the imagery, but with context of the valley bottom to demonstrate visual patterns of inundation in beaver modified streams. We mapped 628 dams (368 intact, 232 breached, 37 blown out) over 23.5 km of riverscape length at 37 sites. In total we conducted 77 surveys at 37 sites (Fig 5-7, S1 Fig, and S2 Fig). While Fig 5 shows 30 examples of the dammed survey condition, Fig 6-7 show examples of both the undammed and dammed condition survey for 12 sites. The schematics consistently point to increases in inundation extent, diversity of inundation type, and relative flow length compared to

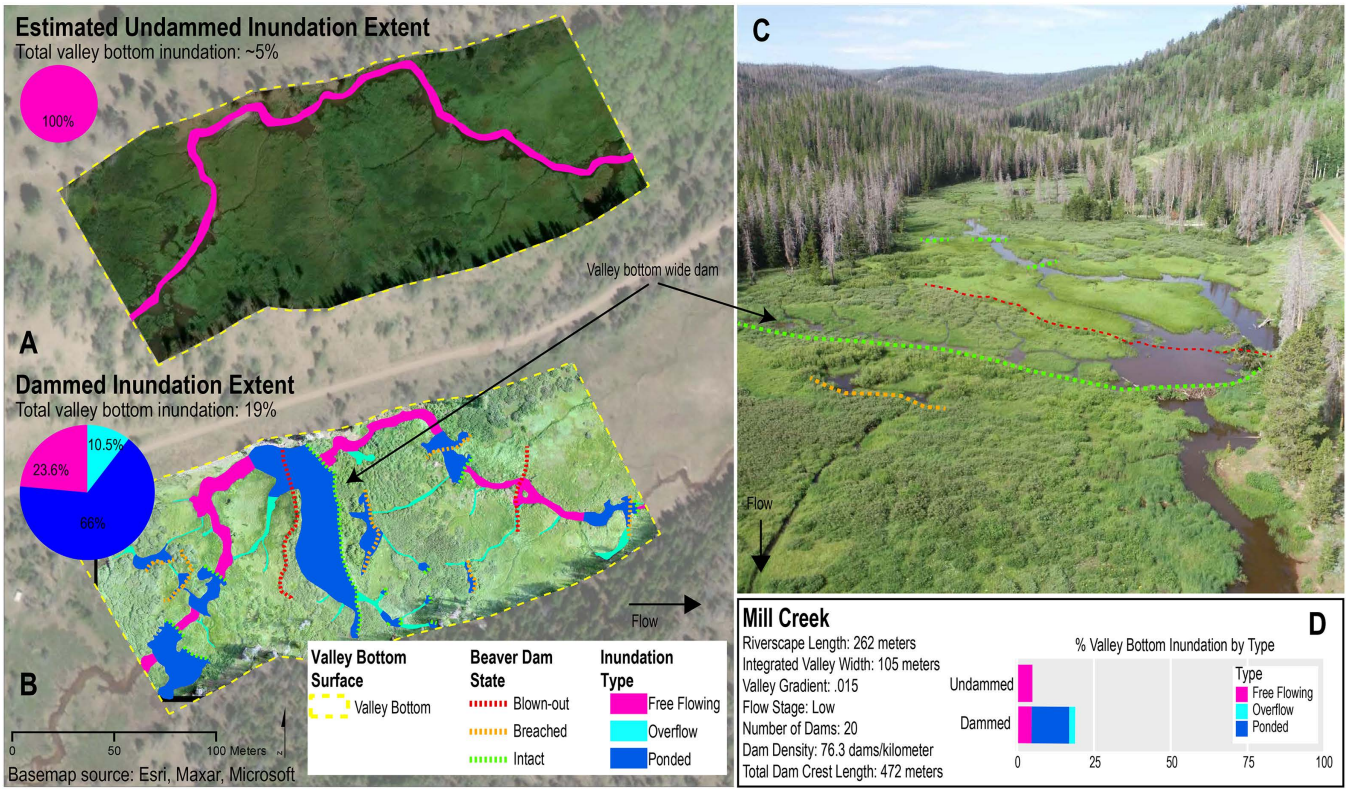


Fig 4. An example of riverscape inundation mapping results for an undammed survey (A) and a dammed survey (B) at Mill Creek, Utah. The oblique photo in (C) was taken during the imagery collection. The valley bottom wide dam shown in the center of the August 2019 survey on the left panel can be seen in the center of the right panel looking upstream. Photos by Karen Bartelt.

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the undammed condition across all settings. Table 2 summarizes this contrast between undammed and dammed sites by flow type and total inundation across the different settings.

For dammed surveys (Table 2), the average percentage of the valley bottom inundated across all sites was 23.2%. By contrast, the average percent of the valley bottom inundated for the same sites in an undammed condition was 6.8%. Although the total surface area of free-flowing inundation generally decreased from the approximated undammed to the dammed condition (except in floodplain sites; Table 2), additional ponded and overflow inundated area increased such that the total percentage of valley bottom inundation increased on average by over 300%.

Diversity of inundation type increased across all sites relative to the undammed condition (Fig 6-7). For the undammed surveys, all the inundated areas mapped were free-flowing. For the dammed surveys, much of this free-flowing inundation was converted to ponded or overflow. Of the total inundated areas mapped across all dammed surveys, 52% were free-flowing, 32% were ponded, and 16% were overflow.

Relative flow length increased from a mean value of 1.3 with a standard deviation of 0.5 for the undammed surveys to 3.2 with a standard deviation value of 1.1 in the dammed surveys (Fig 8). This increase reflects a planform change and splitting of flow from predominantly single threaded into additional anabranches around vegetated islands (i.e., anastomosing), and is also a result of increased sinuosity. The total thalweg length including secondary and overflow channels mapped from undammed sites was 16.5 km, whereas dammed surveys at the same riverscapes represented 39 km (136% difference).

See S1 Table for data from each site.

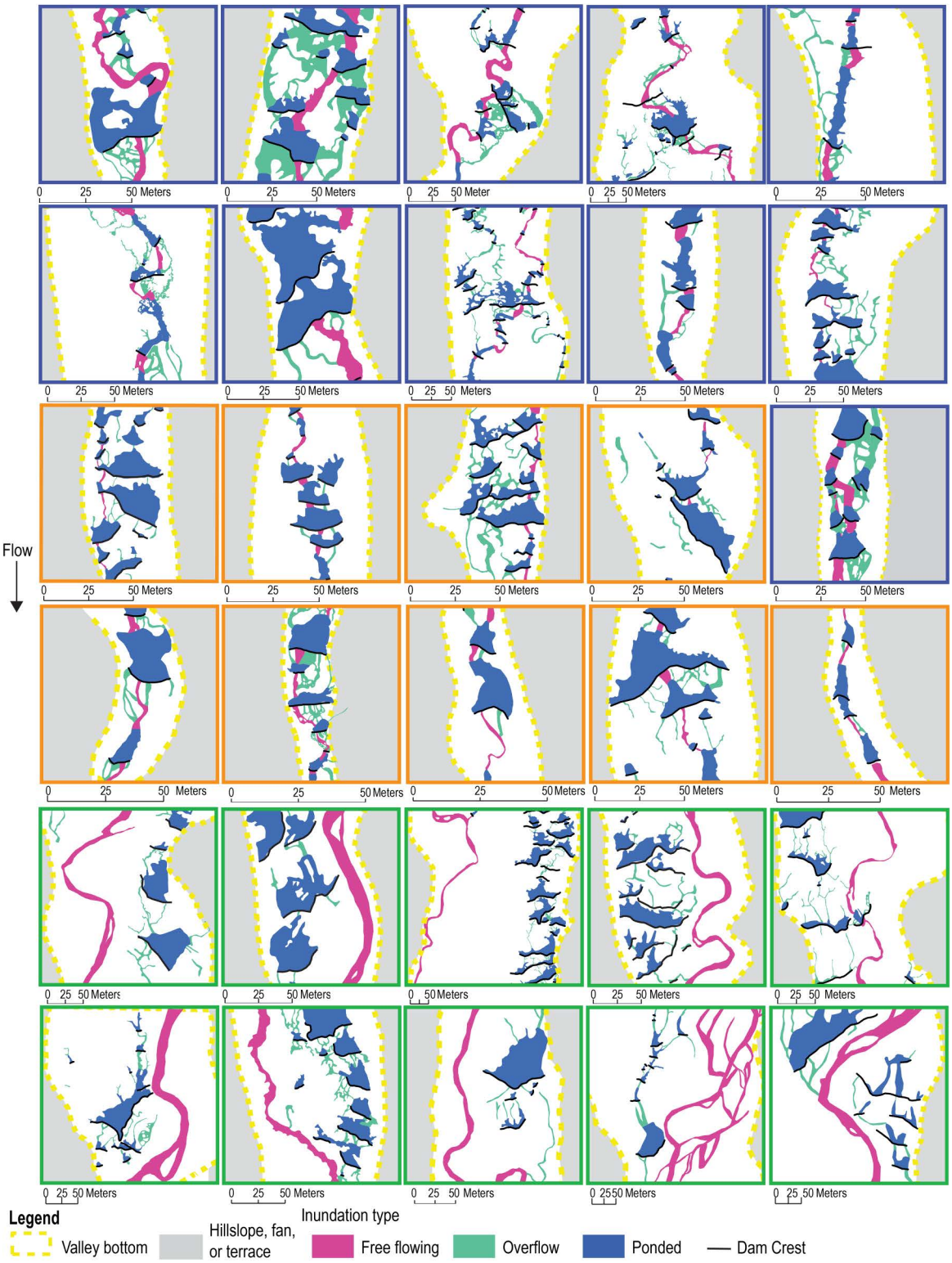


Fig 5. Schematic summary of inundation mapping at 30 surveys influenced by beaver dam building activity. While the figure highlights a large diversity of inundation patterns in different riverscape settings, it also shows a remarkable degree of consistency in terms of flooding patterns. The color outlining each panel represents the classic (blue), steep (orange), and floodplain (green) dam building setting.

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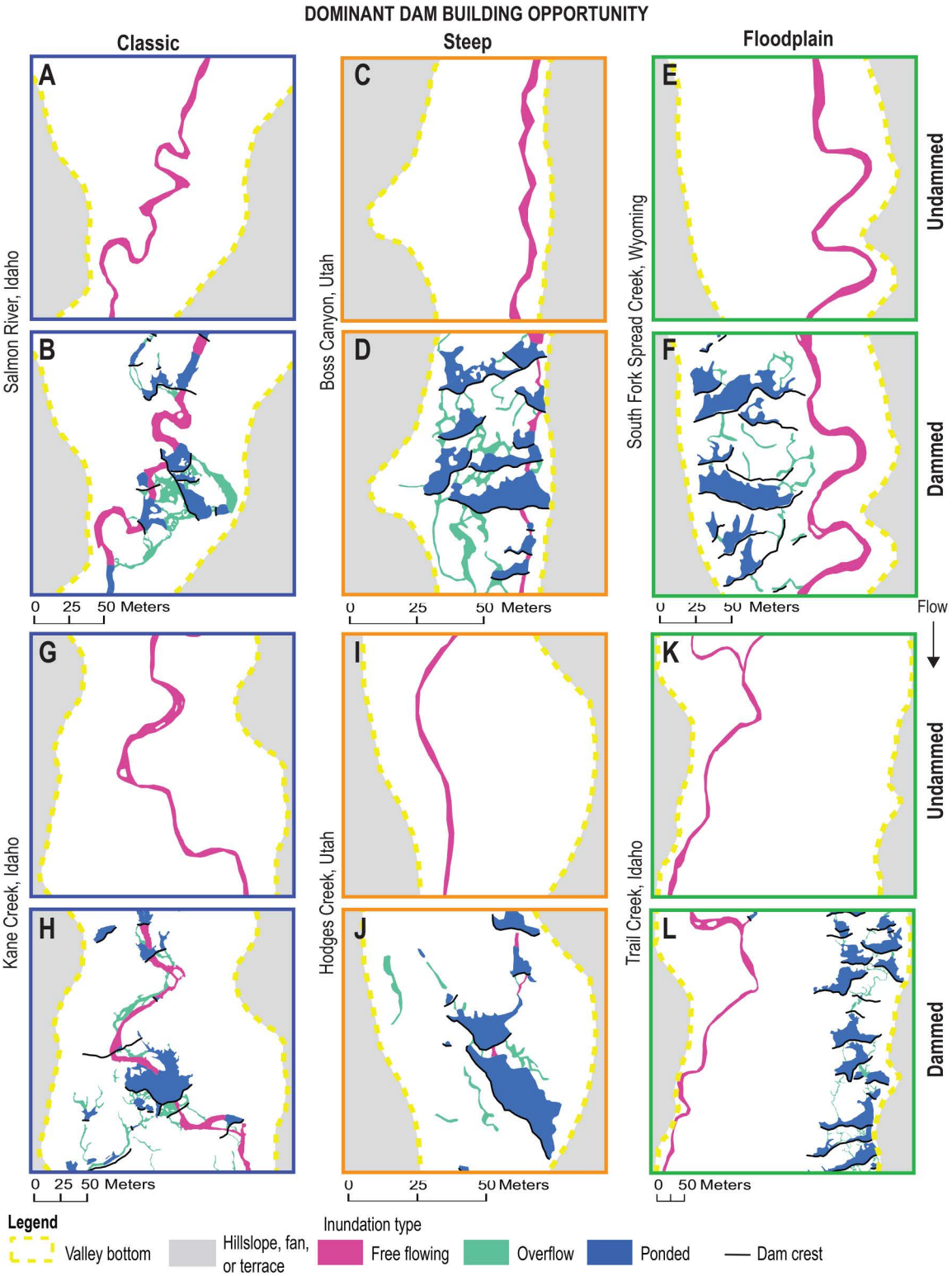


Fig 6. Inundation mapping results across dammed and undammed pairs of surveys at 6 of 37 sites, illustrating the nature of impacts between dammed and undammed conditions across a diversity of riverscapes. The columns are organized by dam building opportunity setting (classic, steep, and floodplain) and the rows alternate showing the undammed and dammed surveys from each site.

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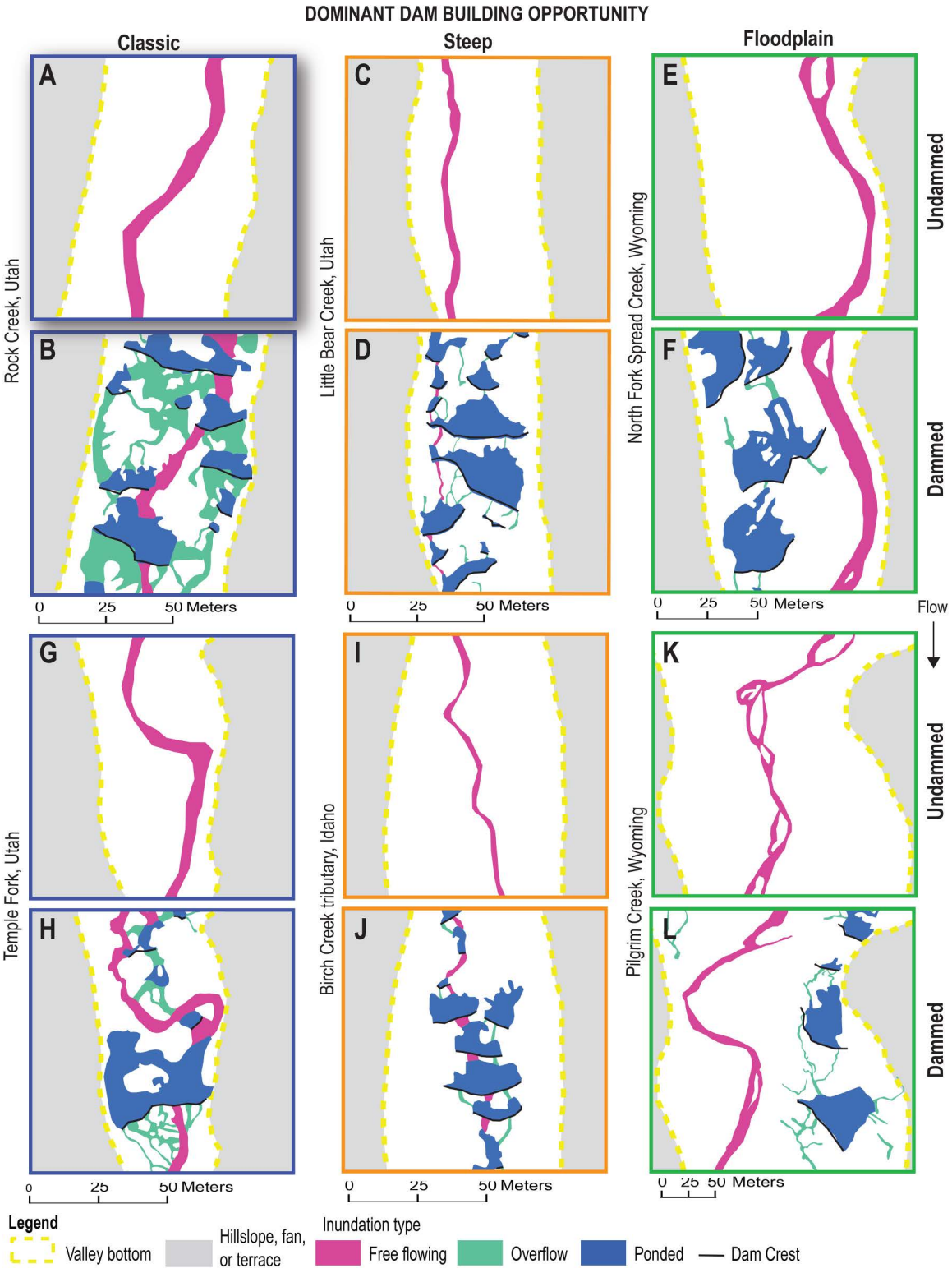


Fig 7. Inundation mapping results across dammed and undammed pairs of surveys at 6 of 37 sites, illustrating the nature of impacts between dammed and undammed conditions across a diversity of riverscapes. The columns are organized by dam building opportunity setting (classic, steep, and floodplain) and the rows alternate showing the undammed and dammed surveys from each site.

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Table 2. Average percent valley bottom inundation by flow type (free flowing, ponded, and overflow) (columns) for each of the three distinctive beaver dam building settings (classic, steep, and floodplain) (rows). The reported upper and lower bounds represent uncertainty estimates determined by imagery resolution.

		Percent of valley bottom inundated			
		Free flowing	Ponded	Overflow	Total inundation
Classic	Undammed	7.7 ± 3.2	0	0	7.7 ± 3.2
	Dammed	5.0 ± 2.8	15.4 ± 9.6	6.4 ± 3.9	26.9 ± 12.8
Steep	Undammed	6.2 ± 4.7	0	0	6.2 ± 4.7
	Dammed	2.4 ± 3.1	17.6 ± 4.8	4.2 ± 5.2	24.1 ± 9.4
Floodplain	Undammed	5.6 ± 2.5	0	0	5.6 ± 2.5
	Dammed	6.0 ± 2.4	7.8 ± 3.0	1.8 ± .8	15.6 ± 3.5
All	Undammed	6.8 ± 3.5	0	0	6.8 ± 3.5
	Dammed	4.7 ± 2.9	13.9 ± 8.0	4.6 ± 4.1	23.2 ± 10.9

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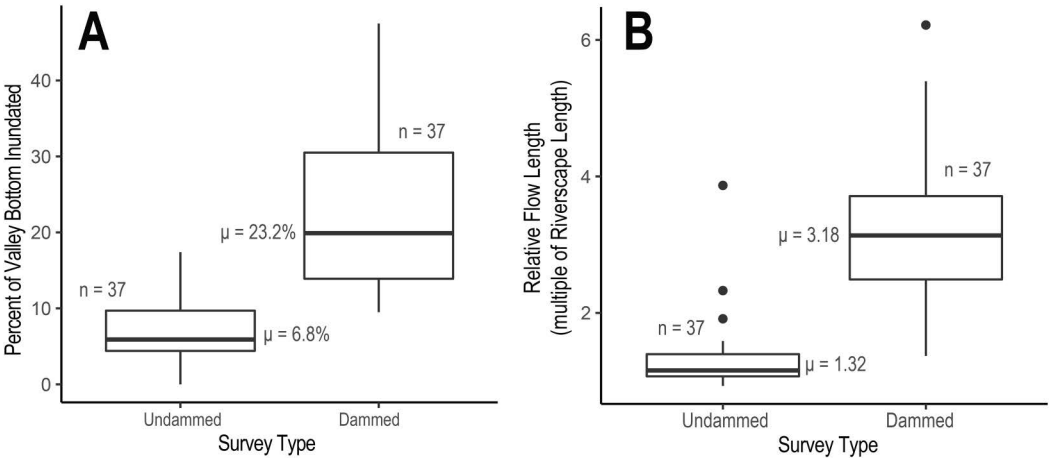


Fig 8. A) Percent valley bottom inundation in undammed and dammed surveys. B) Relative flow length calculated as the total length of thalwegs divided by the valley length for undammed and dammed surveys. The lower extent of the boxplots represents the bottom quartile (25%), the line represents the median, and the upper extent of the box represents the upper quartile (75%). The whiskers extend to the minimum and maximum values (all within 1.5 interquartile range) and outliers are represented by points.

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4 Discussion

Our results and observations support findings from previous literature at individual sites and provide a baseline quantification of inundation patterns in beaver modified streams. Westbrook et al. [22] evaluated the hydrologic effects of two beaver dams on the Colorado River and found that the dams increased the depth, extent, and duration of inundation. A review by Larsen et al. [26] reported that the areal extent of open water in beaver modified streams can be up to 9–12 times greater than the pre-beaver extent. Our findings of increased inundation extent at all 37 sites corroborate and expand previous findings across a larger number of sites and a wide range of physiographic settings. This observed increased inundation extent and diversity can trigger a cascade of hydrologic, geomorphic, and ecological processes documented in previous studies, including but not limited to increased transient water storage, sediment and nutrient retention, and greater habitat complexity to support diverse assemblages of aquatic flora and fauna [e.g., 6,22, 26,37,63]. The inundation type results provide a visual demonstration and quantification of the mosaic of flow types that previous studies

[e.g., 39,49] describe as a conversion of a mostly lotic environment to a mosaic of alternating lotic-lentic environments. The method used provides a tractable way for future investigators to add their empirical observations of beaver dam inundation impacts and place them in context to those reported here. Moreover, with findable, accessible, interoperable, and reusable (FAIR) sharing of data (S1 Text), other investigators can add to this database and grow our empirical awareness of the degree and variability of beaver-forced inundation pattern impacts from beaver dams.

4.1 Interpretation of differences across riverscape settings

It has long been known that beaver dam activity significantly influences inundation patterns. Our findings provide a quantification of the degree of that influence normalized by different riverscapes (i.e., as proportion of valley bottom area). This provides a simple way to intercompare the degree of such impacts across different riverscapes. We showed that beaver dams significantly influence inundation patterns in not only the typically reported classic riverscape settings from Fig 2, but also in the floodplains of larger rivers, as well as first-order streams in steep valley bottoms with gradients equal to or over 6% (Table 2). Although, in general, the results were consistent across the three beaver dam building opportunity settings (Fig 5), we did observe a range of inundation configurations and characteristics, including some end-member observations that stood out in the floodplain and steep settings. As illustrated in Figs 6–7 F & L no dams and no ponding occurred on the primary anabranch of floodplain sites. The lack of dams on the main anabranch of floodplain sites is a result of flood stream power magnitudes that are too high for dams to persist at higher flows [48]. Therefore, when dams occurred in floodplain sites, we did not observe any decrease in the total area of free-flowing inundation at low flows (i.e., from the primary anabranch where free flowing inundated area is converted to ponded) relative to the undammed inundation extent. Instead, we saw an increase in the total inundated area because of the additional ponded and overflow inundation taking place on the floodplain. We also observed that floodplain dams were infrequently breached or blown-out, which is consistent with the characterization of floodplain dams by Bush and Wissinger [49] who noted that these dams are less regularly impacted by mainstem flood disturbance events. From a unit stream power perspective, the same high flow stream power is spread out over a larger area with the structural forcing on floodplain surfaces, hence dissipating the energy acting on any single dam.

We observed that the classic sites were more typically characterized by one or two very large, often valley-wide dams located on the primary anabranch (sometimes referred to in the literature as primary dams [e.g., 8,58,63]). Smaller, "secondary" dams were located upstream or downstream of the primary dam, often on secondary anabranches (Fig 6B & H, Fig 7B). In contrast to this primary-secondary dam configuration, dams in the "steep" dam building opportunity sites were more often characterized by a string-of-pearls configuration consisting of a series of equally large, often nearly valley-bottom-wide dams (Fig 6D and Fig 7D) all located on the primary anabranch. Dams in steep settings were often taller and at higher dam densities than classic or floodplain dams. This could potentially contribute to why steep sites on average had a higher proportion of the valley bottom with overflow inundation relative to the other classic and floodplain sites (Table 2). Beavers tend to flood all the way to the base of an upstream dam in the same complex. Thus, it is logical that in steeper riverscapes, taller and more closely spaced dams are needed to create adequate cover from water depth. The distribution of dam states that we mapped (368 intact, 232 breached, 37 blown out) supports conceptual models that highlight the dynamic nature and ephemeral nature of beaver dams [e.g., 6,64,65] and studies that distinguish between different dam types and dam condition [e.g., 34,39,58] rather than solely focusing on intact dams.

4.2 Inundation patterns as a proxy for hydrologic inefficiency

While we did not directly quantify hydrologic inefficiency nor approximate it by measuring water residence time, we argue that there is a sound conceptual basis for using inundation type diversification, expansion of inundation extent, and increase in relative flow length as proxies for the inefficiency principle of riverscape health from Wheaton et al. [8] (also described in riverscape health principle 3 by Glassic et al. [10]). To illustrate how flow types (i.e., ponded, free-flowing,

overflow) might relate systematically to hydraulics, we overlaid the inundation mapping results at one of our study sites with two-dimensional hydraulic model results from Nahorniak et al. [66] (Fig 9). We found that ponded inundated areas tended to have lower velocity and higher depth magnitudes than free flowing and overflow inundated areas (Fig 9). In this survey, overflow areas tended to be the shallowest inundation type but had a wide range of velocities (Fig 9). If 2D flow vector traces are used, one can divide flow path lengths by velocity and get crude approximations of residence time. We did not do that here, nor are we claiming it is necessary. However, it is logical that diverse hydraulics will give rise to diverse residence times and the simple flow types used in this paper are a reasonable proxy for that.

In all dammed results, increased inundation extent only occurs where dams create a more diverse portfolio of inundation types in the valley bottom. We postulate that this diversified distribution of inundation types is a proxy for more variable and overall longer water residence times where water remains within beaver dammed parts of the riverscape longer as transient water storage. Larsen et al. [26] reviewed the conceptual basis for increased residence times from beaver dams and pointed out that quantifying and measuring residence time is difficult. This may explain why they only found two studies that had actually employed tracer studies to quantify residence times in beaver dam complexes compared to non-dam conditions [36,67]. Such studies are cost prohibitive to perform and replicate across numerous study sites.

Finally, drawing from Glassic et al. [10], in Fig 10 we illustrate the concept of hydrologic inefficiency as an indicator of riverscape health. The simple flow-type classes used here are easy to contrast between traditionally managed riverscapes that are simplified, efficient drainages dominated by free-flowing (Fig 10D) versus hydrologically inefficient riverscapes (e.g., Fig 10A), which have shorter residence times in free-flowing areas (e.g., Fig 10B) and longer residence times in overflow and ponded areas (e.g., Fig 10C). Hydrologic inefficiency can come from other forms of biotically mediated structural forcing like woody and organic debris accumulation, or root mat production [8,68].

4.3 Limitations

This method works best in semi-arid to arid environments and would be more difficult to accomplish in temperate environments due to the tree canopy blocking much of the valley bottom. Some of that is mitigated during beaver dam maintenance with harvest of trees, but aerial imagery will not necessarily be possible to acquire for all settings. Obtaining undammed historical imagery for every site was challenging and not possible. The undammed surveys were therefore conducted using a combination of historic imagery and evidence from upstream and/or downstream undammed portions of the riverscape, which introduces greater uncertainty than the direct mapping of the dammed surveys. Variations in baseflow may also introduce additional uncertainty to inundation results, however, surveys were conducted in snowmelt-driven intermountain west riverscapes during the dry season, when large precipitation events that would affect inundation are rare. The magnitude of the observed difference in inundation between the undammed and dammed surveys is large enough that these uncertainties would be very unlikely to change the findings reported here.

Another potential limitation to the methodology is that if the features are manually delineated in GIS, they then include some amount of user subjectivity. This potential issue might be more thoroughly resolved by incorporating simple remote sensing techniques such as supervised classification programs [e.g., 50,69]. Similarly, from experience walking the sites at the time of imagery collection and then later mapping the inundation based on that imagery, we have found that in general overflow inundation is likely underestimated when based on just visible bands (i.e., RGB). Non-visible bands like near-infrared are known to be helpful in discriminating wet areas [70], and automated delineation based on standard remote sensing techniques could potentially yield more accurate mapping of overflow conditions.

Inundation mapping does not capture subsurface dynamics like hyporheic exchange and groundwater infiltration. However, these processes contribute to an increase in water residence times and transient water storage and are likely crudely correlated with surface water inundation patterns. Further exploring the implications of surface inundation patterns for subsurface hydrology would be useful in future research but were beyond the scope of this study.

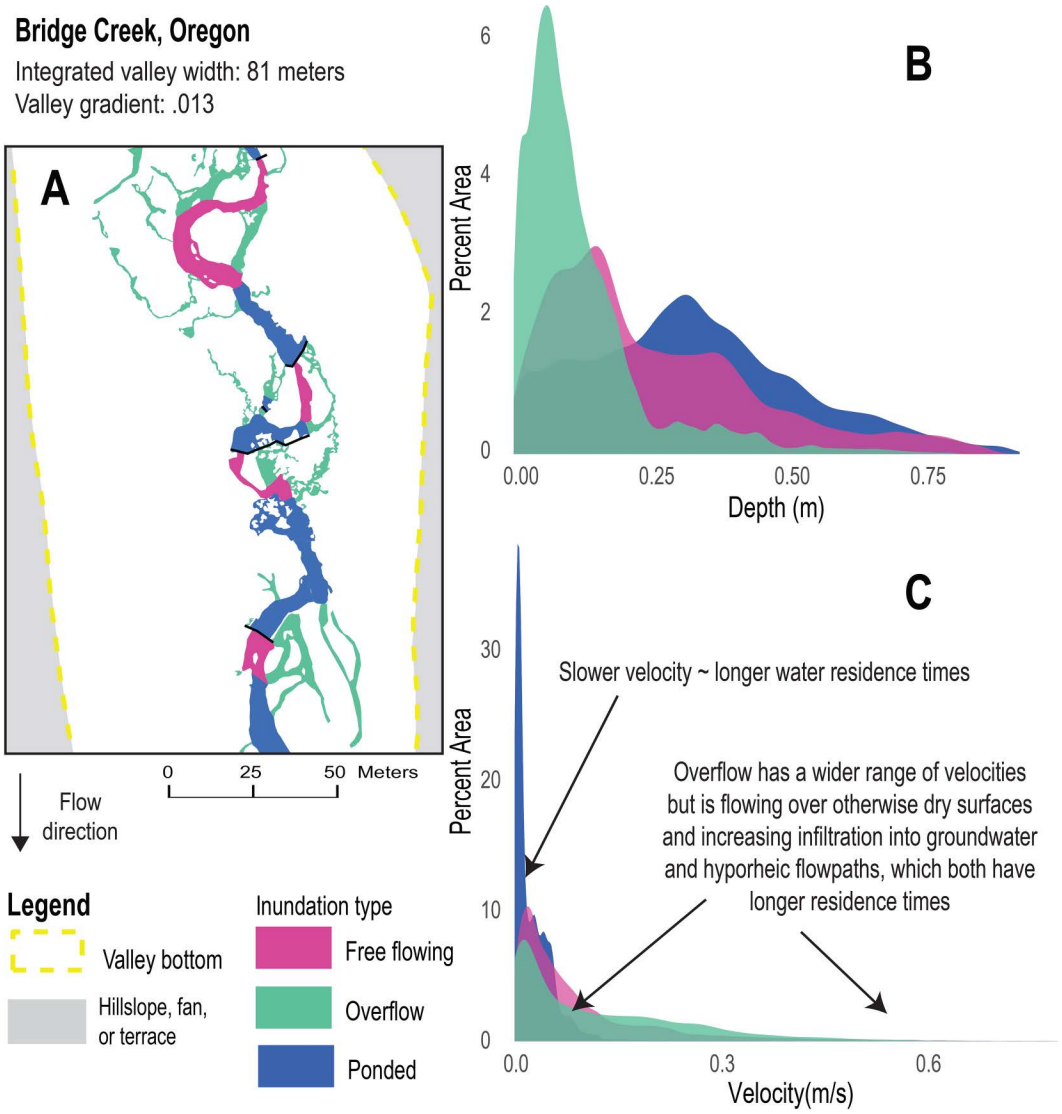


Fig 9. Inundation mapping results at the Lower Owens site on Bridge Creek, Oregon with the distribution of hydraulic variables represented by each inundation type. The mapped inundation extent symbolized by inundation type in **A).** Those inundation types were used as masks to sample hydraulic model results from a 2D hydraulic model for **B)** water depth and **C)** velocity.

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To evaluate primary metrics of percent of valley bottom inundated and proportions of flow types, mapping polygons (manually or by classification) is not the only method. Simple ocular estimates from both the desktop and/or the field could provide reasonable estimates [see 70]. For many riverscapes, this likely yields a +/- 5–15% accuracy, which for change detection between dammed and undammed conditions may be more than adequate to detect a signal.

4.4 Management implications

The results offer simple metrics that can be used as indicators for riverscape health and for framing restoration targets in terms of the degree of structural forcing, inundation patterns, and planform characteristics one might expect in intact, beaver-influenced riverscapes. However, it is important for restoration practitioners and land managers to consider that

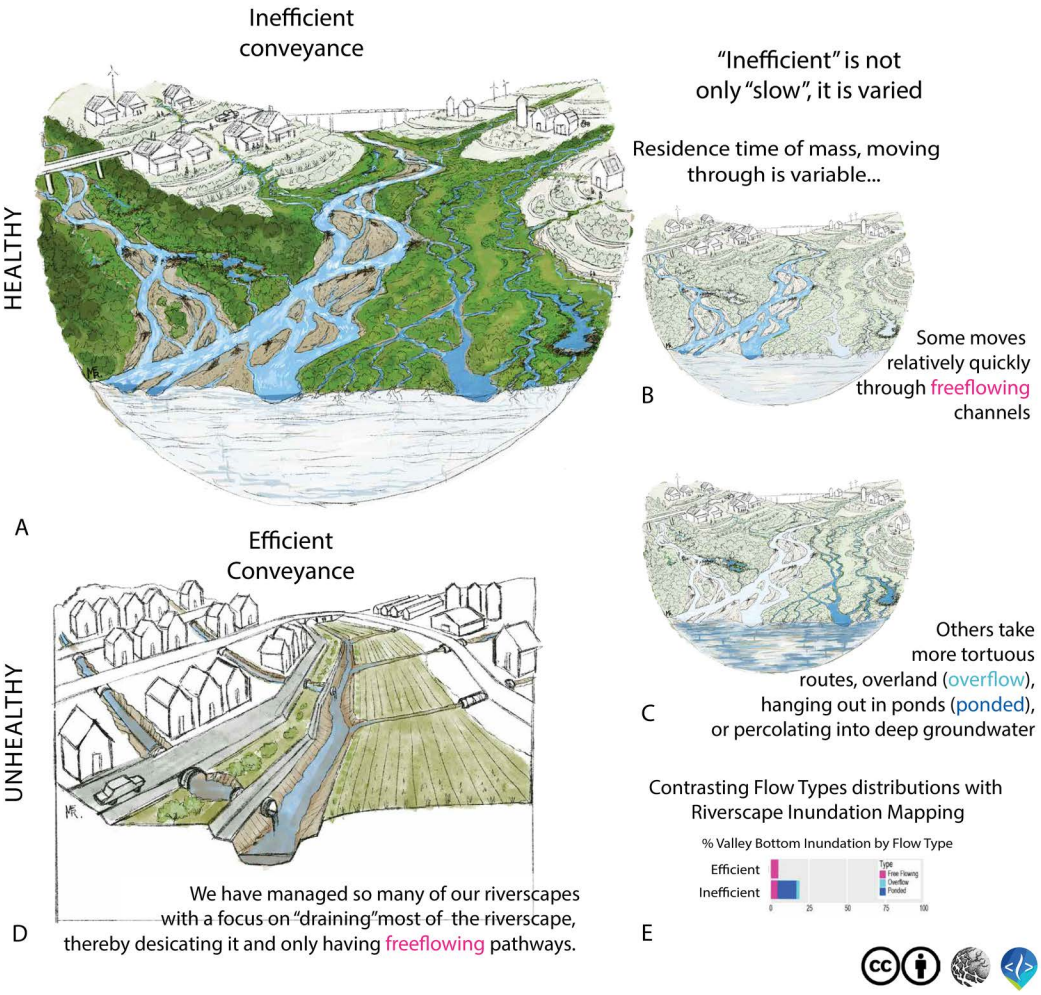


Fig 10. Conceptual model of "Inefficient conveyance" (A) in riverscapes as a principle of riverscape health. The riverscape inundation mapping proposed in this paper is a proxy for this inefficiency and is represented through a diversified portfolio of residence times, with some moving relatively quickly with short residence times (e.g., freeflowing in **(B)**), and others with longer residence times moving through more tortuous routes (e.g., overflowing and ponded **(C)**). The inundation mapping flow types **(E)** do not directly capture the slowest residence times through deep percolation into groundwater, but the slowing and overflow is a proxy directly correlated with such exchange. Healthy riverscapes exhibit more inefficiency **(A)**, whereas unhealthy riverscapes **(D)** are dominated by free flowing pathways we have deliberately engineered and managed for efficient conveyance without attenuating flow within the riverscape.

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the sites evaluated in this study all had long-standing evidence of beaver activity and maintenance. Many of the sites showed evidence of beaver activity for several decades in historical imagery, and showed recent evidence of beaver dam activity and dam maintenance during the site visit. While these sites may represent a reference condition for beaver influenced riverscapes, it is unlikely that the same degree of inundation would be observed without active dam building and maintenance by beavers. Future work could quantify what degree of valley bottom inundation typically results from beaver dam analogs or other forms of restoration. Furthermore, there are many additional output metrics derived from the features mapped in this framework (e.g., dam condition as a function of hydrogeomorphic regime, perimeter to area ratio as an indicator of patchiness and diverse habitat) that could be analyzed to answer other management or research questions not addressed specifically in this study.

5 Conclusion

We quantified the degree of impact that beaver dam activity can have on inundation patterns. The sampling is riverscape focused and uses the valley-bottom (lateral riverscape extent) to normalize metrics across diverse riverscape settings. We found that across 37 beaver dam complexes, the proportion of valley bottom inundation increased by on average over 300% due to the creation of ponded and overflow inundation caused by structural forcing. Our results highlight the influence of beaver dams on inundation patterns in both valleys with rivers larger and valleys steeper than typically included in the literature. While the mapping of inundation patterns is valuable as a stand-alone method, we postulate that inundation patterns could be used as a proxy for other important riverscape attributes (e.g., hydrologic inefficiency). The quantification of inundation patterns and method used here could be especially useful for natural resource managers in the context of riverscape restoration action-effectiveness monitoring.

Key findings

- When present, beaver dams increase the proportion of valley bottom inundation by over 300% on average, and surface water inundation types become more diverse.
- Beaver dams increase valley bottom inundation in a wider range of riverscape environments than often assumed.
- The inundation mapping results may serve as potential proxies to characteristics of riverscape health such as water residence time and hydrologic inefficiency.

Supporting information

S1 Appendix. Beaver dam building opportunity settings.
(DOCX)

S2 Appendix. Flooding at low flow.
(DOCX)

S1 Text. FAIR and riverscape compliant tools and data dissemination.
(DOCX)

S1 Fig. Additional inundation mapping results example A. Inundation mapping results across dammed and undammed pairs of surveys at 6 of 37 sites, illustrating the nature of impacts between dammed and undammed conditions across a diversity of riverscapes. The columns are organized by dam building opportunity setting (classic, steep, and floodplain) and the rows alternate showing the undammed and dammed surveys from each site.
(PDF)

S2 Fig. Additional inundation mapping results example B. Inundation mapping results across dammed and undammed pairs of surveys at 6 of 37 sites, illustrating the nature of impacts between dammed and undammed conditions across a diversity of riverscapes. The columns are organized by dam building opportunity (classic, steep, and floodplain) and the rows alternate showing the undammed and dammed surveys from each site.
(PDF)

S3 Fig. Mapping results of different dam opportunity settings boxplots. A) Total percent valley bottom inundation in undammed and dammed surveys grouped by beaver dam building opportunity settings. B) Total inundated area (m^2) of valley bottom inundation in undammed and dammed surveys grouped by setting. C) Relative flow length for undammed and dammed surveys grouped by setting. The lower extent of the boxplots represents the bottom quartile (25%), the line

represents the median, and the upper extent of the box represents the upper quartile (75%). The whiskers extend to the minimum and maximum values (all within 1.5 interquartile range) and outliers are represented by points.
(PDF)

S1 Table. Data tables. A) Results for each of the classic setting surveys. B) Results for each of the steep setting surveys. C) Results for each of the floodplain setting surveys.
(XLSX)

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Writing – review & editing: Karen Bartelt, Patrick Belmont, Jordan T. Gilbert, Edd Hammill, William W. Macfarlane, W. Carl Saunders, Scott Shahverdian, J. Marshall Wolf, Joseph M. Wheaton.

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