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Valley Bottom Inundation Patterns in Beaver-Modified Streams: A Potential Proxy for Hydrologic Inefficiency

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VALLEY BOTTOM INUNDATION PATTERNS IN BEAVER-MODIFIED STREAMS:

A POTENTIAL PROXY FOR HYDROLOGIC INEFFICIENCY

by

Karen Bartelt

A thesis submitted in partial fulfillment
of the requirements for the degree

of

MASTER OF SCIENCE

in

Watershed Science

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2021

ABSTRACT

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A Potential Proxy for Hydrologic Inefficiency

by

Karen Bartelt, Master of Science

Utah State University, 2021

Major Professor: Dr. Joseph Wheaton
Department: Watershed Sciences

For centuries, rivers in North America have been altered and degraded such that the conveyance of water downstream is unnaturally efficient, often to the detriment of other biophysical processes that function to 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 measured at individual study sites, these methods are often cost-prohibitive and complicated, making them less practical for monitoring at large spatial scales and in diverse settings. We propose a tractable framework to monitor beaver-influenced riverscapes that is based on delineating inundation patterns. We mapped inundation type (free flowing, ponded, and overflowing) and extent in beaver dam complexes in diverse hydrogeomorphic settings. Our mapping of over 75 events of inundation at 37 sites suggests that when structural forcing by beaver dams is present, on average roughly half of surface water inundation is converted from free flowing type to ponded and overflow types. Our mapping demonstrates that with the presence of beaver dams, flooding can occur even at low flows. On average, undammed conditions inundated 6.8% (range of 2.7% to 17.4%) of the valley bottom at low flows, whereas those same sites later occupied by beaver dams inundated 23.3% (range of 9.5% to 47.5%). This research also reveals that low gradients and stream orders most typically documented in past beaver dam studies are unnecessarily restrictive. We report similar magnitudes of impacts in steeper gradient (> 6%) 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 inundation mapping presented here is valuable as a stand-alone methodology, we postulate that the delineation of inundation type and extent can be used as a proxy for physical processes and indicators of riverscape health such as hydrologic inefficiency.

(90 pages)

PUBLIC ABSTRACT

Valley Bottom Inundation Patterns in Beaver-modified Streams:
A Potential Proxy for Hydrologic Inefficiency

Karen Bartelt

For centuries river management and land use actions in North America have caused widespread stream degradation where water now flows downstream with artificially high efficiency. When present, beaver dams slow the flow of water and decrease the efficiency of water conveyance through the landscape. These effects are often to the benefit of the function of natural physical processes and ecology of the stream. The benefits provided by beaver dams have been well studied at small scales, but the methods that these studies rely on are often expensive and time consuming and consequently not feasible to deploy at larger spatial scales or in diverse physical settings. We propose a tractable framework to monitor riverine systems that is based on mapping inundation, or flooding patterns. We mapped inundation area and type (types = free flowing, ponded, and overflow) in beaver dam complexes in diverse physical settings in which beavers tend to build different types of dams. Our mapping of over 75 snapshots of inundation at 37 sites suggest that beaver dams change inundation patterns by creating more diverse surface inundation patterns and slowing down water so that more inundation can occur, even at low flows. On average, at 37 sites, undammed conditions inundate 6.8% (range of 2.7% to 17.4%) of their valley bottoms at low flows. In contrast, sites with beaver dams present inundate 23.3% (range of 9.5% to 47.5%) of the valley bottom at low flows. Undammed sites predominately exhibited free flowing (> 99%)

inundation, whereas dammed sites had a mix of all three inundation types. This research also reveals that low slope and the small size of streams most typically reported in beaver dam studies are unnecessarily restrictive. We report notable changes to inundation patterns in both steeper gradient (> 6%) streams and in the floodplains of larger rivers where beaver do not typically dam the main channel. This research also proposes the use of inundation mapping as a proxy for other important physical processes that are difficult to explicitly measure.

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INTRODUCTION

For centuries in North America and Europe, rivers were managed both intentionally and inadvertently to increase the conveyance and drainage of water (Cluer and Thorne, 2012; Marston et al., 1996; Surian and Rinaldi, 2003). The widespread harvest of beaver and removal of beaver dams are among many anthropogenic activities that perpetuated the channelization and simplification of rivers (Burchsted et al., 2010; Montgomery, 2003; Naiman et al., 1988; Rieman et al., 2015). The removal of wood accumulations and beaver dams has “structurally-starved” degraded stream channels such that water often moves through with artificially high efficiency. In the context of water conveyance, efficiency is characterized by shorter water residence times and travel distances where water moves downstream from point A to point B as efficiently as possible (i.e., an entirely lotic system). Historically, there has often 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., Rai et al., 2017). However, in the last decade there has been a paradigm shift in what characterizes a healthy riverscape that challenges the prioritization of efficiency over a host of other attributes (Castro and Thorne, 2019; Wohl, 2021; Wohl et al., 2021). A central pillar to this paradigm shift is the important role that structural forcing by objects such as large wood or beaver dams plays in the processes that maintain healthy riverscapes (Wheaton et al., 2015; Wohl et al., 2020). In terms of structural forcing, my research focuses specifically on structural forcing that results from beaver dams and their impact on surface water inundation patterns in riverscapes.

Cluer and Thorne (2012) coined the term “Stage 0”, which represents the likely true pre-European (i.e., natural) condition of many streams throughout North America. Stage 0 (and Stage 8) streams are multithreaded, messy, less hydrologically efficient, and encapsulate many elements of the paradigm shift mentioned above (Wohl, 2020). Wheaton et al. (2019) built on this appreciation of Stage 0 streams and summarized the most important elements as four principles of riverscape health: 1) streams need space 2) structure forces complexity and builds resilience 3) the importance of structure varies and 4) inefficient conveyance of water is healthy (Figure 1).

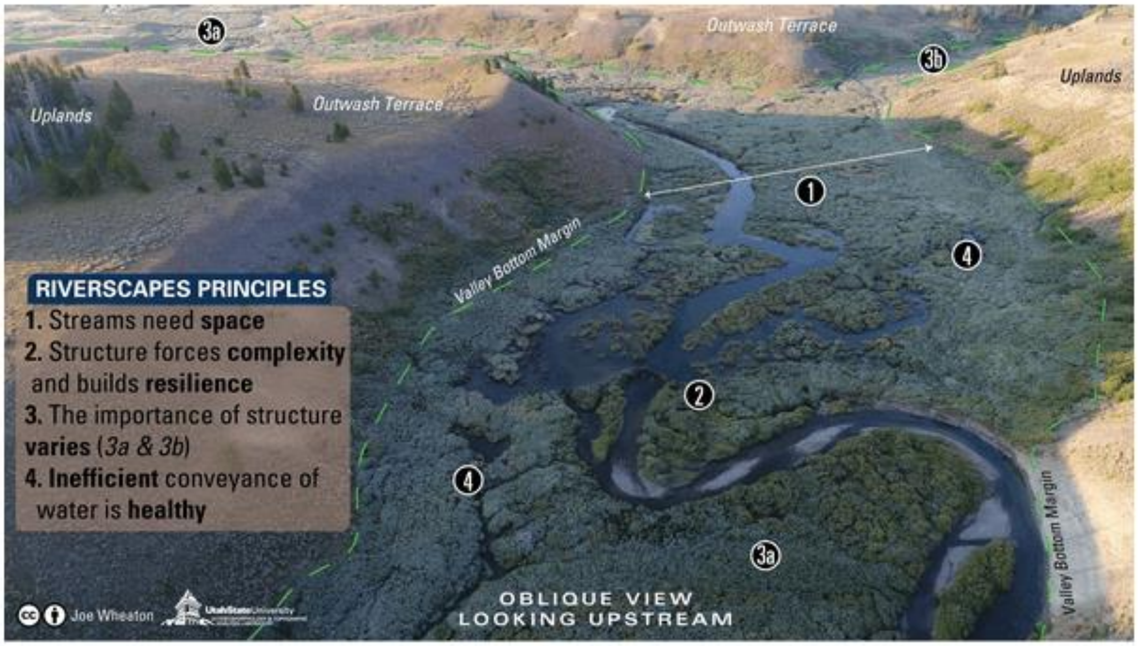


Figure 1. The four principles of riverscape health from Wheaton et al. (2019).

With Riverscape Health Principle 4 (Figure 1), Wheaton et al. (2019) introduced the term hydrologic inefficiency and asserted that it “is a hallmark of a healthy system”. They related hydrologic inefficiency to generally longer and more varied residence times, increased attenuation, decreased longitudinal connectivity, and increased lateral and vertical connectivity; but stopped short of explicitly defining the term. It would be logical to presume that hydrologic inefficiency is the direct opposite of efficient conveyance of water downstream. However, the extreme of this interpretation of hydrologic inefficiency is a reservoir with little to no conveyance downstream (i.e., an entirely lentic system). Wheaton et al. (2019) and the supporting literature they cite (e.g., Burchsted and Daniels, 2014; Covino, 2016; Grant et al., 2016; Wegener et al., 2017) make it clear that when thinking about increased hydrologic inefficiency as a “positive” attribute, it is important to simultaneously consider the other three principles of riverscape health (Figure 1). Doing so essentially promotes inefficiency in moderation. More varied and an overall average increase in water residence times and hydrologic inefficiency is a good thing when in conjunction with dynamic and messy riverscapes. If a riverscape were to reach a condition of maximum hydrologic inefficiency, however, it would be at the cost of the complexity of the system.

The mechanisms by which beaver dams increase hydrologic inefficiency while still promoting the other three principles of riverscape health have been well captured by existing literature at the local scale. Beaver dams act as small-scale longitudinal discontinuities (Burchsted et al., 2010) that alter water conveyance, increase lateral connectivity, and increase riverscape complexity (Wohl, 2016) through a cascade of hydraulic, hydrologic, geomorphic, and ecological feedbacks (Larsen et al., 2021; Wheaton et al., 2019). Beaver dams force flow to pass over, under, through, or around a porous dam (Brazier et al., 2021; Woo and Waddington, 1990) and back up water creating a beaver pond upstream of the dam. Hydraulic models conducted in beaver-modified reaches indicate a significant decrease in velocity, increase in depth, and increase in water residence time in these ponded areas (Majerova et al. (2017); Stout et al. (2017)). Downstream, dams often force complex and multithreaded overflow paths (Gurnell, 1998; Westbrook et al., 2006; Westbrook et al., 2011). Flooding in rivers is typically associated with high flows. However, when beaver dam crest elevations are higher than the adjacent floodplain, floodplain surfaces both upstream and downstream of dams are often inundated even at low flow (Westbrook et al., 2006). The visible increase in surface water inundation on the landscape reflects local changes to water conveyance and hydrologic pathways (Larsen et al., 2020). Increased duration of water flowing over active channel (e.g., otherwise exposed bars) and floodplain surfaces impacts surface-groundwater interactions, increasing infiltration. Increased infiltration (Westbrook et al., 2006) results in an increase in hyporheic exchange, groundwater recharge (Janzen and Westbrook, 2011), and water table elevations (Westbrook et al., 2006). The more complicated flow paths created by beaver dams (Gurnell, 1998; Westbrook et al., 2006), changes to hydraulics (particularly decreased velocity (Majerova et al., 2017)), and changes to surface-groundwater interactions contribute to an increase in water residence time within portions of the beaver dam complex (Jin et al., 2009; Majerova et al., 2017). Surface and subsurface transient water storage increases (Jin et al., 2009; Lautz et al., 2006) and the delivery of water downstream is delayed. Previous studies have captured this transient water storage reflected in a buffered hydrograph in which flood peaks are attenuated, and baseflow magnitude is elevated (Nyssen et al., 2011; Puttock et al., 2017; Wegener et al., 2017; Woo and Waddington, 1990), although a portion of this transient storage is lost to increased evapotranspiration (Fairfax and Small, 2018).

Hydrologic inefficiency can be quantified as water residence time or transient water storage with the use of hydraulic models derived from topographic and velocity data (e.g. Majerova et al., 2017), tracer tests (e.g. Jin et al., 2009; Lautz et al., 2006), and mass balance approaches that rely on discharge measurements (e.g., Majerova et al., 2015; Nyssen et al., 2011; Puttock et al., 2017; Wegener et al., 2017; Woo and Waddington, 1990). However, these data require extensive instrumentation, laborious in-person data collection, and can be time consuming to collect (Bangen et al., 2014a; Carbonneau et al., 2012). The difficulty of collecting these data is exacerbated by the fact that beaver modified systems are inherently complex and thus more time consuming to survey, make measurements and traverse than undammed streams. This is likely why few studies exist at spatial scales larger than the beaver dam complex scale and why we do not have a tractable way to approximate hydrologic inefficiency at larger spatial scales than a single beaver dam or dam complex. Fausch et al. (2002), who popularized the term “riverscapes”, articulated the need for researchers and land managers to expand the spatial scales at which biota and habitat sampling of riverscapes occur such that we are working at scales relevant to the life history events of important species. In short, this means either identifying sampling and modeling approaches that can be done across entire riverscape networks (e.g., Macfarlane et al., 2017; Roux et al., 2015; Wheaton et al., 2017) or sample designs (what you sample at each site) that are rapid or simple enough they can be done within a study design that includes a large and appropriate number of sites.

The relative extent and degree of impact of structurally forcing by beaver dams is a function of the physical setting of the riverscape such as valley setting, valley bottom topography, and flow regime (Hafen et al., 2020; Larsen et al., 2021). Existing literature tends to focus on beaver dams located in low to moderate gradient (< 6%), wadeable streams (e.g., Burchsted and Daniels, 2014; Gurnell, 1998; Naiman et al., 1988; Polvi and Wohl, 2012). This focus on lower gradient and smaller stream sizes is rooted in empirical observations of where beaver often build dams and in the development of habitat suitability index (HSI) models for beaver, which was informed by dam census studies of systems with heavily discouraged beaver populations (e.g. Allen, 1983; Beier and Barrett, 1987; Howard and Larson, 1985; Petro et al., 2015). Despite these persistent oversights and sampling biases in the literature, one of the earliest beaver dam censuses by Retzer (1956) found that 68% of Colorado beaver dam complexes were located at stream gradients less than 6%, 28% at gradients from 7-12%, and 4% at gradients of 13-14%. These findings were foundational for development of the U.S. Fish and Wildlife Service beaver HSI by Allen (1983). Subsequent studies have almost entirely focused on mean gradients of less than 6% (e.g., Dittbrenner et al. (2018); Petro et al. (2018)), ignoring the third of observations in steeper settings. It is important to note that while beaver dam activity is common in what we refer to as classic settings Figure 2 and Appendix A – Beaver Dam Building Opportunities, this setting description restricts the true extent in which beaver dams occur. Macfarlane et al. (2015) observed beaver dams in streams with gradients of up to 23% and explicitly incorporated predictions of beaver dam building capacity in such settings into their BRAT model (Beaver Restoration Assessment Tool: http://brat.riverscapes.xyz). Bush and Wissinger (2016) conceptualized the hydrological differences between classic dams and “floodplain” dams that can occur in the floodplains and secondary anabranches of larger rivers, introducing a less studied floodplain dam setting that we included in Figure 2 and Appendix A(though present in some studies e.g. Burchsted and Daniels, 2014; Wegener et al., 2017; Wohl, 2020). The role and importance of beaver dams in the steep and floodplain settings from Figure 2 and Appendix Ais less studied or understood than that of the classic setting. However, these settings can comprise a large percentage of riverscape lenth in any given watershed where there is capacity for beaver dams (Appendix B).

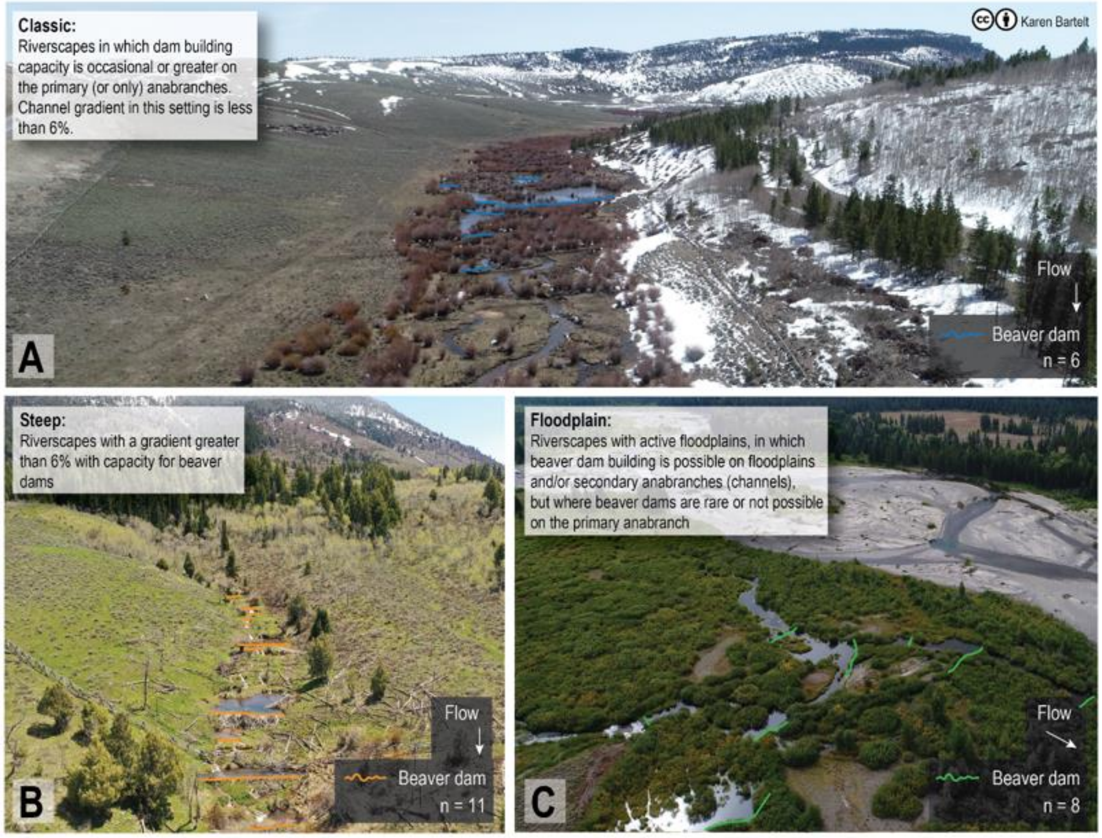


Figure 2. Three of four different dominant riverscape dam building opportunities for beaver (also referred in this paper as settings). A) The classic setting in the top panel represents the beaver dams typically studied in the literature. B) Even though beaver dams in steep (> 6% slope) riverscapes represent over a 1/3 of early reported observations in the literature, they are often ignored. C) The floodplain settings along typically larger rivers and streams where beaver dam building is concentrated on the floodplains. This figure was inspired by Bush and Wissinger (2016). The figure and research described here does not include a fourth setting described by Bush and Wissinger (2016) that consists of spring fed beaver dams.

The purpose of this thesis is to explore how beaver dams impact surface water inundation extent and type as a means to quantify the cumulative effects of beaver dams on riverscape segments. Inundation is one of the more obvious response variables to structural forcing, and visible changes to the extent and nature of inundation reflect many of the beaver dam impacts described above and in previous studies. Furthermore, mapping inundation patterns provides a tractable way to address gaps in existing literature by making it possible to conduct and compare surveys across a) broader spatial extents and b) more physiogeographically diverse settings (such as the settings described in Figure 2) than typically feasible in the past. Here we developed a framework for mapping and quantifying valley bottom inundation patterns and use this framework to provide an initial test of two hypotheses:

H1: The diversity of valley bottom inundation type and the extent of low flow valley bottom inundation both increase with increasing degree of structural forcing by beaver dams.

H_2: The increase in low flow valley bottom inundation diversity and extent is limited to the classic setting and does not occur in the steep and floodplain settings.

Ideally, evidence supporting H_1 and showing a clear relationship between some measure of beaver dams and our response variables could reveal a simple measurement that could be used in beaver-modified systems to predict the extent and type of inundation and thus, associated attributes. While it was beyond the scope of this study to directly measure hydrologic inefficiency and water residence times associated with the inundation patterns we delineated, we postulate that mapping inundation extent and type based on the framework outlined below could be used as a potential proxy for approximating hydrologic inefficiency. Evidence supporting H_2 could provide an explanation and justification for the lack of beaver dam studies located in steep and floodplain settings. By contrast, disproving H_2 could highlight the importance of these under considered riverscapes for beaver dam activity.

CONCEPTUAL FRAMEWORK FOR USE OF INUNDATION PATTERNS AS A PROXY TO QUANTIFY HYDROLOGIC INEFFICIENCY AND OTHER CHARACTERISTICS

As described and cited in the introduction, previous literature has well-captured the local scale links between beaver dams and hydrologic inefficiency by taking intensive measurements of the hydraulic, hydrologic, and geomorphic changes that occur upstream and downstream of dams. We propose a framework for the delineation of inundation types that are based on a distillation of that literature and which could be used as an easy and tractable proxy for hydrologic inefficiency and other physical processes and characteristics.

Hydrologic inefficiency can be expressed as relatively longer water residence times, which can be calculated by dividing a control volume of water by the sum of outflow discharge from that control volume.

Previous research (e.g., Brazier et al., 2021; Larsen et al., 2021) has established that in beaver *ponds*, depth and width both increase, increasing the magnitude of the control volume and thus increasing water residence time. We also know that in beaver ponds velocity decreases, causing a decrease in outflow discharge, further contributing to an increase in water residence time.

Previous research (e.g., Brazier et al., 2021; Larsen et al., 2021) has established that beaver dams often force a planform change from single threaded to multithreaded, where water is diverted from the main channel and flows across the floodplain or through newly formed secondary channels. In terms of water residence time, these *overflow* areas would likely correspond to an increase in water residence time via decreasing velocity because the relative flow length that water is taking downstream is longer and more complex. Furthermore, roughness, which is inversely related to velocity, would likely increase in these areas as water flows across floodplain surfaces that are often vegetated.

Therefore, it is logical to conclude that both beaver ponds and overflow channels exhibit increased water residence times relative to undammed (free flowing) portions of riverscape. Based on this, we propose the delineation of the following three flow types: ponded, overflow, and free flowing as a simple and meaningful first-tier categorization of surface water inundation.

At any snapshot in time, inundation extent can be mapped and its magnitude quantified in a riverscape based on area. Inundation extent reported as an area is important because it directly equates to the amount of aquatic habitat within the riverscape at that time. Inundation extent at high-flows also defines the areas in which there is potential for geomorphic work to occur., To appropriately contextualize the degree of inundation locally, riverscape or valley bottom area provides a simple measure to compare inundated area with by reporting inundation as a proportion of valley bottom area. Inundation proportion is normalized to any riverscape setting because by definition the valley bottom area represents the intrinsic flooding potential of a riverscape and therefore lends to effective intercomparison across diverse sites.

Larsen et al. (2020) describe changes to water storage capacity as the “key hydrological modification from which other impacts follow”. By using inundation patterns as a proxy for water residence time and hydrologic inefficiency, we are essentially quantifying that “key” and thus in theory can approximate the impacts that follow. The distribution of inundation types (free flowing, ponded, and overflowing) and extents (valley bottom inundation proportion) can be a useful indicator for hydrologic, geomorphic, and ecologic characteristics and processes beyond hydrologic inefficiency. For example, the variety and distribution of inundation types within the valley bottom exerts control over the geomorphic processes present (e.g., more deposition and storage in areas with ponded inundation, but potentially a mix of erosion and deposition in overflow areas). Also, a more even distribution of inundation patterns may correspond with more diverse biogeochemical processes (Wegener et al., 2017) and habitat variables that are important to aquatic and riparian biota such as substrate (e.g., Cobb et al., 1992; Riebe et al., 2014) or temperature (Weber et al., 2017).

METHODS

Inundation can be quantified to varying degrees of precision with many different potential methods. These potential methods range from ocular estimates of inundation proportion and flow-type proportion, to manual mapping from coarse, freely available imagery, to supervised classification with remote sensing, to manual digitizing of high resolution ortho-photos, to high-resolution field mapping with survey-grade equipment. We will not test the utility or relative accuracy of these different methods here. Instead, we focus on what can be accomplished from a relatively rapid, but manual digitization of features from readily available (e.g., Google Earth) and/or easily acquirable (e.g., consumer-grade drones) high-resolution aerial imagery. We focus on this approach because the digitization of visible features off of high-resolution ortho-photos is a widely used method (e.g., Carbonneau et al., 2012; Carbonneau et al., 2020; Donovan et al., 2019; Green et al., 2019), and we wish to focus more on establishing an initial, empirical baseline of typical values of inundation patterns across different physical settings. We therefore sampled sites across the Intermountain West that encompassed each of the dam building opportunities described in Figure 2.

Sample Design

We define a site as a riverscape segment, which extends laterally to the valley bottom extents, and longitudinally to the upstream and downstream extent of the zone of influence of a beaver dam complex or multiple complexes with overlapping zones of influence (typically spanning between 100 m and 800 m). At each site, we followed a three-step process of 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 (see Figure 3). Also, at each site at least two data capture events were repeated to capture when possible a low flow event both with and without beaver dam activity. At some sites, additional data capture events represented different degrees of beaver dam activity and/or intermediate or high flow inundation events.

Imagery Acquisition

Basemap imagery for digitization for all surveys was acquired with an unmanned aerial vehicle (UAV), or from available satellite 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 Drone Deploy to produce a 2cm resolution orthomosaic image (e.g. Carbonneau et al., 2020; Oakland, 2020). We used historic imagery from Google Earth or NAIP (20 to 300 cm resolution) to capture undammed conditions at previous snapshots in time representing undammed conditions.

Site Characterization

In addition to the settings described in the introduction (Figure 2), a suite of hydrogeomorphic attributes were used to characterize and differentiate sites (Table 1). To contextualize the relative impact of beaver dam activity on different riverscapes, we mapped the riverscape or valley bottom extents (Fryirs et al., 2015) which provided a basis for normalization. For each site, we used multiple lines of evidence to delineate the valley bottom margins for the site. These included satellite imagery and field

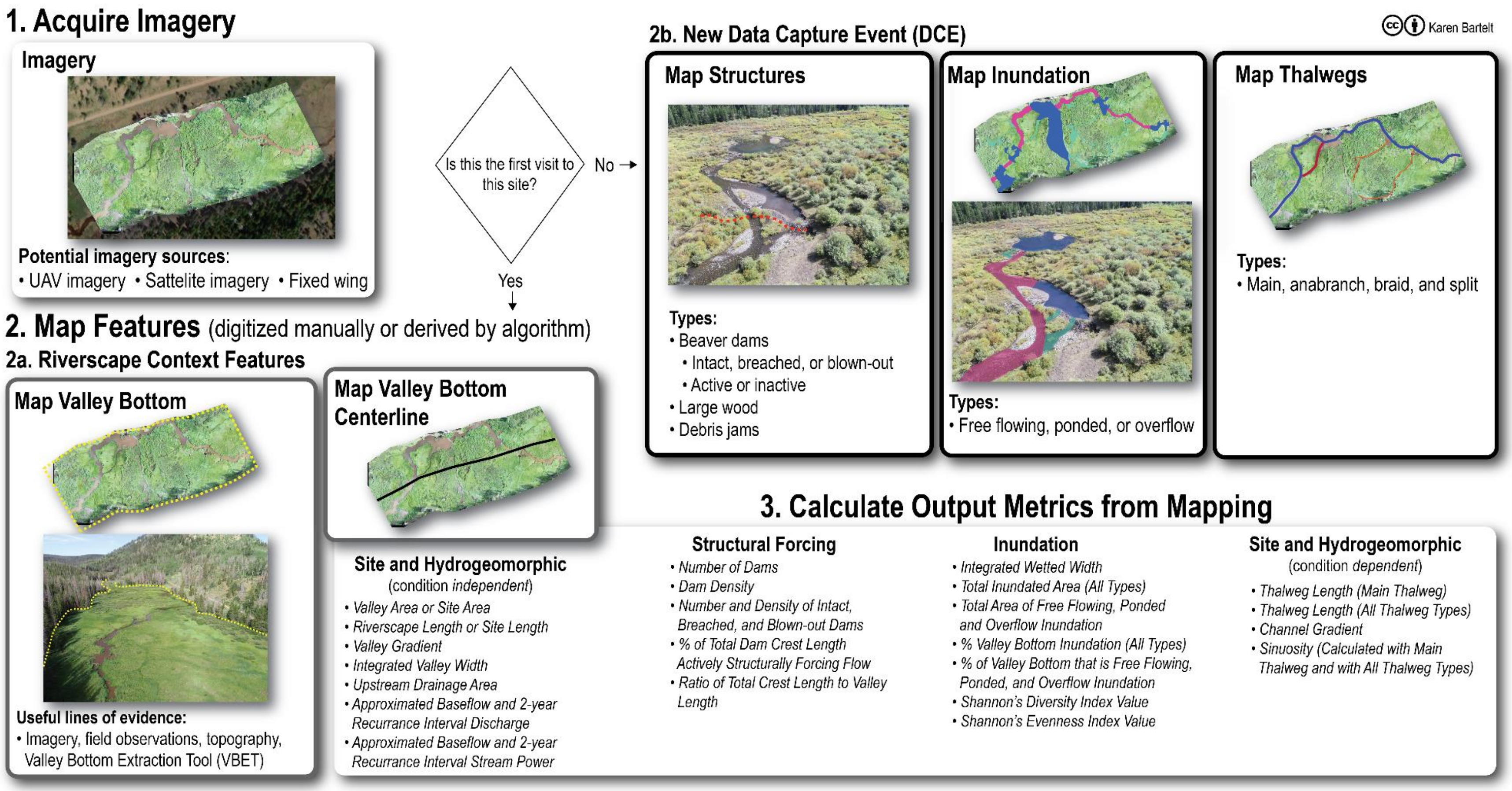


Figure 3. The sample design at each site can be broken into 3 main steps: imagery acquisition, mapping features, and metric calculation. After imagery was acquired (step 1), if it was the first survey at a site, we mapped the riverscape context features which are the valley bottom extent and valley bottom centerline (step 2a) and should not change between surveys. Next, and for any subsequent surveys when step 2a had already been completed, we mapped structures, inundation, and thalwegs (step 2b). Finally, summary metrics were calculated from the mapped features (step 3).

observations to refine estimates of the valley bottom margin that were derived using the Valley Bottom Extraction Tool (Gilbert et al., 2016) with inputs of channel position from National Hydrographic Dataset (NHD+ HR) and topography from National Elevation Dataset (NED) digital elevation models (DEMs). Although lateral valley bottom boundaries can plausibly expand through time (e.g., if a hillslope or terrace is eroded into by an active channel), we assumed here they are constant to establish a consistent basis for normalization. Next, we interpolated a valley bottom center line and used this to characterize valley bottom or site length. We then calculated integrated valley bottom width for the 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 meter buffer of the upstream and downstream end of the valley bottom centerline from NED DEMs, divided that difference by the site length (Macfarlane et al. (2015). To characterize site hydrology, we used approximated baseflow and 2 year recurrence interval discharge, and stream power from the Macfarlane et al. (2017) Beaver Restoration Assessment Tool (BRAT – http://brat.riverscapes.xyz) with inputs of channel position from NHD+HR, topography from NED, and USGS regional curves (Table 1).

Mapping and Attributing Structurally Forced Features

At each site, two or more surveys were performed from different imagery dates to represent at least one beaver dammed and undammed condition. For each available image (representing a distinct survey), we digitized features representing beaver dam activity and their hydraulic zone of influence at the time of survey (Shahveridan et al. 2019b). These features included dam crests, thalwegs, and inundation extent and type. This

Table 1. List of metrics used to characterize sites in terms of hydrogeomorphic, structural forcing and inundation.

Metric	Units
Site	
valley or site area	*m* ^{2}
Hydrogeomorphic	
integrated valley width	*m*
upstream drainage area	*km* ^{2}
baseflow discharge	*cfs*
2 year recurrance interval discharge	*cfs*
baseflow stream power	*watts*
2 year recurrance interval discharge	*cfs*
2 year recurrance interval stream power (watts)	*watts*
channel gradient	*dimensionless*
channel length	*m*
valley gradient	*dimensionless*
valley length or site length	*m*
sinuosity - main thalweg (calculated as the main thalweg length divided by the valley length)	*dimensionless*
Relative Flow Length (sum of all thalweg lengths divided by riverscape length)	*dimensionless*
percent of total thalweg length that is the main thalweg	*percent*
Structural Forcing	
number of dams	*count*
dam density	*dams/km*
number of intact dams	*count*
number of breached dams	*count*
number of blown out dams	*count*
ratio of dam crest length to the valley length (for all dams)	*dimensionless*
ratio of dam crest length to the valley length (for active dam crest length)	*dimensionless*
ratio of dam crest length to the valley length (for active dam crest length)	*dimensionless*
crstPctAct of dam crest length to the valley length (for intact dams)	*percent*
Inundation	
integrated wetted width	*m*
total inundated area	*m* ^{2}
total area of free flowing inundation	*m* ^{2}
total area of ponded inundation	*m* ^{2}
total area of overflow inundation	*m* ^{2}
percent of valley bottom that is inundated	*percent*
range of estimated percent valley bottom inundation when accounting for uncertainty	*percent - percent*
percent of valley bottom with free flowing inundation	*percent*
percent of valley bottom with ponded inundation	*percent*
percent of valley bottom with overflow inundation	*percent*
Shannon's Diversity Index Value	*dimensionless*
Shannon's Evenness Index Value	*dimensionless*

approach incorporates planimetric measures often described in the literature (e.g., Hafen et al. 2020). For consistency, all features were digitized in GIS at a map panel zoom of 1:250 and are described below. Additionally, UAV imagery collection provided an opportunity for a field visit to acquire visual evidence and verification of features, which were delineated and interpreted at the desktop after the visit.

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 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 (note, if topography is available, these dam crests should connect to cells of equal elevation on the digital elevation model at each end of the crest).

For each digitized dam crest, we determined two categorical attributes that together help characterize dam condition and beaver dam activity: dam state and crest type. 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. (2020). For the crest type attribute, we determined the length of the crest that was actively ponding flow at the time of the survey. Beaver dams are dynamic and can fluctuate in both physical dimensions and structural condition, which together help dictate the amount and nature of active structural forcing by the dam. Throughout its lifespan, a single beaver dam may transition between different structural conditions or dam states. Newly constructed or actively maintained dams tend to be characterized by an intact dam condition and fully maintain a pond upstream of the dam (Hafen, 2017). When beaver dams fail due to disturbances like high flow events, they may transition to a breached or blown out dam condition, characterized by a less extensive backwater influence and lower water surface elevation. They typically remain in this condition until further damaged, fully removed, or repaired by beaver (Hafen, 2017; Welsh, 2012). Many unmaintained beaver dams that are intact, can also have lower water levels behind them and subsequently less extensive backwater influences.

From the digitized dam crests and associated attributes, we derived a variety metrics to characterize structural forcing including the total number of dams and the percent of total dam crest length that was active crest type. Of the derived metrics we used five that were normalized by valley bottom length or area to characterize the degree of structural forcing for intersite comparison: percent of BRAT-estimated dam capacity realized, linear dam density, dam density by area, a ratio of total active dam crest length to riverscape length, and the total active dam crest length divided by riverscape area.

MAPPING THALWEGS

The hydrogeomorphic attributes we described above under Site Characterization 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 four thalweg types adapted from the Kramer-Anderson et al. (2020) Geomorphic Unit Tool (GUT - http://gut.riverscapes.xyz/); main, anabranch, split, and braid.

- **Main** – the thalweg that follows the deepest point of the primary anabranch.

- **Anabranch** – thalwegs that follow the deepest point of a fully formed (i.e., has an active channel bed) secondary anabranch that is longer than 2 bankfull channel widths. These begin at difluences from the main thalweg, and rejoin the main at downstream confluences.
- **Split** – thalwegs that follow the deepest point of structurally forced difluences around structural elements (e.g. boulders, mid-channel woody jams, remnant beaver dams, etc.).
- **Braid –** thalwegs within the primary anabranch that are not the main thalweg and are not structurally forced by large wood or beaver dams. These typically depart at diffluences around mid-channel bars and return from the main thalweg or an anabranch thalweg and were mostly observed in the larger classic and floodplain sites.

We used the main thalweg to calculate the channel gradient with the same method used to calculate valley gradient above (Macfarlane et al., 2015). To characterize planform changes, we calculated metrics based on the thalweg lengths and type. We calculated relative flow length by dividing the total thalweg length by the valley bottom length. We also calculated the percent of total thalweg length that is the main thalweg, and the sinuosity of the main thalweg.

MAPPING INUNDATION

For each survey, we mapped inundation by digitizing a polygon around the wetted edge visible in the aerial imagery. The relatively high zoom level (1:250) was chosen because the resolution of the imagery was high enough to support mapping at this scale, but it also was broad enough to visualize most of the channel width or ponds. We inferred between visible boundaries where vegetation or shadows obscured the water's edge. We estimated inundation area uncertainty for each survey based on the resolution of the imagery used to digitize survey features. These were used to derive two buffered polygons representing an upper and lower bound on the maximum and minimum proportion of the valley bottom that was inundated.

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). We defined these classes in Figure 4 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. Burchsted and Daniels, 2014; Laurel and Wohl, 2019). Because these classes are visually identifiable, they have the potential to have identifiable spectral signatures and be derived through a supervised classification with remote sensing (e.g. Carbonneau et al., 2020). However, for this study and initial reporting we did not want to introduce additional methodological uncertainties, and first wanted to explore the existence and ease of discriminating these classes through manual classification and digitization. The free flowing class could be broken further into uniform, convergent, divergent, eddy and wake classes for studies more focused on in-

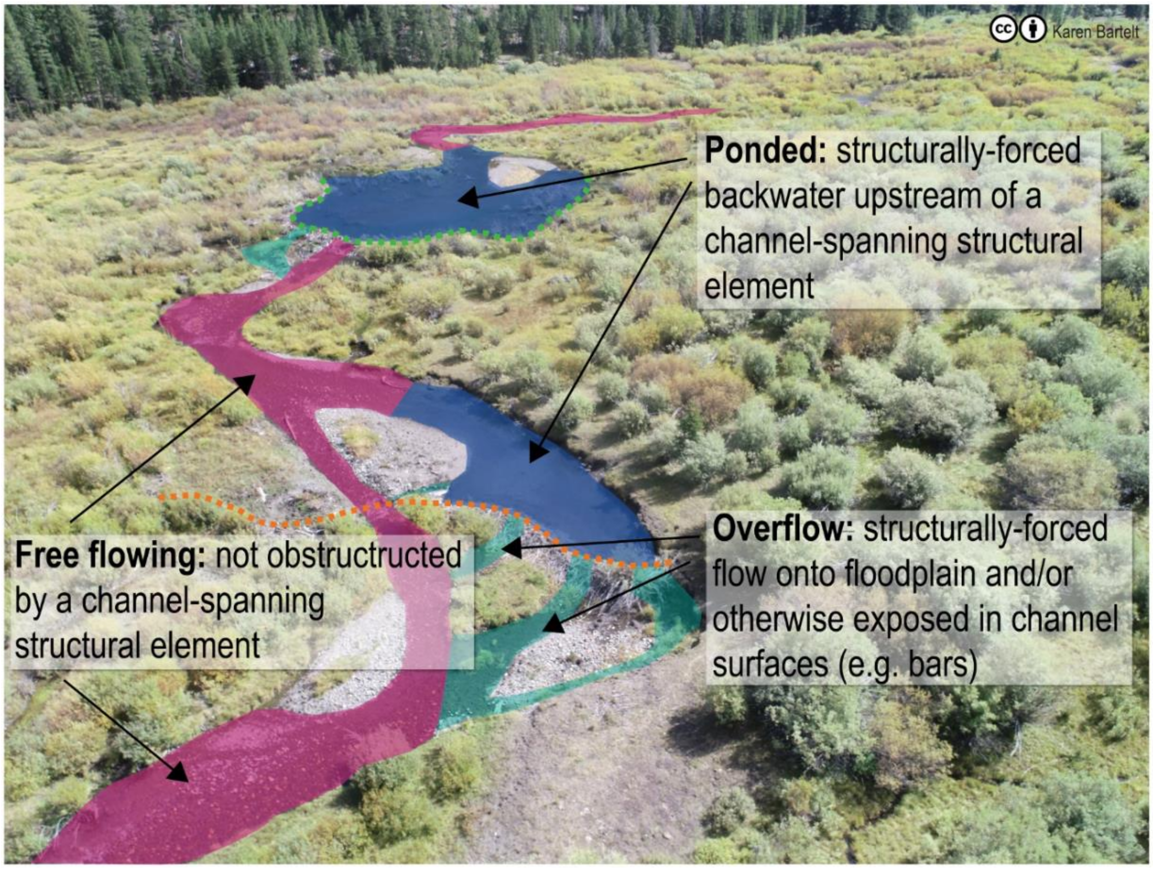


Figure 4. The definition and an example of each inundation type. The short-dashed lines represent dam crests, and the color represents the dam state (the upstream dam is intact and shown in green, the downstream dam is breached and shown in orange).

channel impacts of structural forcing. This might help discriminate impacts of other types of structural forcing or planform forcing on hydraulics but was not deemed necessary for the purpose of this study focused on beaver dam activity.

Once the inundation types were classified, we used these data to derive the area of total area of each first-tier inundation type. We then divided the inundated area by the valley bottom area to derive the percent of total inundation and each inundation type, providing a normalized measure of inundation to facilitate intersite comparison. We estimated the integrated wetted width by dividing the total inundated area by the valley bottom length. To characterize the diversity of inundation types we calculated the

Shannon's Evenness Index (also referred to as Shannon Equitability or Shannon Evenness) value for each survey, a metric often used to describe spatial heterogeneity (e.g., Laurel and Wohl, 2019; Wyrick and Pasternack, 2014). The Shannon's Evenness Index value was calculated as follows:

$$SHEI = \frac{-\sum_{i=1}^{m}(P_i * lnP_i)}{\ln m}$$

Where P_i is equal to the proportion of the valley bottom occupied by each inundation type i and m is equal to the number of inundation types present in the valley bottom. In this case m was equal to four to include the three inundation types (free flowing, ponded, overflow), and dry.

Algorithms, Tools & Data Management

This workflow and the algorithms were packaged into an open-source, Riverscapes-Compliant, research-grade tool with a mix of Python, ArcPy, and R scripts in a tool we call RIM (Riverscape Inundation Mapper: http://rim.riverscapes.xyz). A protocol is available online (RIM - https://riverscapes.github.io/inundation/Documentation/). All the data from each site analysis is packaged into a Riverscapes-Compliant riverscapes project (https://riverscapes.xyz/Tools/Technical_Reference/Documentation_Standards/Riverscapes_Projects/), available from a Riverscapes Warehouse (http://data.riverscapes.xyz. The data from each site can be downloaded, visualized, and explored into ArcMap using RAVE (http://rave.riverscapes.xyz/).

Site Selection

Our overall survey design aimed to sample across a broad hydrogeomorphic and physiographic range of riverscapes throughout the Intermountain West. We conducted 77 surveys at 37 sites in 11 watersheds (Figure 5). For each site, at least two surveys were conducted: a current condition or dammed survey, and an approximated undammed condition survey. Undammed condition was based on pre-existing satellite imagery (typically within last decade) and evidence from undammed portions of the riverscape located upstream or downstream of the site.

We selected seventeen sites that fit the classic setting from Figure 2 as well as ten sites each from the steep and floodplain settings. The sites cover a range of valley widths, gradient, and locations within the drainage network, and varying degrees of active structural forcing from beaver dam activity (Table 2). Site lengths range from 30 – 500 meters to cover the full longitudinal extent of local beaver dam impacts. In general, the "floodplain" sites had wider valley bottoms on average (μ = 220 m) than classic (μ = 77 m) and steep (μ = 40 m) sites. 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 6.0% valley gradient and tended to have smaller upstream drainage areas (μ= 10.5 km2) then classic (μ= 51.4 km^2). "Floodplain" sites tended to be supported by bigger rivers and thus had the highest upstream drainage area (μ= 102.1 km^2), approximated Q2 flow magnitude (μ= 202.4 cfs), and approximated Q2 stream power magnitude (μ= 686 watts/m).

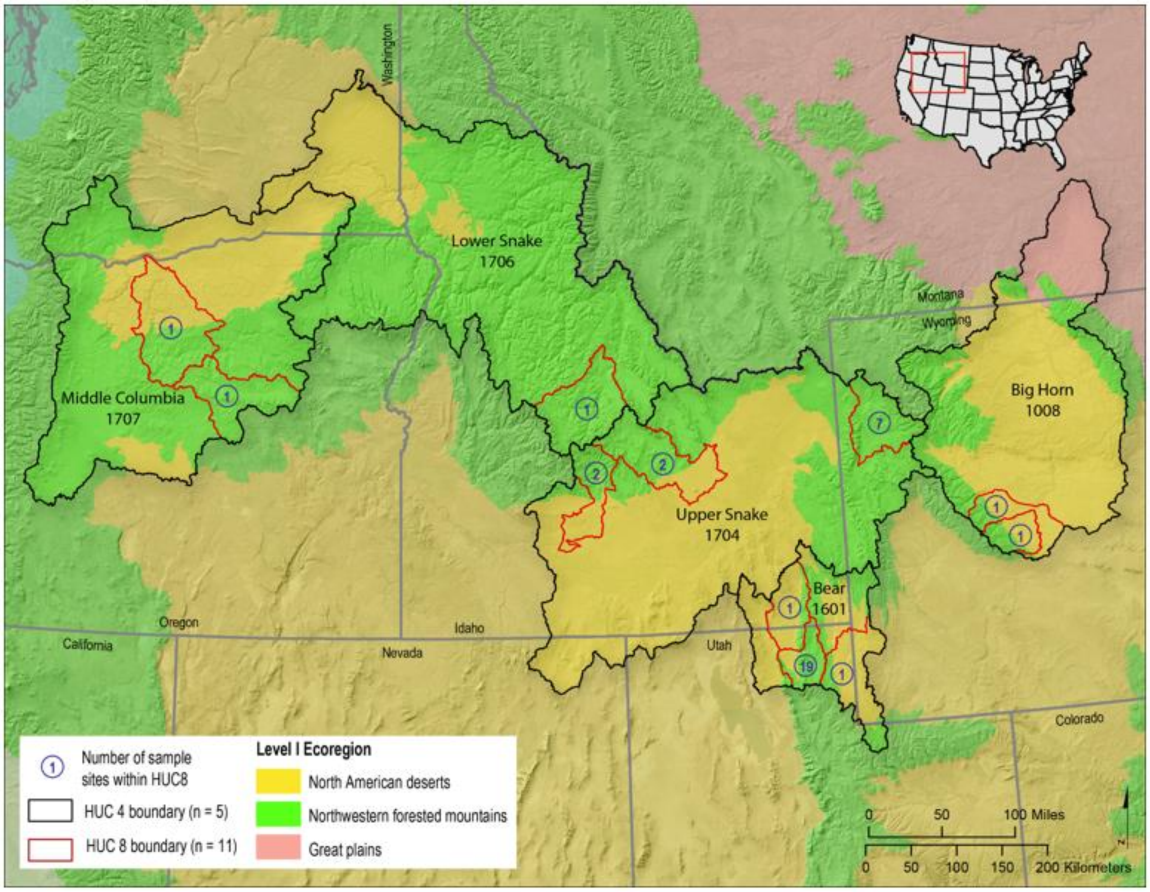
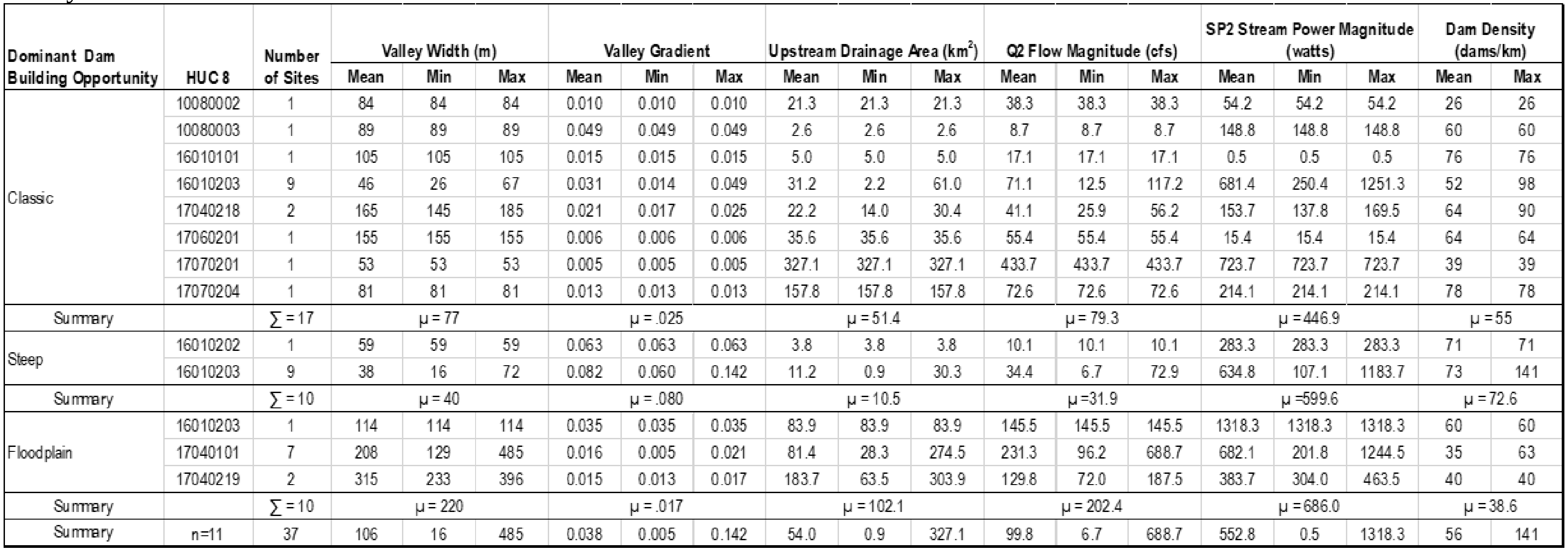


Figure 5. Location of HUC 4 (black) and HUC 8 (red) watersheds with the number of study sites (blue circles) located in each. In total we conducted surveys at 37 sites in 11 different watersheds that span 3 different level 1 ecoregions (symbolized by color).

Table 2. The 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, and so dam density was calculated using only the dammed condition surveys.



Dominant Dam Building Opportunity	HUC 8	Number of Sites	Valley Width (m)			Valley Gradient			Upstream Drainage Area (km^2)			Q2 Flow Magnitude (cfs)			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	38.3	38.3	54.2	54.2	54.2	26	26
	10080003	1	89	89	89	0.049	0.049	0.049	2.6	2.6	2.6	8.7	8.7	8.7	148.8	148.8	148.8	60	60
	16010101	1	105	105	105	0.015	0.015	0.015	5.0	5.0	5.0	17.1	17.1	17.1	0.5	0.5	0.5	76	76
	16010203	9	46	26	67	0.031	0.014	0.049	31.2	2.2	61.0	71.1	12.5	117.2	681.4	250.4	1251.3	52	98
	17040218	2	165	145	185	0.021	0.017	0.025	22.2	14.0	30.4	41.1	25.9	56.2	153.7	137.8	169.5	64	90
	17060201	1	155	155	155	0.006	0.006	0.006	35.6	35.6	35.6	55.4	55.4	55.4	15.4	15.4	15.4	64	64
	17070201	1	53	53	53	0.005	0.005	0.005	327.1	327.1	327.1	433.7	433.7	433.7	723.7	723.7	723.7	39	39
	17070204	1	81	81	81	0.013	0.013	0.013	157.8	157.8	157.8	72.6	72.6	72.6	214.1	214.1	214.1	78	78
Summary		∑ = 17	μ = 77			μ = .025			μ = 51.4			μ = 79.3			μ = 446.9			μ = 55	
Steep	16010202	1	59	59	59	0.063	0.063	0.063	3.8	3.8	3.8	10.1	10.1	10.1	283.3	283.3	283.3	71	71
	16010203	9	38	16	72	0.082	0.060	0.142	11.2	0.9	30.3	34.4	6.7	72.9	634.8	107.1	1183.7	73	141
Summary		∑ = 10	μ = 40			μ = .080			μ = 10.5			μ =31.9			μ =599.6			μ = 72.6	
Floodplain	16010203	1	114	114	114	0.035	0.035	0.035	83.9	83.9	83.9	145.5	145.5	145.5	1318.3	1318.3	1318.3	60	60
	17040101	7	208	129	485	0.016	0.005	0.021	81.4	28.3	274.5	231.3	96.2	688.7	682.1	201.8	1244.5	35	63
	17040219	2	315	233	396	0.015	0.013	0.017	183.7	63.5	303.9	129.8	72.0	187.5	383.7	304.0	463.5	40	40
Summary		∑ = 10	μ = 220			μ = .017			μ = 102.1			μ = 202.4			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	6.7	688.7	552.8	0.5	1318.3	56	141

RESULTS

Results are shown first at an individual site to illustrate the mapping available at all 37 sites, and highlight a typical example of the impacts of structural forcing on inundation patterns. We then report the summary results across all sites. Detailed results for all surveys and sites are located in Appendix B – Site Specific Results, and schematic summaries are shown in Appendix C. Finally, we discuss the evaluation of hypotheses H_1 and H_2.

Example of Site-Specific Results

Figure 6 shows the low flow undammed and dammed surveys within a ~260 m riverscape segment of one of the classic sites we surveyed in the Uintah Mountains of Utah near the Wyoming border. 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, we observed evidence of old beaver dams, some of which were actively ponding water at the time of the survey and others that were not. In addition to sometimes backing up water, these old dams left other physical imprints to the valley bottom such as lines of willow extending across the valley bottom, 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 the 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, we did not observe other significant or potential sources of structural forcing (e.g., large wood recruitment, boulders, etc.) within this site.

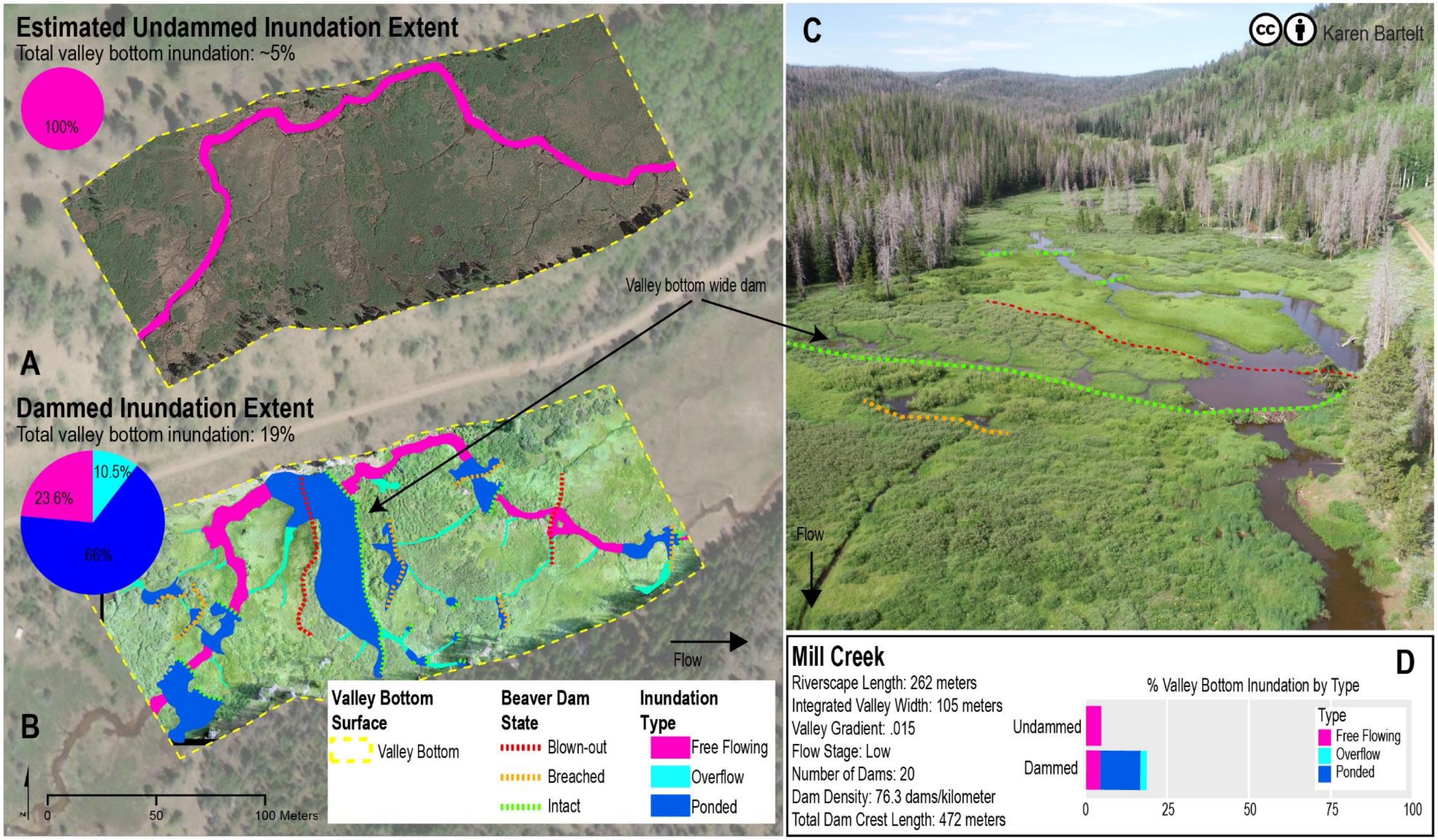


Figure 6. The previous page shows an example of riverscape inundation mapping results for an undammed survey (A) and a dammed survey (B) data capture events. The oblique photo in (C) was taken during the imagery collection. The valley-wide dam shown in the center of the August 2019 survey on the left panel can be seen in the center of the right panel looking upstream.

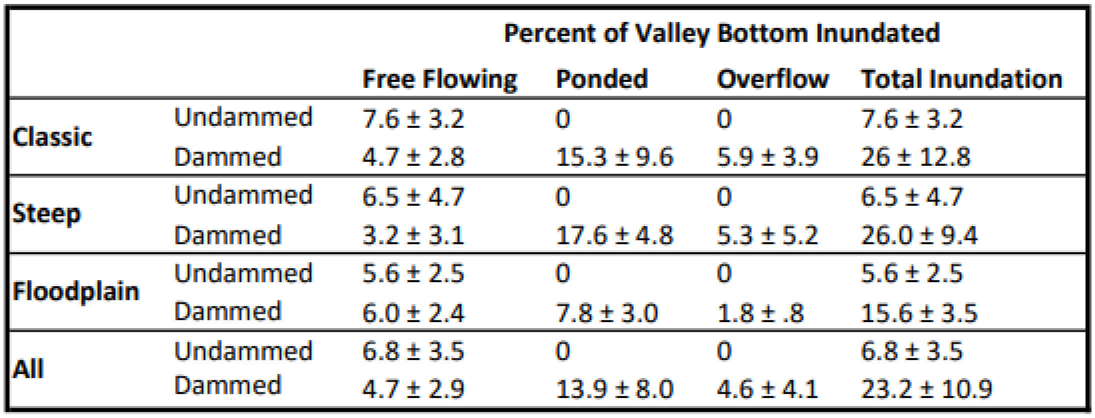
The undammed survey (Figure 6A) shows that at low flow without dams, Mill Creek's inundation is contained entirely within a single active free flowing primary channel (integrated wetted width = 3.5 m). The inundated area was measured to be 1281 ± 455 m^2, or 4.7% of the valley bottom (Figure 6A & D). In the dammed survey (Figure 6B & C) that was conducted using imagery acquired in August 2019, there were twenty beaver dams (dam density = 76.3 dams/km of riverscape) 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 (Figure 6D). Beaver dams caused the total thalweg length to double because of addition of anabranches and areas of split flow.

In the case of Mill Creek, a single valley bottom-wide dam forced multiple areas of overflow as sheetflow and secondary channels (Figure 6). This dam alone led to 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.

Summary Inundation Results

We used the Mill Creek site as an example of the impacts of structural forcing with imagery provided as context. We visually simplify these results into riverscape inundation schematics across the rest of the sites by portraying the inundation extent and type without the imagery, but with context of valley bottom (Figure 7 & Figure 8; see Appendix C for complete results). In total we conducted 77 surveys at 37 sites. We mapped 628 dams (368 intact, 232 breached, 37 blown out) over 23.5 kilometers of riverscape length. The schematics consistently point to increases in inundation extent, diversity of inundation type, and relative flow length increased relative to the undammed condition across all settings (see Appendix B for full results by site).   Table 3 summarizes this contrast between undammed and undammed sites by flow type and total inundation across the different settings.

T**able 3.** The average percent of the valley bottom inundated by flow type (columns) for each of the three distinctive beaver dam building settings (rows).



		Percent of Valley Bottom Inundated			
		Free Flowing	**Ponded**	**Overflow**	**Total Inundation**
Classic	Undammed	7.6 ± 3.2	0	0	7.6 ± 3.2
	Dammed	4.7 ± 2.8	15.3 ± 9.6	5.9 ± 3.9	26 ± 12.8
Steep	Undammed	6.5 ± 4.7	0	0	6.5 ± 4.7
	Dammed	3.2 ± 3.1	17.6 ± 4.8	5.3 ± 5.2	26.0 ± 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

For dammed surveys, the total inundated area mapped was 250,233 ± 27,256 m^2, representing on average 23.2% of valley bottom area. By contrast, for the total inundated area mapped for baseflow conditions in undammed sites was 92,107± 55,600 m^2, representing on average 6.8% of valley bottom area.

The increase in average percent valley bottom inundation from an average of 6.8% in undammed to 23.2% in dammed was significant (Table 3 and Figure 9, $P < 0.0001$). Although the total surface area of free-flow inundation generally decreased from

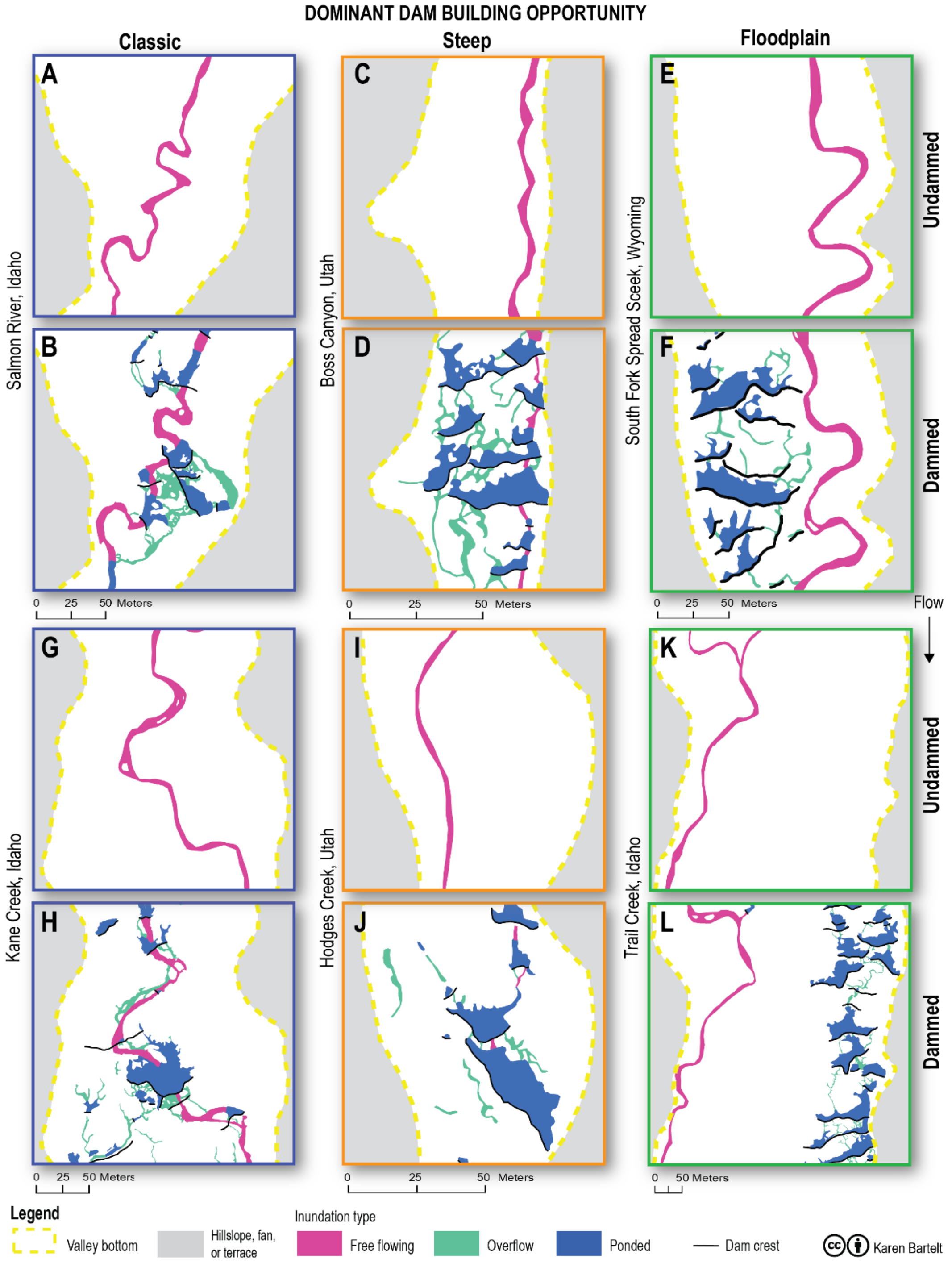


Figure 7. The previous page shows an example of inundation mapping results across 6 of 37 sites (see Appendix B – Site Specific Results for remaining sites). The columns are organized by dominant dam building opportunity (classic, steep, and floodplain) and the rows alternate showing the undammed and dammed survey from each site.

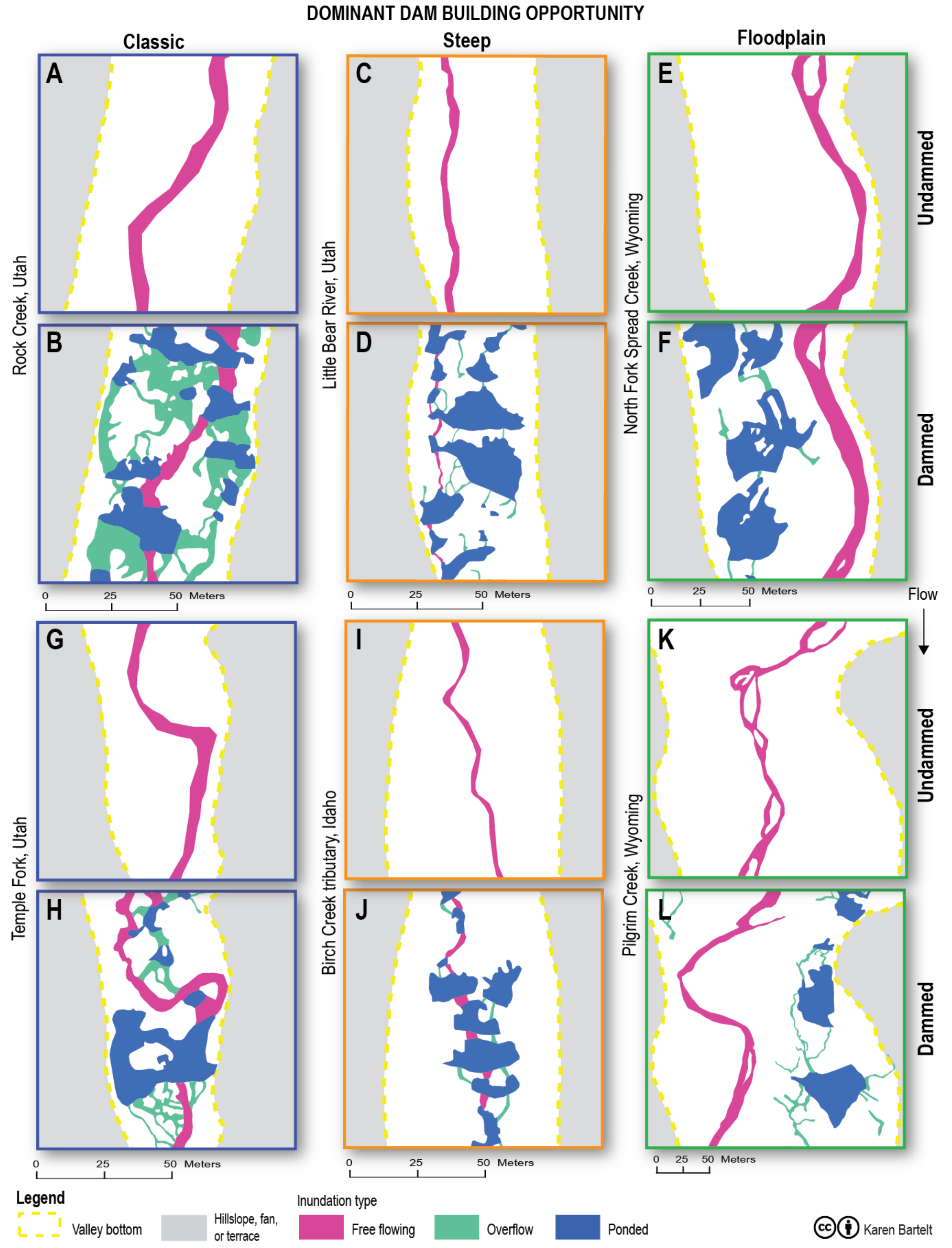


Figure 8. The previous page shows an example of inundation mapping results across 6 of 37 sites (see Appendix B – Site Specific Results for the remaining sites). The columns are organized by dominant dam building opportunity (classic, steep, and floodplain) and the rows alternate showing the undammed and dammed survey from each site.

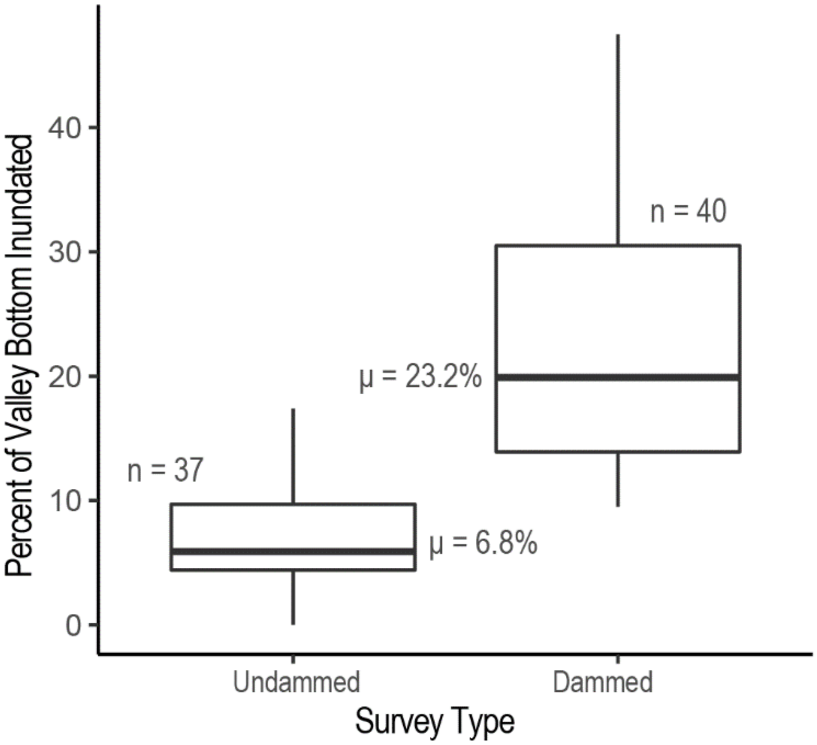


Figure 9. Boxplot of percent valley bottom inundation in undammed and dammed surveys. The lower extent of the boxplots represents the bottom quartile (25%), the line represents the median, and the upper extent of the box represents the upper quartile (75%). The whiskers extend to the minimum and maximum values (all within 1.5 interquartile range).

the approximated undammed to the dammed condition (except in floodplain sites; Table 3), additional ponded and overflow inundated area increased such that the total extent of inundation increased on average by over 400%.

Changes to the diversity of inundation types was reflected in an increase of the average Shannon's Evenness value from 0.17 in the undammed surveys to 0.51 in the dammed condition (Figure 10A) with respective standard deviation values of 0.07 and 0.16. For the dammed surveys, we mapped 80,072 m^2 of free flowing inundation (52% of total), 129,265 m^2 of ponded inundation (32% of total), and 40,896 m^2 of overflow inundation (16% of total).

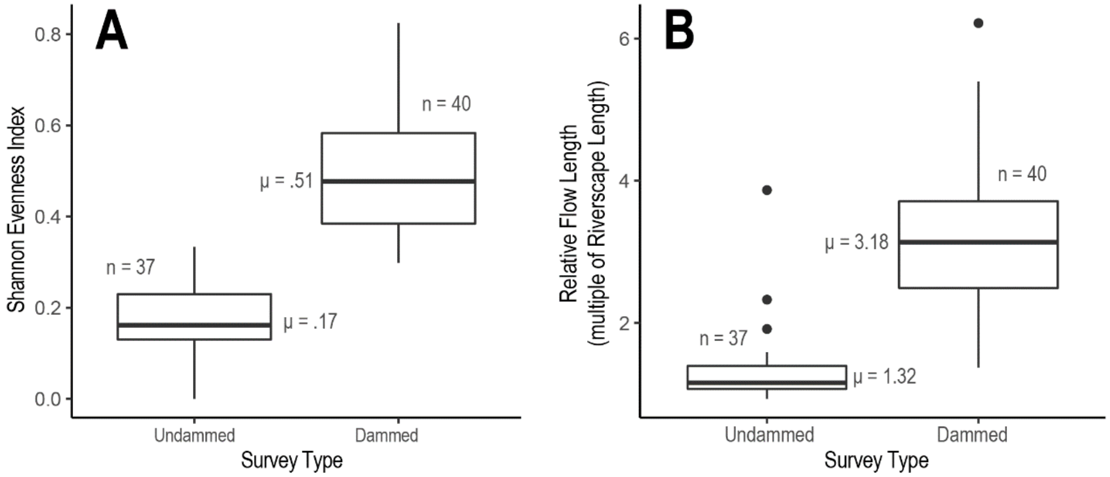


Figure 10. A) Shannon's Evenness Index value calculated for undammed and dammed surveys. B) Relative flow length calculated as the total length of thalwegs divided by the valley length for undammed and dammed surveys. The box represents the 25, median, and 75%. The whiskers extend to a maximum of 1.5 interquartile range, and outliers are represented by points.

Relative flow length increased from a mean value of 1.32 with a standard deviation of 0.51 for the undammed surveys to 3.18 with a standard deviation value of 1.11 in the dammed surveys (Figure 10B). This increase partly reflects the splitting of flow into additional anabranches around vegetated islands (i.e., anastamosting) but 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.

In general, the results were consistent across the three beaver dam building opportunity settings, but we did observe some differences. Some of these variations are difficult to discriminate quantitatively from our derived metrics but can be visually observed and are worth describing. As illustrated in the four floodplain sites in Figure 7F

& L and F & L, no dams and no ponding occurred on the primary anabranch. In contrast to the classic (e.g., Figure 7B & H and B & H) and “steep” sites (e.g., Figure 7D & J and Figure 8D & J) where dams almost always occur on the primary anabranch, 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). Instead, we saw an increase in the total inundated area because of additional ponded and overflow inundation taking place on the floodplain. We also observed that floodplain dams were less often breached or blown out than dams in classic and steep sites.

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. Brazier et al., 2021; Wheaton et al., 2019)). Smaller, “secondary” dams were located upstream or downstream of the primary dam, often on secondary anabranches (Figure 6B Figure 7B & H and Figure 8B & H) The primary dams are typically the site of the main lodge for the colony, whereas the presence of secondary dams as well as canals laterally reflect beaver dam activity literally flooding their way to additional forage and building materials (Brazier et al., 2021). In contrast to this primary-secondary dam configuration, dams in the “steep” dam building opportunity sites were more often characterized by a series of equally large, often valley-bottom-wide (Figure 7D and Figure 8D) or nearly valley-bottom-wide dams (Figure 7J and Figure 8J) all located on the primary anabranch. Almost by definition, the “floodplain” sites do not have valley-bottom-wide dams, because dams are not build across them main channel.

Hypothesis Testing

To test H_1 we evaluated the relationship between the degree of structural forcing by beaver dams at the time of the survey and the total percent of valley bottom inundation, the diversity of inundation type, and relative flow length for all the dammed surveys. We were not able to identify a metric capturing degree of structural forcing by beaver dams that adequately predicted inundation extent, inundation type, or relative flow length for our dataset (See Appendix C – Summary Results, for R, R^2 and p values for each relationship). The total active dam crest length divided by the riverscape area showed the strongest correlation with the percent of the valley bottom inundated with an R^2 value of 0.32 (Figure 11A), but we did not think this relationship warranted the support of H_1 without further analysis. Figure 11 shows the relationship between the two measurements we used to characterize structural forcing by beaver dams that most correlated with the percent of valley bottom inundation; total length of active dam crest divided by valley area (Figure 11A) and dam density by area (Figure 11B). We attribute this lack of a clear link between the metrics that we tested to be an indication that the relationship between structural forcing and inundation patterns is just not simple enough to be captured by a univariate model. Therefore, the results of this study did not support H_1. However, the results demonstrate strong differences between the undammed and dammed survey at each site, regardless of the degree to which structural forcing was present during the dammed survey.

Contrary to H_2, we observed that similarly to the classic settings, steep and floodplain settings (Figure 2) also showed an increase in inundation extent, inundation type diversity, and relative flow length in the dammed surveys relative to the undammed surveys (Figure 12). At first glance, the increase in percent total low flow valley bottom inundation appears to be less pronounced in the floodplain setting (Figure 12C).

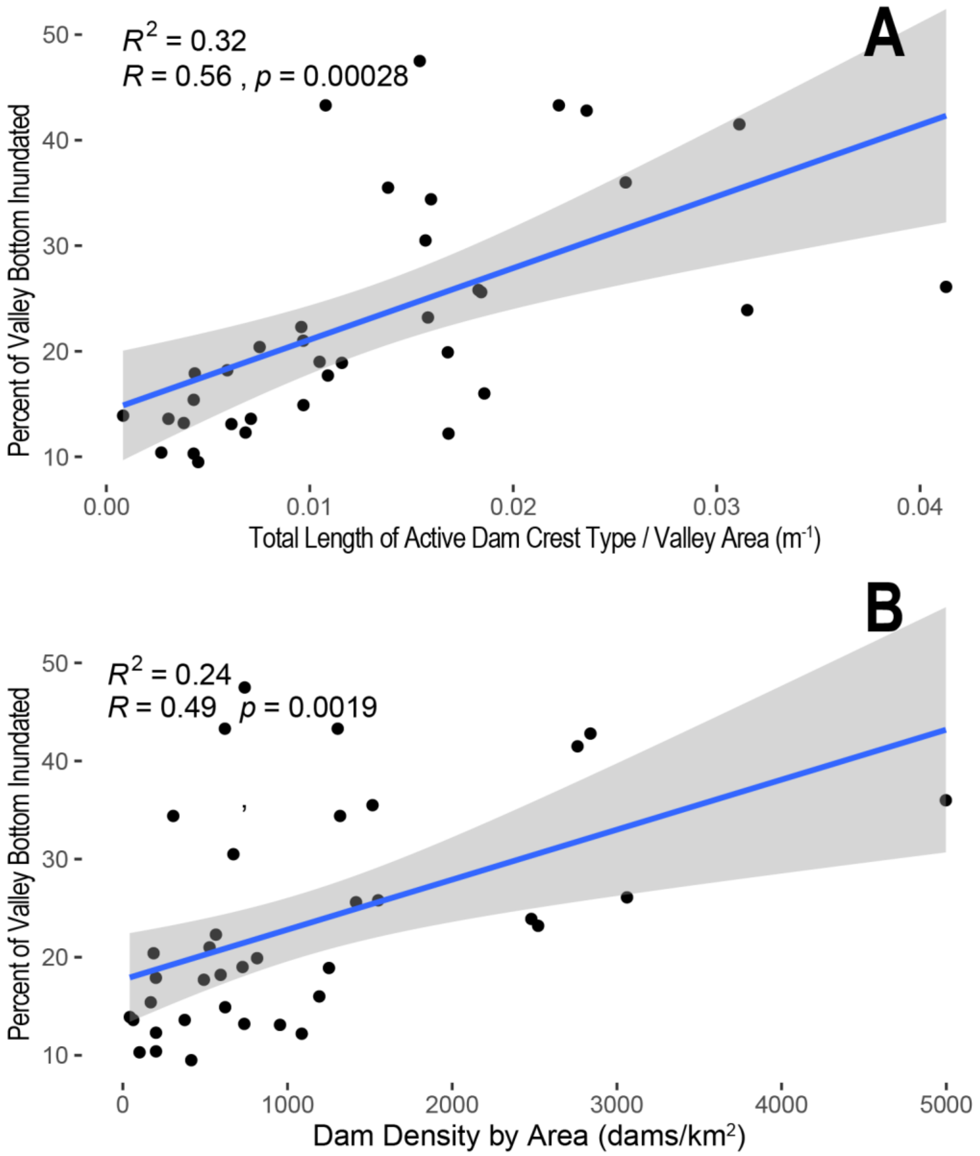


Figure 11. Examples of weak, positive relationships with linear regression between response variable of percent of valley bottom inundated (Y-axis) and two measures of degree of structural forcing by beaver (x-axis). For a) this was based on total length of active dam crest divided by valley area and b) on areal dam density.

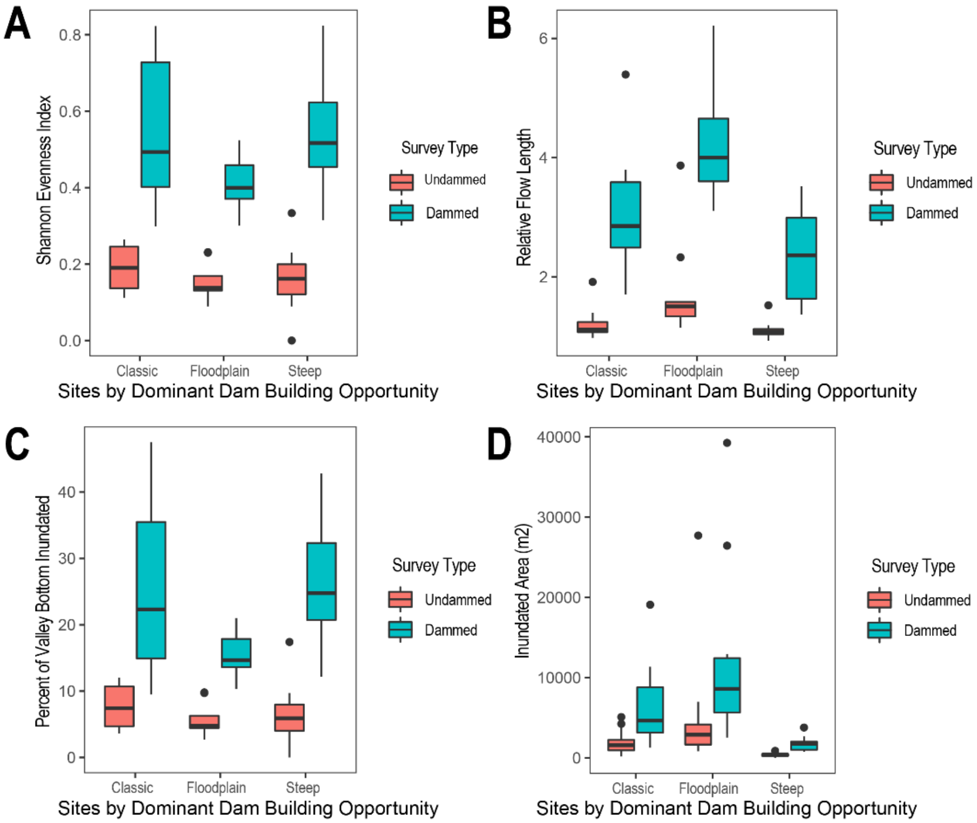


Figure 12. A) Shannon's evenness calculated for undammed and dammed surveys grouped by setting. B) Sinuosity for undammed and dammed surveys grouped by setting C) Total percent valley bottom inundation in undammed and dammed surveys grouped by setting D) Total inundated area (m2) of valley bottom inundation in undammed and dammed surveys grouped by setting.

However, when comparing the increase in total valley bottom inundation as the aerial increase rather than the increase expressed as a proportion of the total valley bottom area, the increase in total inundated area is actually most pronounced in the floodplain setting (Figure 12D).

DISCUSSION

The results described here support and expand the findings of previous literature. Westbrook et al. (2006) 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 recent review by Larsen et al. (2020) 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. We observed an increase of low flow inundation extent at over 37 beaver dam complexes, corroborating and expanding past findings across a larger number of sites and a wide range of physiographic settings. The mapping and proportions of inundation types in dammed surveys provides a visual demonstration and quantification of what previous studies (e.g., Burchsted and Daniels, 2014; Bush and Wissinger, 2016) describe as a conversion of a mostly lotic environment to a mosaic of alternating lotic-lentic environments. The distribution of dam states that we mapped (368 intact, 232 breached, 37 blown out) supports conceptual models that highlight the dynamic nature of beaver dams (e.g., Johnson, 2018; Naiman et al., 1988) and studies that distinguish between different dam types and dam condition (e.g., Burchsted and Daniels, 2014; Hafen et al., 2020; Woo and Waddington, 1990). We observed a range of dam configurations and characteristics, with some end-member observations that stood out in the floodplain and steep settings that we evaluated. For example, consistent with what is suggested by the BRAT model, the lack of dams on the main anabranch of floodplain sites is likely a result of flood stream power magnitudes that are too high for dams to persist at higher flows. Also, the fact that floodplain dams were infrequently breached or blown-out makes sense based on the characterization of floodplain dams by Bush and Wissinger (2016) who noted that these dams are not as regularly impacted by main stem floods events. From a unit stream power perspective, the same high flow stream power is being spread out over a larger area with the structural forcing on floodplain surfaces, hence likely dissipating the energy acting on any single dam. Dams in steep settings were often taller and at higher dam densities than classic or floodplain dams. Presumably because steep valleys are typically also narrower, dams tended to occur in a string of pearls configuration as a series of consecutive, large dams rather than the primary/secondary dam configuration that we more commonly observed in classic sites.

Contrary to our second hypothesis, the results showed that beaver dams significantly impact inundation patterns in the floodplain of large, high-order rivers and in steep valley bottoms with gradients over 6%. These observations support the assertion and inclusion of steep riverscapes in the BRAT beaver dam capacity model by Macfarlane et al. (2015) and indicate that the role of beaver dams is also important in steep and floodplain settings. We hypothesize that the reason that these settings are less studied in beaver dam literature is essentially a result of biased dam sampling in early beaver dam censusing studies (e.g., Allen, 1983; Beier and Barrett, 1987; Howard and Larson, 1985; Petro et al., 2015). Such studies were potentially biased because so many riverscapes were already in a degraded state and/or far below carrying capacity at the time of sampling. Essentially, the collective, initial understanding of where beaver build dams likely comes from surveys of riverscapes with unnaturally low beaver dam capacity and density which can be explained by looking at river management history including but also extending beyond the widespread removal of beaver dams and near extirpation of beaver. Land use and degradation has been particularly concentrated in floodplain settings. By the time early dam censuses were conducted, much of the nutrient rich floodplains of major rivers had already been converted for agricultural use and thus, fewer dams were observed there. Moreover, if beaver populations in floodplain systems are below capacity, and easy bank lodging opportunities exist on the deeper main channels, there is less of a need for beaver to spill over and build dams in these floodplain areas. A similar argument can be made for land use in the steep setting and a lack of beaver dams present here during dam census studies. Firstly, these steep riverscapes were heavily impacted by logging practices and grazing. Heavy wood removal would limit food and building material and thus reduce the suitability of these areas for beaver and the likelihood of beaver occupation. Secondly, we have observed that we frequently see high degrees of beaver dam activity in steep settings when they are a tributary to a classic, “feeder” riverscape that has reached carrying capacity for beaver dams. Given what we know about the history of beaver trapping and the near extirpation of beaver, it is logical that steep settings may have been some of the earliest abandoned riverscapes because beaver dam density decreased everywhere, including adjacent classic riverscapes that we observed to be “feeders” to the steep tributaries. Appendix B demonstrates how much the distribution of riverscape settings where beaver can build dams can vary by watershed.

Merits of Framework and Study

Perhaps the most significant contribution here is the pragmatic feasibility of implementation of our proposed methodology. The method provides a clear and tractable starting point to contextualize hydrologic, geomorphic, and ecological effects of beaver dam activity. More direct monitoring of hydrologic, geomorphic and ecological processes and responses are typically limited to small site numbers and spatial extents due to feasibility. At the core of the method are a set of indicators that are tied to the findings of previous beaver dam literature. Depending on the precision deemed “necessary”, a variety of protocols could be developed to arrive at these indicator values. Here, we used relatively high-precision and resolution (2 cm) UAV imagery, which could be acquired rapidly as the basemap for the map digitization to then derive the metrics from those polyline and polygon geometries for quantifying these metrics. For the specific methods used in this study, the site visit and imagery collection for each site took about 1 hour excluding travel time. The desktop mapping portion of the workflow took anywhere from 1 – 5 hours depending on site size and complexity, making the methodology time and cost effective. More precise (and laborious) methods or less precise (and more rapid) methods could be employed to produce similar results. Our results revealed very dramatic differences between proportion of valley bottom inundated in dammed and undammed surveys at the same low flows, which could have been detected with less precise methods. For example, from a change detection perspective, simple ocular estimates of proportion of the valley bottom inundated could probably have been estimated to plus or minus 5% to 10% accuracy. Similarly, the proportions of flow types could likely have been estimated between the three classes to +/- 10% to 20%. If we rely on map-based digitizing or field surveying of polygon features, the framework proposed can be replicated from a desktop using relatively coarse, freely available imagery and datasets of lower resolution, or higher resolution commercial satellite imagery or survey-grade ortho-photo mapping from fixed wing or commercial-grade UAV.

Inundation patterns as a proxy, and other future work

While we did not directly quantify hydrologic inefficiency by measuring water residence time, we propose that there is a sound conceptual basis for using inundation type and extent as a proxy for the inefficiency principle of riverscape health (**Figure 1**) which is described above prior to the methods section. The use of ponded, overflow, and free flowing as the delineated inundation types is based on known physical changes that occur in the ponds and overflow channels that dams create. We demonstrated that increased inundation extent occurs where dams create a more diverse portfolio of inundation types in the valley bottom. We postulate (but have not definitively shown here) that this diversified distribution of inundation types is a proxy for more variable and overall longer water residence times where water remains on the landscape longer as transient water storage. Without a direct form of structural forcing pushing water out of the channel and onto the floodplain, the more diverse inundation types and the increase in low flow inundation extent does not occur (i.e., free flowing, hydrologically efficient). While subsurface changes like hyporheic pathways and increased infiltration to groundwater cannot be mapped with this method, they also contribute to an increase in water residence times and transient water storage and are likely crudely correlated with surface water inundation patterns.

Beyond implications directly related to surface inundation patterns and hydrologic inefficiency, this research presents a jumping off point to better understand and quantify the effect of beaver dams at the riverscape scale. Future work could be done to:

a) Evaluate quantitative relationships between the inundation types mapped and other physical processes and characteristics. Inundation patterns would have obvious implications for local hydraulics, hydrology, geomorphology, ecology, and biogeochemistry.

b) Use this method and the relationships in (a) to predict watershed scale impacts of beaver dams based on our knowledge of where beaver dams are likely to occur.

As a preview of future work that could be done to more concretely establish the use of inundation patterns as proxies for other stream characteristics such as hydrologic inefficiency, we conducted a preliminary evaluation of the depth and velocity distribution associated with each inundation type. We compared the results of inundation mapping and a 2D hydraulic model reported in Nahorniak et al. (2018) and produced from CHaMP – (Columbia Habitat Monitoring Program (Bouwes, 2014)) for a stream reach on Bridge Creek, Oregon. We overlaid the inundation mapping results over the hydraulic model results and extracted the distribution of depth and velocity values for each inundation type. We observed some initial patterns in the depth and velocity distributions represented by the three different inundation types. Ponded inundated areas tended to have lower velocity and higher depth magnitudes than free flowing and overflow inundation (Figure 13B and Figure 13C). In this particular survey, overflow areas tended to be the most shallow inundation type but had a wide range of velocities (Figure 13B and Figure 13C). It is readily tractable to pull velocity traces from 2D and 3D hydraulic models, which could give a flow length. When velocities are tracked along these flow traces, a running time along each trace can be used to come up with a rough estimate of residence time.

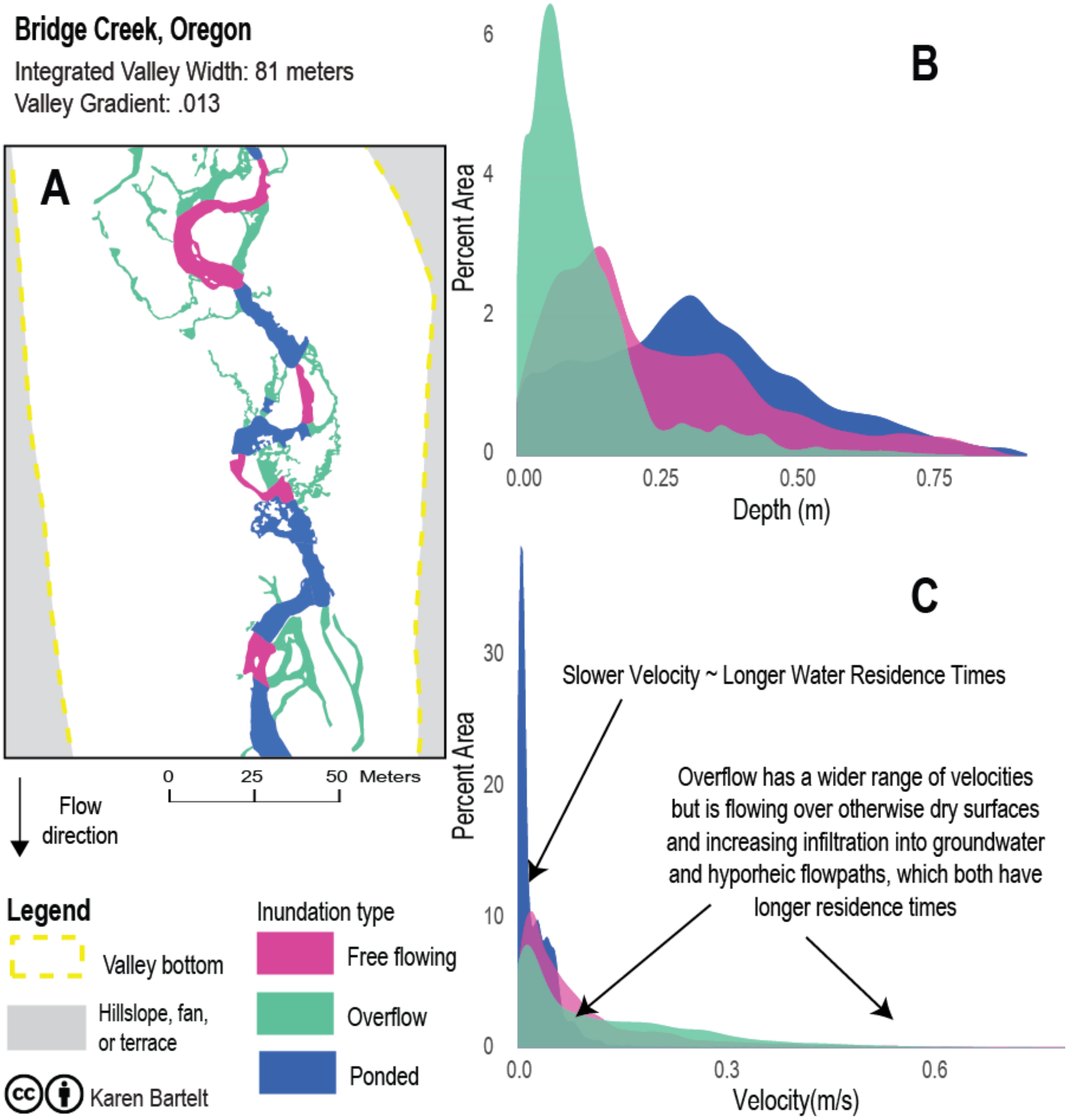


Figure 13. Inundation mapping results at the Lower Owens site on Bridge Creek, Oregon with the distribution of hydraulic variables represented by each inundation type. A) The mapped inundation extent symbolized by inundation type. The valley bottom extent is shown by a dashed yellow line. B) the distribution of depth values for each inundation type. C) The distribution of velocity values for each inundation type.

Limitations

There are potential limitations to this methodology that should be considered for those looking to apply it elsewhere. One potential limitation is the difficulty of using aerial imagery to delineate features in some small, (width < 2m) forested streams due to the tree canopy blocking much of the valley bottom. This was not an issue for the sites in this study because the UAV imagery resolution was high enough that features were possible to visualize and map. In most sites, even in undammed settings, if tree cover obscures part of the inundated area, enough was visible to reliably infer inundation polygon boundaries between the obscured canopy-covered areas. This is often not a major issue in beaver-modified streams because beaver harvest of trees lessens canopy cover around a generally increased inundated area, reducing the proportion of canopy cover obscuring the active channel.

Another potential limitation to this study is that if the features are manually delineated in GIS they then include some amount of user subjectivity (Bangen et al., 2014b). To minimize user subjectivity in this study all surveys were mapped by the same person (the author), who had ample familiarity with beaver dam complexes and their characteristics. This potential issue might be more thoroughly resolved by incorporating simple remote sensing techniques such as supervised classification programs (e.g. Carbonneau et al., 2020; Carbonneau and Dietrich, 2016). Similarly, from experience walking the sites at the time of imagery collection and then later mapping the inundation based off 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 (Huang et al., 2018), and automated delineation based on standard remote sensing techniques could potentially yield more accurate mapping of overflow.

It is logical to assume that inundation extent is a function of discharge, and this is often the case. In other words, overflow or overbank flooding should take place during “floods” or high flows. Thus, it is prudent to consider how sensitive our inundation extent and type results are to flow stage or discharge at the time of the survey. For this study, any sites for which we were not able to conduct a dammed survey at baseflow, we conducted the corresponding undammed survey at a similar flow stage. In undammed conditions, all 37 surveys matched conventional wisdom with all inundation contained within the active channel and dominated by 90% to 100% free flowing flow types. However, our surveys of dammed conditions all show “flooding” even during non-“flood” flows.

To begin to explore how sensitive inundation extent and patterns might be to flow stage, we illustrate how inundation changed between surveys at three different “dammed” flows and one “undammed” low flow survey at one site (Figure 14). The discharge data (Figure 14A) was derived from a stage discharge relationship from measurements taken at a gage <1km from the Right Hand Fork site (Neilson, 2020), and represent a high flow (spring runoff recession limb) and three baseflow conditions. The distribution and extent of inundation at all three dammed surveys clearly contrast with the inundation extent and type of the undammed survey condition (Figure 14C). Surprisingly, the extent and distribution of inundation remained fairly consistent between the three dammed surveys though they were conducted at different flow stages (slight increase in overflow at the highest flow). With enough structural forcing present, it appeared that inundation extent was not actually strongly correlated to flow. At Right Hand Fork there were portions of the floodplain that were dry in Figure 14B during the highest flow survey that became inundated in Figure 14F, the lowest flow survey. This was in part a result of new beaver dam activities (new dam construction, maintenance and expansion) by beaver near the upstream extent of the site that occurred between the June and November survey dates. This phenomenon of an increased prevalence of beaver dam activity at low flows relative to higher flows is something we observed at multiple different sites. This could be because at higher flows, beaver do not need to focus as much on building and maintaining dams because water depth is likely adequate without dam maintenance from elevated discharge. Then, when discharge decreases, beaver dam building activities increase to better control and maintain adequate water depths for swimming and keeping under water entrances to their lodges submerged. When beaver dam activities increase as flows decrease like we observed at the upstream end of Right Hand Fork, it adds to the degree of retention that structural forcing already provides to valley bottom inundation extent as flows decrease. Although it was beyond the scope of this study, it would be valuable to track these patterns more extensively through time at different sites.

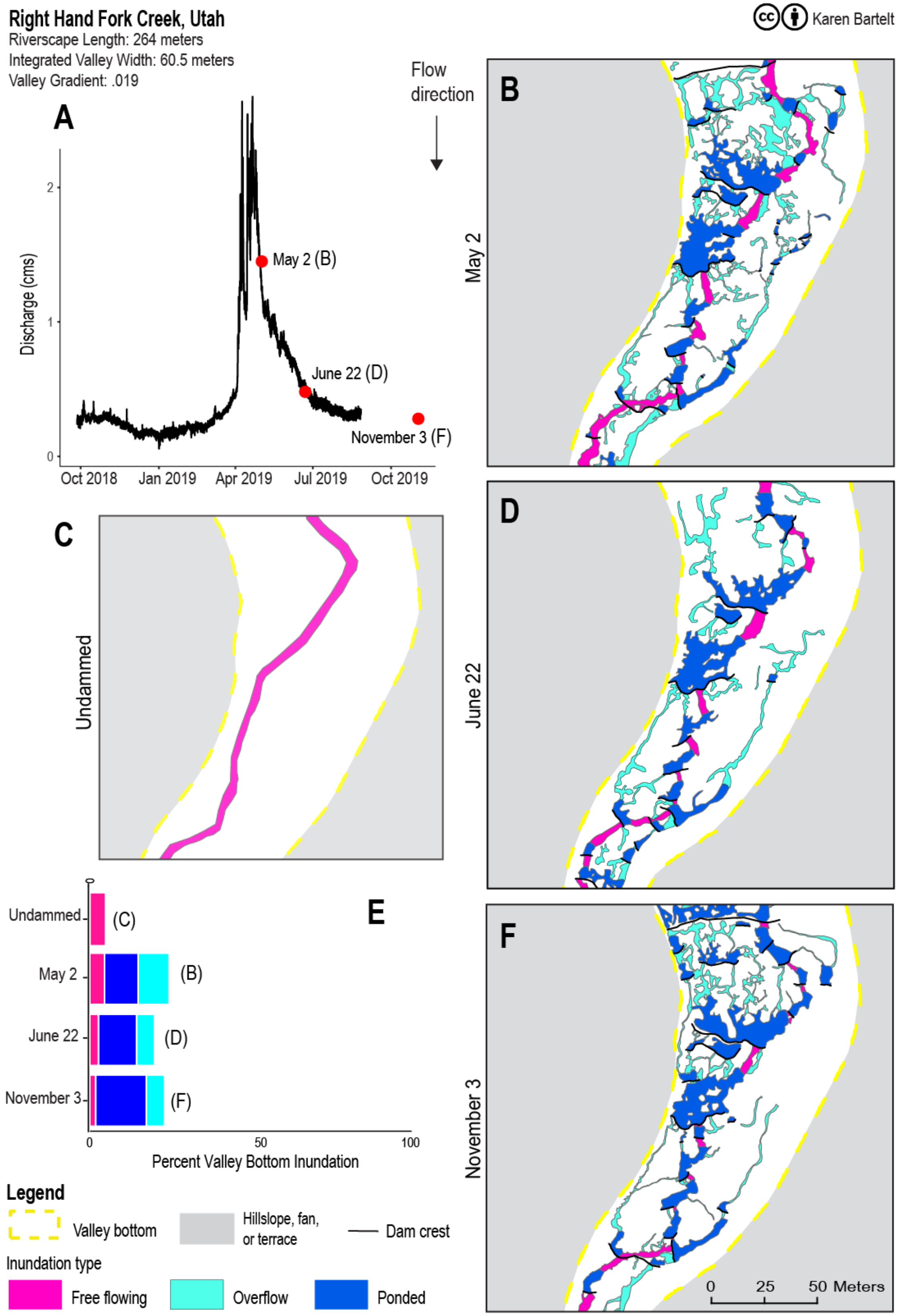

Right Hand Fork Creek, Utah
Riverscape Length: 264 meters
Integrated Valley Width: 60.5 meters
Valley Gradient: .019
Karen Bartelt
A
Discharge (cms)
0
1
2
Oct 2018
Jan 2019
Apr 2019
Jul 2019
Oct 2019
May 2 (B)
June 22 (D)
November 3 (F)
Flow direction
B
May 2
C
Undammed
D
June 22
E
Undammed
(C)
May 2
(B)
June 22
(D)
November 3
(F)
0
50
100
Percent Valley Bottom Inundation
F
November 3
0
25
50 Meters
Legend
Valley bottom
Hillslope, fan, or terrace
Dam crest
Inundation type
Free flowing
Overflow
Ponded

Figure 14. The inundation patterns for 4 surveys at Right Hand Fork Creek, Utah with a hydrograph to provide flow stage context. A) A hydrograph showing discharge from October 2018 to October 2019 at a gage < 1km downstream of the Right Hand Fork site. The dates of the dammed surveys we conducted are represented by red points. Flow data had not yet been released at the time of analysis for the November 3rd survey date and so the discharge value at this point was estimated from the previous November. B) Valley bottom, dam crest, and inundation mapping for the highest flow survey based on imagery collected on May 2, 2019. C) Valley bottom and approximated inundation mapping for an undammed condition. D) Valley bottom, dam crest, and inundation mapping a survey based on imagery collected on June 22, 2019. E) The percent of valley bottom inundation extent and type for each survey date. F) Valley bottom, dam crest, and inundation. mapping for the lowest flow survey based on imagery collected on November 3, 2019.

The methodology used here could be especially useful for natural resource managers and in the context of stream restoration monitoring. It can be used to quantify the impact of restoration projects and capture the full longitudinal and lateral extent of project boundaries. The riverscape inundation mapping methodology provides a tractable way to estimate the scale of the impacts associated with beaver facilitated restoration, and quantify indicators for comparison of the effects of beaver dams across diverse hydrogeomorphic settings with simple BACI (before-after-control-intervention) study designs. The results provide grounding for framing realistic restoration targets (often described as a reference condition) in terms of the degree of structural forcing, inundation patterns, and planform characteristics you might expect in intact beaver-modified riverscapes. 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, etc.) that could be analyzed to answer other management or research questions not addressed specifically in this study.

CONCLUSION

We propose the mapping of inundation patterns as a way to quantify the effects of beaver dams on riverscape processes and characteristics. Using this framework, we demonstrated that at 37 beaver dam complexes low flow inundation extent increased by on average over 400% due to the creation of ponded and overflow inundation directly caused by structural forcing. We demonstrated that the impact of beaver dams on inundation patters is also prevalent in valleys steeper than typically included in existing literature and valleys with rivers larger than typically included in the literature. The framework is readily feasible to implement expeditiously over broader spatial and temporal scales than stream monitoring is typically done. Finally, 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). We outlined future research that could be conducted to establish such links and further increase the utility of this framework.

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APPENDICES

APPENDIX A

BEAVER DAM BUILDING OPPORTUNITIES

In the Introduction, we proposed the concept of three different types of beaver dam building opportunities: classic, floodplain and steep (Figure 2). To illustrate how potentially important steep and floodplain dominant dam building opportunities may be and how their prevalence might differ between the perennial riverscape of different watersheds, we show two contrasting Rocky Mountain Watersheds in Figure A - 1. We used the Little Bear-Logan (HUC 16010203) and the Snake Headwaters (HUC17040101). First, the riverscapes were screened to identify only riverscapes where beaver could build dams using the beaver dam capacity outputs from the Beaver Restoration Assessment Tool (BRAT – http://brat.riverscapes.xyz). In these examples, 78% of total riverscape length of the Little Bear-Logan watershed with present day capacity for beaver dam building fits into the classic setting, with 4% in the floodplain setting and 18% in the steep setting. By contrast, in the Snake Headwaters watershed over half of riverscape length that has present day capacity for dam building had dominant dam building opportunities best characterized by the steep (33%) or floodplain (16%) settings. Less than half (43%) of riverscape length with current beaver dam capacity in this watershed fall into the classic setting typically studied in beaver dam literature. Both examples underscore that 20 to 50% of the riverscapes in which dam building opportunities are possible are not typically considered in the literature (e.g. Burchsted and Daniels, 2014; Dittbrenner et al., 2018; Hafen et al., 2020; Karran et al., 2017; Petro et al., 2018).

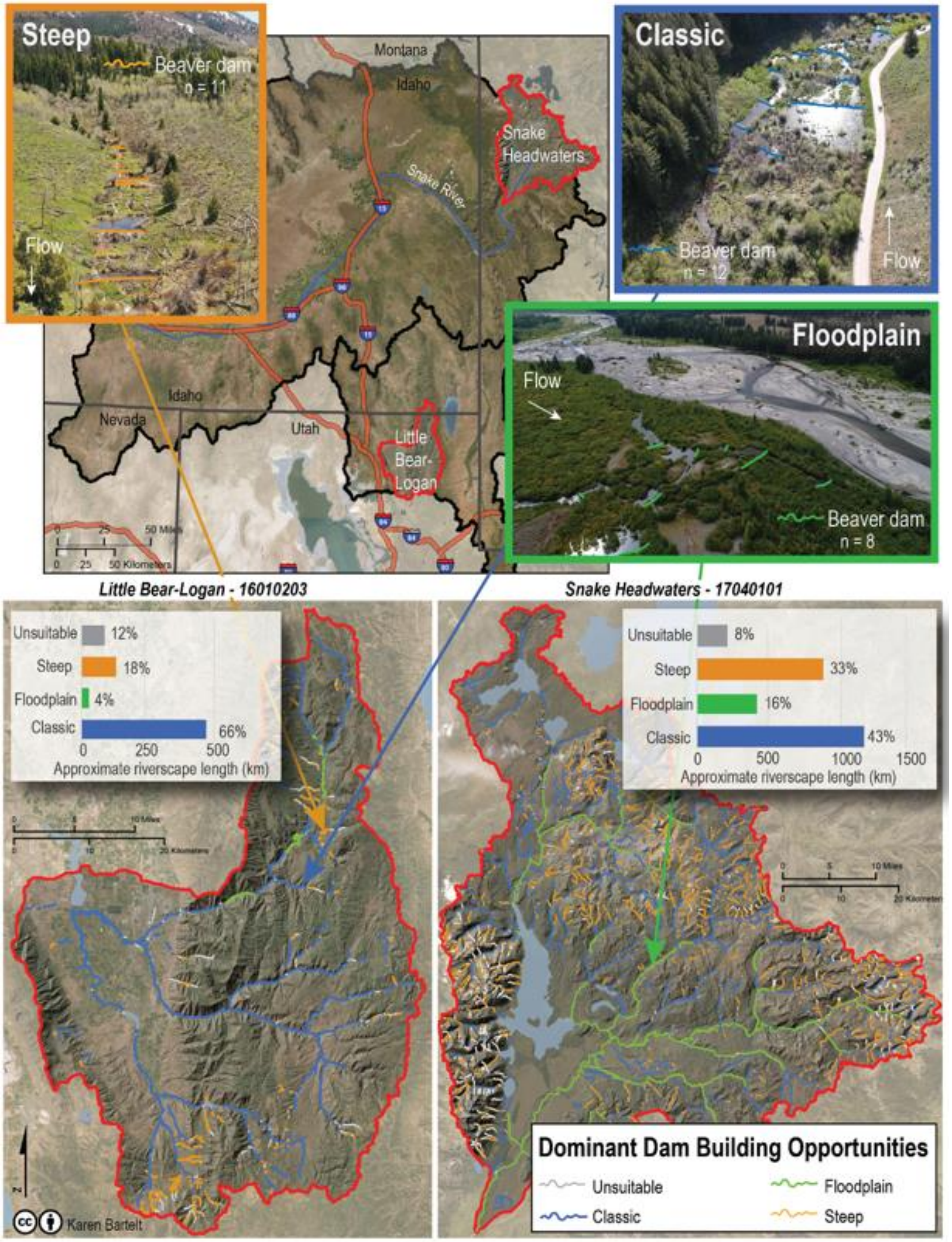

Figure A-1. Illustration of total availability of different beaver dam building opportunities in two contrasting physiographic settings. For both watersheds, the BRAT (http://brat.riverscapes.xyz) model was used to filter (in grey as unsuitable) the portions of the perennial riverscape network where beaver dam building is not possible. The remaining areas of the Little Bear - Logan and Snake Headwaters watersheds are symbolized by dominant dam building opportunities.

APPENDIX B

SITE SPECIFIC RESULTS

This appendix provides supplementary tables and figures containing the data from each survey and some summary statistics.

Table B-1. A list of all 37 sites at which we conducted at least one dammed survey and one undammed survey, with the watershed ID and name.

Site ID	Site Name	HUC 8 ID	HUC 8 Name
beaver_creek_wy	Beaver Creek, Wyoming	10080002	Little Wind
twin_creek_wy	Twin Creek, Wyoming	10080003	Popo Agie
mill_creek	Mill Creek, Utah	16010101	Upper Bear
beaver_creek_a	Beaver Creek A, Utah	16010203	Little Bear-Logan
beaver_creek_b	Beaver Creek B, Utah	16010203	Little Bear-Logan
pole_hollow	Pole Hollow, Utah	16010203	Little Bear-Logan
RH_fork_a	Right Hand Fork A, Utah	16010203	Little Bear-Logan
RH_fork_mid	Right Hand Fork mid, Utah	16010203	Little Bear-Logan
rock_creek_low	Rock Creek, Utah	16010203	Little Bear-Logan
spawn_c	Spawn Creek C, Utah	16010203	Little Bear-Logan
temple_a	Temple Fork A, Utah	16010203	Little Bear-Logan
temple_b	Temple Fork B, Utah	16010203	Little Bear-Logan
kane_creek	Kane Creek, Utah	17040218	Big Lost
summit_creek	Summit Creek, Idaho	17040218	Big Lost
salmon_river	Salmon River, Idaho	17060201	Upper Salmon
murderers_a	Murderers Creek, Oregon	17070201	Upper John Day
lower_owens	Lower Owens, Bridge Creek, Oregon	17070204	Lower John Day
franklin_basin	Logan River, Franklin Basin, Utah	16010203	Little Bear-Logan
ditch_creek	Ditch Creek, Wyoming	17040101	Snake Headwaters
NF_spread_a	North Fork Spread Creek, Wyoming	17040101	Snake Headwaters
pacific_creek_b	Pacific Creek B, Wyoming	17040101	Snake Headwaters
pilgrim_creek_a	Pilgrim Creek A, Wyoming	17040101	Snake Headwaters
SF_spread_a	South Fork Spread Creek A, Wyoming	17040101	Snake Headwaters
SF_spread_b	South Fork Spread Creek B, Wyoming	17040101	Snake Headwaters
SF_spread_c	South Fork Spread Creek C, Wyoming	17040101	Snake Headwaters
big_wood_b	Big Wood, Idaho	17040219	Big Wood
trail_creek	Trail Creek, Idaho	17040219	Big Wood
birch_saw	Tributary to Birch Creek, Idaho	16010202	Middle Bear
boss_canyon	Boss Canyon, Utah	16010203	Little Bear-Logan
hodges_creek	Hodges Creek, Utah	16010203	Little Bear-Logan
little_bear_low	Lower Little Bear Creek, Utah	16010203	Little Bear-Logan
little_bear_up	Upper Little Bear Creek, Utah	16010203	Little Bear-Logan
spawn_a	Spawn Creek A, Utah	16010203	Little Bear-Logan
spawn_trib	Tributary to Spawn Creek, Utah	16010203	Little Bear-Logan
temple_trib_a	Tributary A to Temple Fork, Utah	16010203	Little Bear-Logan
temple_trib_b	Tributary B to Temple Fork, Utah	16010203	Little Bear-Logan
temple_woody	Upper Temple Fork, Utah	16010203	Little Bear-Logan

The following tables contain metrics calculated from all sites grouped by dominant dam building opportunity.

Table B-2. Results of the metrics from Table 1 for each survey. This table shows the first half of the classic dominant dam building opportunity surveys.

CLASSIC Dominant Dam Building Opportunity	**Site Name and Survey (dammed or undammed)**																
Metric	beaver_creek_a: dammed	beaver_creek_a: undammed	beaver_creek_b: dammed	beaver_creek_b: undammed	beaver_creek_wy: dammed	beaver_creek_wy: undammed	kane_creek: dammed	kane_creek: undammed	lower_owens: dammed	lower_owens: undammed	mill_creek: dammed	mill_creek: undammed	murderers_a: dammed	murderers_a: undammed	pole_hollow: dammed	pole_hollow: undammed	RH_fork_a: dammed
Site																	
Valley Area (m^2)	52205	52205	7968	7968	55549	55549	84397	84397	35624	35624	27517	27517	17630	17630	14156	14156	15980
Hydrogeomorphic																	
Integrated Valley Width (*m*)	67.3	67.3	35.4	35.4	83.6	83.6	185.2	185.2	81.3	81.3	104.9	104.9	52.6	52.6	52.2	52.2	60.5
Upstream Drainage Area (km^2)	39.2	39.2	42.0	42.0	21.3	21.3	30.4	30.4	157.8	157.8	5.0	5.0	327.1	327.1	2.2	2.2	50.9
Baseflow Discharge (*cfs*)	9.9	9.9	10.1	10.1	2.0	2.0	1.6	1.6	0.9	0.9	0.9	0.9	13.5	13.5	5.0	5.0	10.5
2 Year Recurrence Interval Discharge (*cfs*)	86.9	86.9	91.0	91.0	38.3	38.3	56.2	56.2	72.6	72.6	17.1	17.1	433.7	433.7	12.5	12.5	103.6
Baseflow Stream Power (*watts*)	28.5	28.5	126.6	126.6	2.8	2.8	4.9	4.9	2.7	2.7	0.0	0.0	22.6	22.6	170.5	170.5	54.9
2 Year Recurrence Interval Stream Power (*watts*)	250.4	250.4	1143.8	1143.8	54.2	54.2	169.5	169.5	214.1	214.1	0.5	0.5	723.7	723.7	427.9	427.9	539.3
Flow Stage at the Time of the Survey	moderate	moderate	moderate	moderate	moderate	low	low	low	low	low	low	low	low	low	moderate	low	moderate
Channel Gradient	0.012	0.013	0.047	0.043	0.008	0.008	0.009	0.011	0.012	0.012	0.003	0.003	0.006	0.006	0.045	0.041	0.020
Channel Length (*m*)	951.3	867.5	252.1	229.5	867.5	787.4	859.5	763.5	533.0	523.8	366.0	366.0	381.2	364.2	307.7	300.1	310.7
Valley Gradient	0.014	0.014	0.048	0.048	0.010	0.010	0.017	0.017	0.013	0.013	0.015	0.015	0.005	0.005	0.049	0.049	0.021
Valley Length or Site Length (*m*)	775.6	775.6	225.4	225.4	664.1	664.1	455.8	455.8	438.0	438.0	262.2	262.2	335.5	335.5	271.3	271.3	264.3
Sinuosity - (calculated as the main thalweg length divided by the valley length)	1.2	1.1	1.1	1.0	1.3	1.2	1.9	1.7	1.2	1.2	1.4	1.4	1.1	1.1	1.1	1.1	1.2
Relative Flow Length	3.5	1.1	2.9	1.0	2.8	1.2	3.8	1.9	3.6	1.2	3.1	1.4	2.2	1.1	1.7	1.1	3.6
Percent of Total Thalweg Length that is the Main Thalweg (%)	0.4	1	0.4	1	0.5	1	0.5	0.9	0.3	1	0.4	1	0.5	1	0.7	1	0.3
Structural Forcing																	
Number of Dams	31	0	22	0	17	0	17	0	34	0	20	0	13	0	8	0	20
Dam Density (*dams/km*)	40	0	97.6	0	25.6	0	37.3	0	77.6	0	76.3	0	38.7	0	29.5	0	75.7
Number of Intact Dams	8	0	21	0	14	0	8	0	4	0	12	0	2	0	4	0	6
Number of Breached Dams	17	0	1	0	0	0	8	0	24	0	6	0	7	0	4	0	14
Number of Blown out Dams	6	0	0	0	3	0	1	0	5	0	2	0	4	0	0	0	0
Ratio of Dam Crest Length to the Valley Length (for all dams)	0.4	0	1.2	0	0.7	0	1	0	1.3	0	1.8	0	0.3	0	0.6	0	0.9
Ratio of Dam Crest Length to the Valley Length (for active dam crest length)	0.4	0	1.1	0	0.7	0	0.5	0	0.5	0	1.1	0	0.2	0	0.5	0	0.7
Ratio of Dam Crest Length to the Valley Length (for active dam crest length)	0.2	0	1.1	0	0.7	0	0.4	0	0.1	0	0.7	0	0	0	0.3	0	0.3
Percent of Total Dam Crest Length that is Actively Structurally-Forcing Flow	84	0	97	0	89	0	51	0	41	0	61	0	55	0	87	0	84
Inundation																	
Integrated Wetted Width (*m*)	10	4	13	4	22	7	10	6	9	3	14	4	6	5	10	2	10
Total Inundated Area (m^2)	9512	3838	3305	856	19083	5098	8799	4251	4679	1374	5236	1281	2335	1736	3162	557	3019
Total Area of Free Flowing Inundation (m^2)	3547	3838	729	856	1720	5098	3574	4251	916	1374	1229	1281	941	1736	167	557	422
Total Area of Ponded Inundation (m2)	2629	0	1826	0	12327	0	3280	0	1816	0	3467	0	800	0	2379	0	1762
Total Area of Overflow Inundation (m2)	3335	0	750	0	5037	0	1944	0	1947	0	540	0	594	0	616	0	835
Percent of Valley Bottom that is Inundated (%)	18	7	42	11	34	9	10	5	13	4	19	5	13	10	22	4	19
Range of Estimated Valley Bottom Inundation when Accounting for Uncertainty	17.3 - 19.1	3.8 - 10.9	39.9 - 43	3 - 18.7	33.8 - 34.9	6.7 - 11.6	10 - 10.9	0 - 13.3	12.2 - 14.1	0 - 14	18.5 - 19.6	3 - 6.3	12.5 - 14	0 - 43.8	21.8 - 22.9	0 - 10	17.8 - 20
Percent of Valley Bottom with Free Flowing Inundation (%)	6.8	7.4	9.1	10.7	3.1	9.2	4.2	5	2.6	3.9	4.5	4.7	5.3	9.8	1.2	3.9	2.6
Percent of Valley Bottom with Ponded Inundation (%)	5	0	22.9	0	22.2	0	3.9	0	5.1	0	12.6	0	4.5	0	16.8	0	11
Percent of Valley Bottom with Overflow Inundation (%)	6.4	0	9.4	0	9.1	0	2.3	0	5.5	0	2	0	3.4	0	4.3	0	5.2
Shannon's Diversity Index Value	0.67	0.26	1.09	0.34	0.94	0.31	0.44	0.20	0.53	0.16	0.65	0.19	0.53	0.32	0.68	0.16	0.66
Shannon's Evenness Index Value	0.49	0.19	0.79	0.25	0.68	0.22	0.32	0.14	0.38	0.12	0.47	0.14	0.38	0.23	0.49	0.12	0.48

Table B-3. Results of the metrics from Table 1 for each survey. This table shows the second half of the classic dominant dam building opportunity surveys.

CLASSIC Dominant Dam Building Opportunity	**Site Name and Survey (dammed or undammed)**																
Metric	RH_fork_a: undammed	RH_fork_mid: dammed	RH_fork_mid: undammed	rock_creek_low: dammed	rock_creek_low: undammed	salmon_river: dammed	salmon_river: undammed	spawn_c: dammed	spawn_c: undammed	summit_creek: dammed	summit_creek: undammed	temple_a: dammed	temple_a: undammed	temple_b: dammed	temple_b: undammed	twin_creek_wy: dammed	twin_creek_wy: undammed
Site																	
Valley Area (m^2)	15980	18059	18059	19162	19162	48145	48145	2703	2703	75648	75648	5276	5276	8069	8069	37238	37238
Hydrogeomorphic																	
Integrated Valley Width (*m*)	60.5	32.8	32.8	49.5	49.5	155	155	26	26	144.5	144.5	43.3	43.3	46.4	46.4	89.3	89.3
Upstream Drainage Area (km^2)	50.9	26.7	26.7	61.0	61.0	35.6	35.6	13.5	13.5	14.0	14.0	20.0	20.0	25.3	25.3	2.6	2.6
Baseflow Discharge (*cfs*)	10.5	9.0	9.0	11.0	11.0	4.2	4.2	7.7	7.7	0.7	0.7	8.4	8.4	8.9	8.9	0.2	0.2
2 Year Recurrence Interval Discharge (*cfs*)	103.6	67.0	67.0	117.2	117.2	55.4	55.4	42.3	42.3	25.9	25.9	55.1	55.1	64.5	64.5	8.7	8.7
Baseflow Stream Power (*watts*)	54.9	114.9	114.9	117.6	117.6	1.2	1.2	110.1	110.1	4.0	4.0	85.0	85.0	70.0	70.0	3.5	3.5
2 Year Recurrence Interval Stream Power (*watts*)	539.3	852.2	852.2	1251.3	1251.3	15.4	15.4	606.5	606.5	137.8	137.8	555.1	555.1	506.4	506.4	148.8	148.8
Flow Stage at the Time of the Survey	low	moderate	low	moderate	low	low	low	moderate	low	moderate	low	low	low	low	low	moderate	low
Channel Gradient	0.021	0.028	0.028	0.032	0.033	0.004	0.004	0.038	0.038	0.019	0.015	0.012	0.009	0.021	0.021	0.046	0.053
Channel Length (*m*)	282.2	635.6	597.4	429.3	415.3	437.7	433.1	105.8	106.2	818.3	650.1	171.4	141.0	227.3	222.8	456.2	407.5
Valley Gradient	0.021	0.030	0.030	0.036	0.036	0.006	0.006	0.038	0.038	0.025	0.025	0.016	0.016	0.027	0.027	0.049	0.049
Valley Length or Site Length (*m*)	264.3	550.6	550.6	387.5	387.5	310.6	310.6	104.1	104.1	523.5	523.5	121.8	121.8	174.0	174.0	417.2	417.2
Sinuosity - (calculated as the main thalweg length divided by the valley length)	1.1	1.2	1.1	1.1	1.1	1.4	1.4	1.0	1.0	1.6	1.2	1.4	1.2	1.3	1.3	1.1	1.0
Relative Flow Length	1.1	2.0	1.1	2.7	1.1	3.2	1.4	2.5	1.0	5.4	1.2	3.8	1.2	2.3	1.3	2.5	1.0
Percent of Total Thalweg Length that is the Main Thalweg (%)	1	0.6	1	0.4	1	0.4	1	0.4	1	0.3	1	0.4	1	0.6	1	0.4	1
Structural Forcing																	
Number of Dams	0	28	0	25	0	20	0	2	0	47	0	8	0	5	0	25	0
Dam Density (*dams/km*)	0	50.8	0	64.5	0	64.4	0	19.2	0	89.8	0	65.7	0	28.7	0	59.9	0
Number of Intact Dams	0	22	0	4	0	6	0	2	0	23	0	0	0	4	0	18	0
Number of Breached Dams	0	4	0	18	0	13	0	0	0	23	0	7	0	0	0	7	0
Number of Blown out Dams	0	2	0	3	0	1	0	0	0	1	0	1	0	0	0	0	0
Ratio of Dam Crest Length to the Valley Length (for all dams)	0	0.6	0	1.2	0	0.9	0	0.4	0	1.5	0	0.8	0	0.8	0	1.4	0
Ratio of Dam Crest Length to the Valley Length (for active dam crest length)	0	0.6	0	1.1	0	0.7	0	0.4	0	1.4	0	0.6	0	0.5	0	1.4	0
Ratio of Dam Crest Length to the Valley Length (for active dam crest length)	0	0.5	0	0.1	0	0.3	0	0.4	0	0.8	0	0	0	0.5	0	1.1	0
Percent of Total Dam Crest Length that is Actively Structurally-Forcing Flow	0	91	0	92	0	75	0	100	0	94	0	73	0	70	0	99	0
Inundation																	
Integrated Wetted Width (*m*)	6	7	3	19	5	10	4	12	2	14	6	11	5	15	4	25	4
Total Inundated Area (m^2)	1755	4658	1536	8294	2250	4558	1749	1283	196	11268	3609	1875	634	3495	958	11363	1597
Total Area of Free Flowing Inundation (m^2)	1755	1042	1536	1649	2250	1591	1749	122	196	2050	3609	586	634	360	958	242	1597
Total Area of Ponded Inundation (m2)	0	2891	0	3388	0	1844	0	880	0	7076	0	947	0	2587	0	10066	0
Total Area of Overflow Inundation (m2)	0	725	0	3257	0	1123	0	281	0	2142	0	341	0	548	0	1056	0
Percent of Valley Bottom that is Inundated (%)	11	26	9	43	12	10	4	48	7	15	5	36	12	43	12	31	4
Range of Estimated Valley Bottom Inundation when Accounting for Uncertainty	8.8 - 13.2	24.7 - 26.9	4.5 - 12.6	41.9 - 44.7	0.3 - 26.2	9.1 - 9.8	1.9 - 5.3	46 - 48.9	0 - 17.3	14.3 - 15.5	0.8 - 8.9	34.1 - 37	4.4 - 20.1	42.5 - 44.2	6.9 - 17	29.9 - 31.2	2.6 - 6
Percent of Valley Bottom with Free Flowing Inundation (%)	11	5.8	8.5	8.6	11.7	3.3	3.6	4.5	7.2	2.7	4.8	11.1	12	4.5	11.9	0.6	4.3
Percent of Valley Bottom with Ponded Inundation (%)	0	16	0	17.7	0	3.8	0	32.6	0	9.4	0	17.9	0	32.1	0	27	0
Percent of Valley Bottom with Overflow Inundation (%)	0	4	0	17	0	2.3	0	10.4	0	2.8	0	6.5	0	6.8	0	2.8	0
Shannon's Diversity Index Value	0.35	0.81	0.29	1.14	0.36	0.41	0.16	1.08	0.26	0.56	0.19	1.01	0.37	1.01	0.36	0.74	0.18
Shannon's Evenness Index Value	0.25	0.58	0.21	0.82	0.26	0.30	0.11	0.78	0.19	0.40	0.14	0.73	0.26	0.73	0.26	0.53	0.13

Table B-4. Results of the metrics from Table 1 for each survey. This table shows the first half of the steep dominant dam building opportunity surveys.

STEEP Dominant Dam Building Opportunity	**Site Name and Survey (dammed or undammed)**									
Metric	birch_saw: dammed	birch_saw: undammed	boss_canyon: dammed	boss_canyon: undammed	hodges_creek: dammed	hodges_creek: undammed	little_bear_low: dammed	little_bear_low: undammed	little_bear_up: dammed	little_bear_up: undammed
Site										
Valley Area (*m* ^{2})	6706	6706	8467	8467	16571	16571	13493	13493	6207	6207
Hydrogeomorphic										
Integrated Valley Width (*m*)	59.2	59.2	41.3	41.3	59.5	59.5	71.5	71.5	46	46
Upstream Drainage Area (*km* ^{2})	3.8	3.8	30.3	30.3	8.7	8.7	18.8	18.8	11.3	11.3
Baseflow Discharge (*cfs*)	0.6	0.6	9.3	9.3	6.9	6.9	8.3	8.3	7.4	7.4
2 Year Recurrence Interval Discharge (*cfs*)	10.1	10.1	72.9	72.9	31.4	31.4	52.9	52.9	37.5	37.5
Baseflow Stream Power (*watts*)	17.6	17.6	141.2	141.2	129.0	129.0	133.7	133.7	232.4	232.4
2 Year Recurrence Interval Stream Power (*watts*)	283.3	283.3	1105.9	1105.9	586.7	586.7	850.9	850.9	1183.7	1183.7
Flow Stage at the Time of the Survey	low	low	low	moderate	low	low	low	low	low	low
Channel Gradient	0.078	0.069	0.060	0.057	0.061	0.073	0.064	0.077	0.128	0.142
Channel Length (*m*)	120.0	119.3	220.1	224.7	271.2	259.6	214.8	213.7	149.0	144.4
Valley Gradient	0.063	0.063	0.063	0.063	0.070	0.070	0.074	0.074	0.142	0.142
Valley Length or Site Length (*m*)	113.3	113.3	205.2	205.2	278.7	278.7	188.7	188.7	134.8	134.8
Sinuosity - (calculated as the main thalweg length divided by the valley length)	1.1	1.1	1.1	1.1	1.0	0.9	1.1	1.1	1.1	1.1
Relative Flow Length	1.5	1.1	3.5	1.1	1.4	0.9	3.2	1.1	2.5	1.1
Percent of Total Thalweg Length that is the Main Thalweg (%)	0.7	1	0.3	1	0.7	1	0.4	1	0.4	1
Structural Forcing										
Number of Dams	8	0	21	0	18	0	11	0	19	0
Dam Density (*dams/km*)	70.6	0	102.4	0	64.6	0	58.3	0	140.9	0
Number of Intact Dams	5	0	12	0	13	0	11	0	19	0
Number of Breached Dams	3	0	8	0	5	0	0	0	0	0
Number of Blown out Dams	0	0	0	0	0	0	0	0	0	0
Ratio of Dam Crest Length to the Valley Length (for all dams)	1.3	0	1.4	0	1.1	0	1.2	0	1.9	0
Ratio of Dam Crest Length to the Valley Length (for active dam crest length)	1.1	0	1.3	0	1	0	1.2	0	1.9	0
Ratio of Dam Crest Length to the Valley Length (for active dam crest length)	1	0	1	0	0.7	0	1.2	0	1.9	0
Percent of Total Dam Crest Length that is Actively Structurally-Forcing Flow	85.2	0.0	94.4	0.0	96.4	0.0	100.0	0.0	100.0	0.0
Inundation										
Integrated Wetted Width (*m*)	9	2	9	2	8	2	13	4	11	3
Total Inundated Area (*m* ^{2})	1073.4	232.0	2024.7	495.5	2024.2	452.1	2691.9	750.2	1621.2	364.3
Total Area of Free Flowing Inundation (*m* ^{2})	86	232	210	496	86	452	152	750	48	364
Total Area of Ponded Inundation (m2)	920	0	1211	0	1685	0	2173	0	1493	0
Total Area of Overflow Inundation (m2)	68	0	604	0	254	0	367	0	80	0
Percent of Valley Bottom that is Inundated (%)	16	4	24	6	12	3	20	6	26	6
Range of Estimated Valley Bottom Inundation when Accounting for Uncertainty	15.4 - 16.7	0 - 10.3	22.3 - 25.5	1.9 - 9.9	11.7 - 12.8	0 - 12.4	19.1 - 20.8	1.2 - 10.1	25 - 27.2	0.2 - 12.6
Percent of Valley Bottom with Free Flowing Inundation (%)	1.3	3.5	2.5	5.9	0.5	2.7	1.1	5.6	0.8	5.9
Percent of Valley Bottom with Ponded Inundation (%)	13.7	0	14.3	0	10.2	0	16.1	0	24.1	0
Percent of Valley Bottom with Overflow Inundation (%)	1	0	7.1	0	1.5	0	2.7	0	1.3	0
Shannon's Diversity Index Value	0.52	0.15	0.77	0.22	0.44	0.12	0.62	0.22	0.66	0.22
Shannon's Evenness Index Value	0.38	0.11	0.55	0.16	0.31	0.09	0.45	0.16	0.48	0.16

Table B-5. Results of the metrics from Table 1 for each survey. This table shows the second half of the steep dominant dam building opportunity surveys.

STEEP Dominant Dam Building Opportunity	**Site Name and Survey (dammed or undammed)**									
Metric	spawn_a: dammed	spawn_a: undammed	spawn_trib: dammed	spawn_trib: undammed	temple_trib_a: dammed	temple_trib_a: undammed	temple_trib_b: dammed	temple_trib_b: undammed	temple_woody: dammed	temple_woody: undammed
Site										
Valley Area (*m^2*)	2274	2274	2802	2802	14831	14831	3966	3966	4579	4579
Hydrogeomorphic										
Integrated Valley Width (*m*)	25.1	25.1	15.7	15.7	32.6	32.6	19	19	29.7	29.7
Upstream Drainage Area (*km^2*)	11.5	11.5	2.0	2.0	0.9	0.9	2.1	2.1	15.5	15.5
Baseflow Discharge (*cfs*)	7.4	7.4	4.9	4.9	4.0	4.0	4.9	4.9	7.9	7.9
2 Year Recurrence Interval Discharge (*cfs*)	38.0	38.0	11.6	11.6	6.7	6.7	12.1	12.1	46.3	46.3
Baseflow Stream Power (*watts*)	127.8	127.8	153.4	153.4	63.6	63.6	89.0	89.0	109.1	109.1
2 Year Recurrence Interval Stream Power (*watts*)	656.7	656.7	365.8	365.8	107.1	107.1	218.5	218.5	637.6	637.6
Flow Stage at the Time of the Survey	low	low	low	moderate	low	low	low	low	moderate	low
Channel Gradient	0.070	0.067	0.118	0.118	0.059	0.072	0.053	0.053	0.055	0.054
Channel Length (*m*)	93.6	97.0	211.9	211.9	530.8	466.1	230.3	230.3	167.2	159.1
Valley Gradient	0.072	0.072	0.127	0.127	0.073	0.073	0.060	0.060	0.059	0.059
Valley Length or Site Length (*m*)	90.7	90.7	178.8	178.8	455.4	455.4	209.0	209.0	154.4	154.4
Sinuosity - (calculated as the main thalweg length divided by the valley length)	1.0	1.1	1.2	1.2	1.2	1.0	1.1	1.1	1.1	1.0
Relative Flow Length	2.2	1.1	2.8	1.2	1.9	1.0	1.5	1.5	3.1	1.0
Percent of Total Thalweg Length that is the Main Thalweg (*%*)	0.5	1	0.4	1	0.6	1	0.7	0.7	0.4	1
Structural Forcing										
Number of Dams	3	0	14	0	21	0	10	0	13	0
Dam Density (*dams/km*)	33.1	0	78.3	0	46.1	0	47.9	0	84.2	0
Number of Intact Dams	3	0	11	0	19	0	7	0	10	0
Number of Breached Dams	0	0	1	0	2	0	3	0	3	0
Number of Blown out Dams	0	0	2	0	0	0	0	0	0	0
Ratio of Dam Crest Length to the Valley Length (for all dams)	0.4	0	0.4	0	0.6	0	0.3	0	0.8	0
Ratio of Dam Crest Length to the Valley Length (for active dam crest length)	0.4	0	0.4	0	0.6	0	0.3	0	0.7	0
Ratio of Dam Crest Length to the Valley Length (for active dam crest length)	0.4	0	0.4	0	0.6	0	0.3	0	0.7	0
Percent of Total Dam Crest Length that is Actively Structurally-Forcing Flow	100.0	0.0	96.3	0.0	100.0	0.0	94.7	0.0	93.8	0.0
Inundation										
Integrated Wetted Width (*m*)	8	2	5	2	7	2	4	0	12	3
Total Inundated Area (*m^2*)	783.2	195.6	1008.6	488.6	3790.7	887.6	918.5	0.0	1959.2	442.2
Total Area of Free Flowing Inundation (*m^2*)	80	196	189	489	312	888	119	0	467	442
Total Area of Ponded Inundation (m2)	588	0	431	0	2983	0	721	0	802	0
Total Area of Overflow Inundation (m2)	115	0	388	0	496	0	79	0	690	0
Percent of Valley Bottom that is Inundated (*%*)	34	9	36	17	26	6	23	0	43	10
Range of Estimated Valley Bottom Inundation when Accounting for Uncertainty	33.1 - 35.8	0 - 21.2	32.6 - 39.5	0.7 - 37.5	24.6 - 26.5	0.1 - 13.4	22 - 24.4	0 - 0	41.1 - 44.5	1.6 - 18
Percent of Valley Bottom with Free Flowing Inundation (*%*)	3.5	8.6	6.8	17.4	2.1	6	3	0	10.2	9.7
Percent of Valley Bottom with Ponded Inundation (%)	25.9	0	15.4	0	20.1	0	18.2	0	17.5	0
Percent of Valley Bottom with Overflow Inundation (%)	5.1	0	13.8	0	3.3	0	2	0	15.1	0
Shannon's Diversity Index Value	0.90	0.29	1.03	0.46	0.74	0.23	0.70	0.00	1.14	0.32
Shannon's Evenness Index Value	0.65	0.21	0.74	0.33	0.53	0.16	0.50	0.00	0.82	0.23

Table B-6. Results of the metrics from Table 1 for each survey. This table shows the first half of the floodplain dominant dam building opportunity surveys.

Floodplain Dominant Dam Building Opportunity	**Site Name and Survey (dammed or undammed)**								
Metric	big_wood_b: dammed	big_wood_b: undammed	ditch_creek: dammed	ditch_creek: undammed	franklin_basin: dammed	franklin_basin: undammed	NF_spread_a: dammed	NF_spread_a: undammed	pacific_creek_b: dammed
Site									
Valley Area (*m* ^{2})	64961	64961	44678	44678	34178	34178	53557	53557	282089
Hydrogeomorphic									
Integrated Valley Width (*m*)	232.9	232.9	175.4	175.4	113.6	113.6	146	146	484.7
Upstream Drainage Area (*km* ^{2})	303.9	303.9	49.4	49.4	83.9	83.9	54.4	54.4	274.5
Baseflow Discharge (*cfs*)	1.7	1.7	5.1	5.1	11.9	11.9	5.6	5.6	33.0
2 Year Recurrence Interval Discharge (*cfs*)	187.5	187.5	156.0	156.0	145.5	145.5	169.5	169.5	688.7
Baseflow Stream Power (*watts*)	4.2	4.2	23.8	23.8	107.8	107.8	16.5	16.5	9.7
2 Year Recurrence Interval Stream Power (*watts*)	463.5	463.5	732.6	732.6	1318.3	1318.3	498.0	498.0	201.8
Flow Stage at the Time of the Survey	moderate	low	low	low	moderate	moderate	high	low	low
Channel Gradient	0.008	0.010	0.011	0.011	0.031	0.031	0.009	0.011	0.001
Channel Length (*m*)	412.1	324.4	336.4	334.3	344.6	344.6	414.7	409.5	741.8
Valley Gradient	0.013	0.013	0.020	0.020	0.035	0.035	0.012	0.012	0.005
Valley Length or Site Length (*m*)	279.0	279.0	254.8	254.8	300.7	300.7	366.9	366.9	581.9
Sinuosity - (calculated as the main thalweg length divided by the valley length)	1.5	1.2	1.3	1.3	1.1	1.1	1.1	1.1	1.3
Relative Flow Length	3.9	1.2	4.1	1.3	3.7	1.1	3.1	1.4	6.2
Percent of Total Thalweg Length that is the Main Thalweg (*%*)	0.4	1	0.3	1	0.3	1	0.4	0.8	0.2
Structural Forcing									
Number of Dams	11	0	9	0	18	0	10	0	12
Dam Density (*dams/km*)	39.4	0	35.3	0	59.9	0	27.3	0	20.6
Number of Intact Dams	8	0	6	0	18	0	7	0	4
Number of Breached Dams	2	0	2	0	0	0	3	0	8
Number of Blown out Dams	1	0	1	0	0	0	0	0	0
Ratio of Dam Crest Length to the Valley Length (for all dams)	1.1	0	1.5	0	1.1	0	1.3	0	0.5
Ratio of Dam Crest Length to the Valley Length (for active dam crest length)	1	0	1.2	0	1.1	0	1.1	0	0.4
Ratio of Dam Crest Length to the Valley Length (for active dam crest length)	0.9	0	1.1	0	1.1	0	0.8	0	0.2
Percent of Total Dam Crest Length that is Actively Structurally-Forcing Flow	87.4	0.0	76.8	0.0	100.0	0.0	91.4	0.0	85.5
Inundation									
Integrated Wetted Width (*m*)	24	13	16	4	21	6	26	6	53
Total Inundated Area (*m* ^{2})	10026.5	4093.8	5487.4	1238.6	7191.4	2123.6	10937.7	2395.8	39235.0
Total Area of Free Flowing Inundation (*m* ^{2})	5809	4094	1250	1239	2124	2124	3637	2396	28121
Total Area of Ponded Inundation (m2)	3258	0	3423	0	3816	0	6818	0	7969
Total Area of Overflow Inundation (m2)	959	0	814	0	1252	0	482	0	3145
Percent of Valley Bottom that is Inundated (*%*)	15	6	12	3	21	6	20	5	14
Range of Estimated Valley Bottom Inundation when Accounting for Uncertainty	12.9 - 18.2	4.6 - 8	8.2 - 17.6	0.8 - 5.1	20.4 - 21.7	2.9 - 9.7	16.2 - 24.9	3.2 - 5.7	11.4 - 16.5
Percent of Valley Bottom with Free Flowing Inundation (*%*)	8.9	6.3	2.8	2.8	6.2	6.2	6.8	4.5	10
Percent of Valley Bottom with Ponded Inundation (%)	5	0	7.7	0	11.2	0	12.7	0	2.8
Percent of Valley Bottom with Overflow Inundation (%)	1.5	0	1.8	0	3.7	0	0.9	0	1.1
Shannon's Diversity Index Value	0.57	0.24	0.48	0.13	0.73	0.23	0.67	0.18	0.51
Shannon's Evenness Index Value	0.41	0.17	0.35	0.09	0.52	0.17	0.48	0.13	0.37

Table B-7. Results of the metrics from Table 1 for each survey. This table shows the second half of the floodplain dominant dam building opportunity surveys.

FLOODPLAIN Dominant Dam Building Opportunity	**Site Name and Survey (dammed or undammed)**								
Metric	big_wood_b: dammed	big_wood_b: undammed	ditch_creek: dammed	ditch_creek: undammed	franklin_basin: dammed	franklin_basin: undammed	NF_spread_a: dammed	NF_spread_a: undammed	pacific_creek_b: dammed
Site									
Valley Area (m^2)	64961	64961	44678	44678	34178	34178	53557	53557	282089
Hydrogeomorphic									
Integrated Valley Width (*m*)	232.9	232.9	175.4	175.4	113.6	113.6	146	146	484.7
Upstream Drainage Area (km^2)	303.9	303.9	49.4	49.4	83.9	83.9	54.4	54.4	274.5
Baseflow Discharge (*cfs*)	1.7	1.7	5.1	5.1	11.9	11.9	5.6	5.6	33.0
2 Year Recurrence Interval Discharge (*cfs*)	187.5	187.5	156.0	156.0	145.5	145.5	169.5	169.5	688.7
Baseflow Stream Power (*watts*)	4.2	4.2	23.8	23.8	107.8	107.8	16.5	16.5	9.7
2 Year Recurrence Interval Stream Power (*watts*)	463.5	463.5	732.6	732.6	1318.3	1318.3	498.0	498.0	201.8
Flow Stage at the Time of the Survey	moderate	low	low	low	moderate	moderate	high	low	low
Channel Gradient	0.008	0.010	0.011	0.011	0.031	0.031	0.009	0.011	0.001
Channel Length (*m*)	412.1	324.4	336.4	334.3	344.6	344.6	414.7	409.5	741.8
Valley Gradient	0.013	0.013	0.020	0.020	0.035	0.035	0.012	0.012	0.005
Valley Length or Site Length (*m*)	279.0	279.0	254.8	254.8	300.7	300.7	366.9	366.9	581.9
Sinuosity - (calculated as the main thalweg length divided by the valley length)	1.5	1.2	1.3	1.3	1.1	1.1	1.1	1.1	1.3
Relative Flow Length	3.9	1.2	4.1	1.3	3.7	1.1	3.1	1.4	6.2
Percent of Total Thalweg Length that is the Main Thalweg (%)	0.4	1	0.3	1	0.3	1	0.4	0.8	0.2
Structural Forcing									
Number of Dams	11	0	9	0	18	0	10	0	12
Dam Density (*dams/km*)	39.4	0	35.3	0	59.9	0	27.3	0	20.6
Number of Intact Dams	8	0	6	0	18	0	7	0	4
Number of Breached Dams	2	0	2	0	0	0	3	0	8
Number of Blown out Dams	1	0	1	0	0	0	0	0	0
Ratio of Dam Crest Length to the Valley Length (for all dams)	1.1	0	1.5	0	1.1	0	1.3	0	0.5
Ratio of Dam Crest Length to the Valley Length (for active dam crest length)	1	0	1.2	0	1.1	0	1.1	0	0.4
Ratio of Dam Crest Length to the Valley Length (for active dam crest length)	0.9	0	1.1	0	1.1	0	0.8	0	0.2
Percent of Total Dam Crest Length that is Actively Structurally-Forcing Flow	87.4	0.0	76.8	0.0	100.0	0.0	91.4	0.0	85.5
Inundation									
Integrated Wetted Width (*m*)	24	13	16	4	21	6	26	6	53
Total Inundated Area (m^2)	10026.5	4093.8	5487.4	1238.6	7191.4	2123.6	10937.7	2395.8	39235.0
Total Area of Free Flowing Inundation (m^2)	5809	4094	1250	1239	2124	2124	3637	2396	28121
Total Area of Ponded Inundation (m2)	3258	0	3423	0	3816	0	6818	0	7969
Total Area of Overflow Inundation (m2)	959	0	814	0	1252	0	482	0	3145
Percent of Valley Bottom that is Inundated (%)	15	6	12	3	21	6	20	5	14
Range of Estimated Valley Bottom Inundation when Accounting for Uncertainty	12.9 - 18.2	4.6 - 8	8.2 - 17.6	0.8 - 5.1	20.4 - 21.7	2.9 - 9.7	16.2 - 24.9	3.2 - 5.7	11.4 - 16.5
Percent of Valley Bottom with Free Flowing Inundation (%)	8.9	6.3	2.8	2.8	6.2	6.2	6.8	4.5	10
Percent of Valley Bottom with Ponded Inundation (%)	5	0	7.7	0	11.2	0	12.7	0	2.8
Percent of Valley Bottom with Overflow Inundation (%)	1.5	0	1.8	0	3.7	0	0.9	0	1.1
Shannon's Diversity Index Value	0.57	0.24	0.48	0.13	0.73	0.23	0.67	0.18	0.51
Shannon's Evenness Index Value	0.41	0.17	0.35	0.09	0.52	0.17	0.48	0.13	0.37

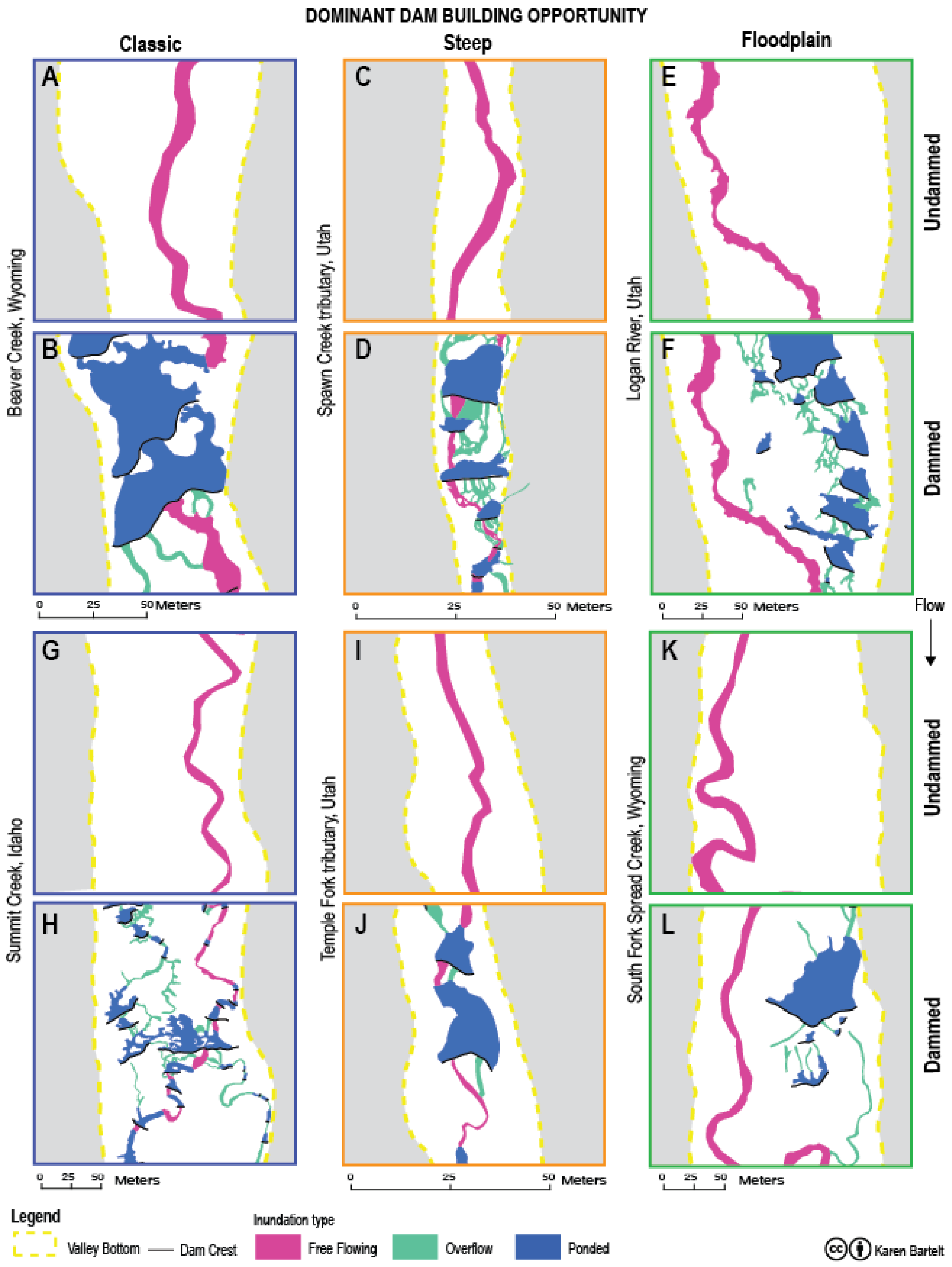

Figure B-1. Example of inundation mapping results across 6 of 37 sites. The columns are organized by dominant dam building opportunity (classic, steep, and floodplain) and the rows alternate showing the undammed and dammed survey from each site.

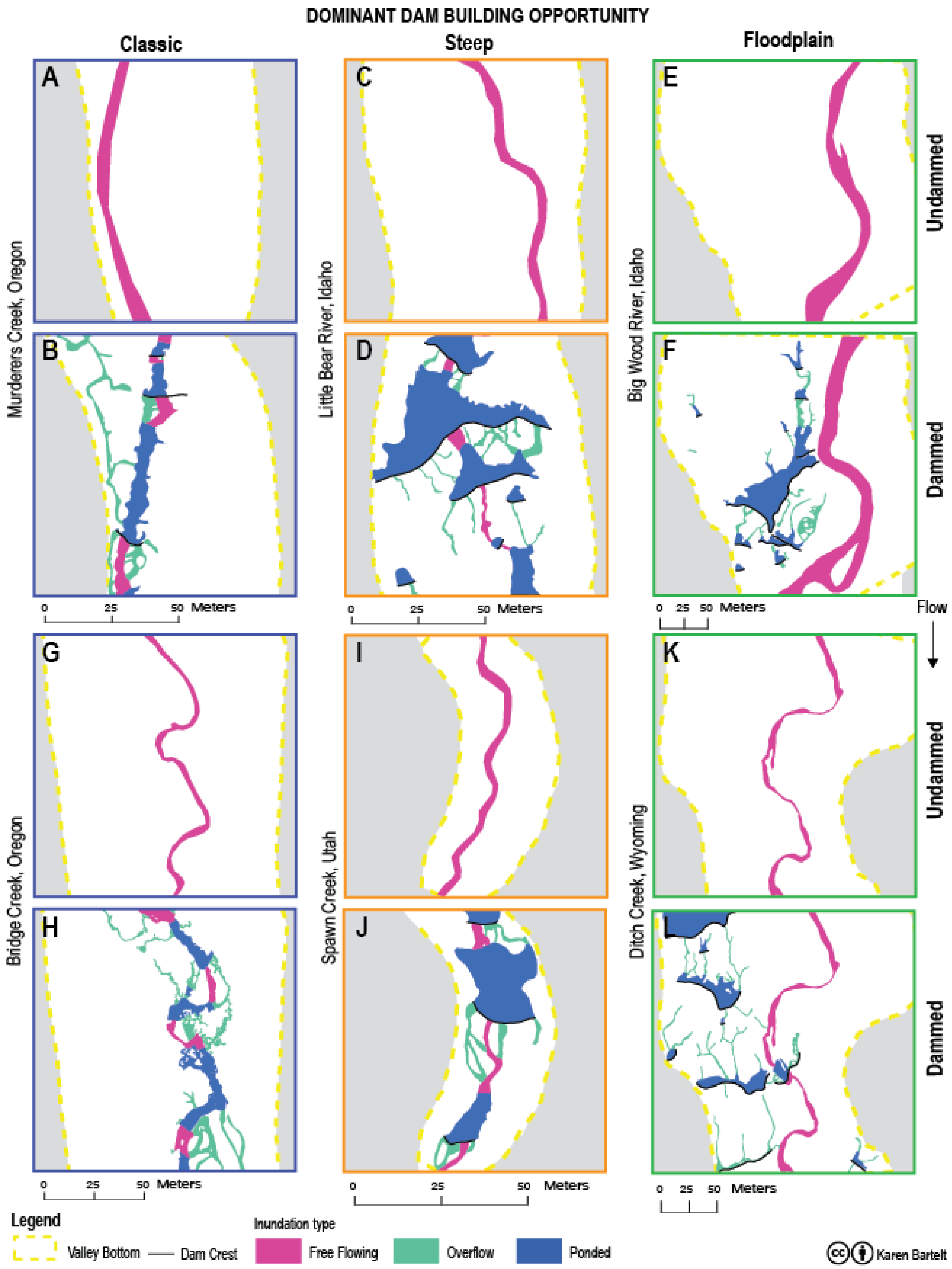

Figure B-2. Example of inundation mapping results across 6 of 37 sites. The columns are organized by dominant dam building opportunity (classic, steep, and floodplain) and the rows alternate showing the undammed and dammed survey from each site.

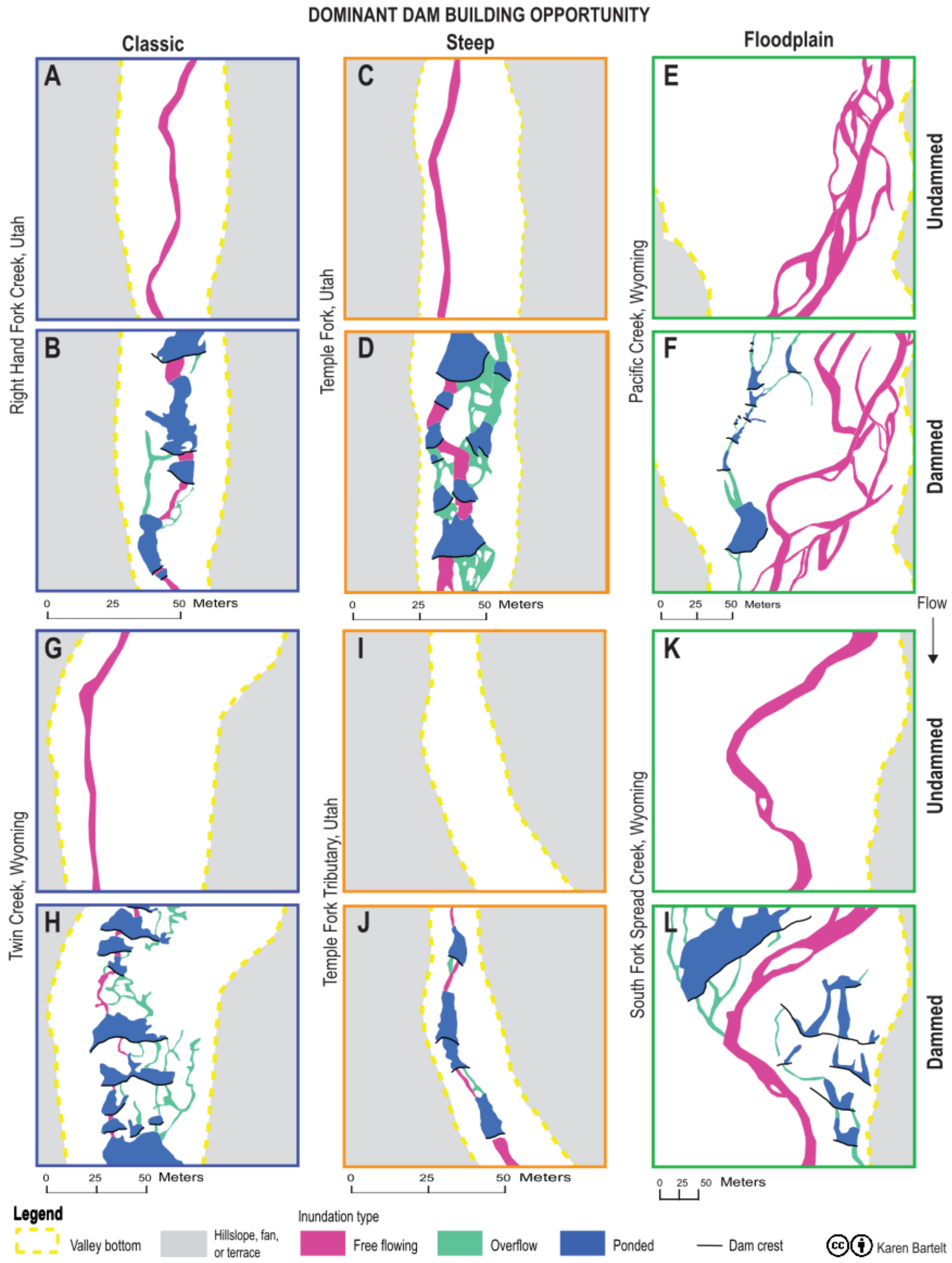

Figure B-3. Example of inundation mapping results across 6 of 37 sites. The columns are organized by dominant dam building opportunity (classic, steep, and floodplain) and the rows alternate showing the undammed and dammed survey from each site.

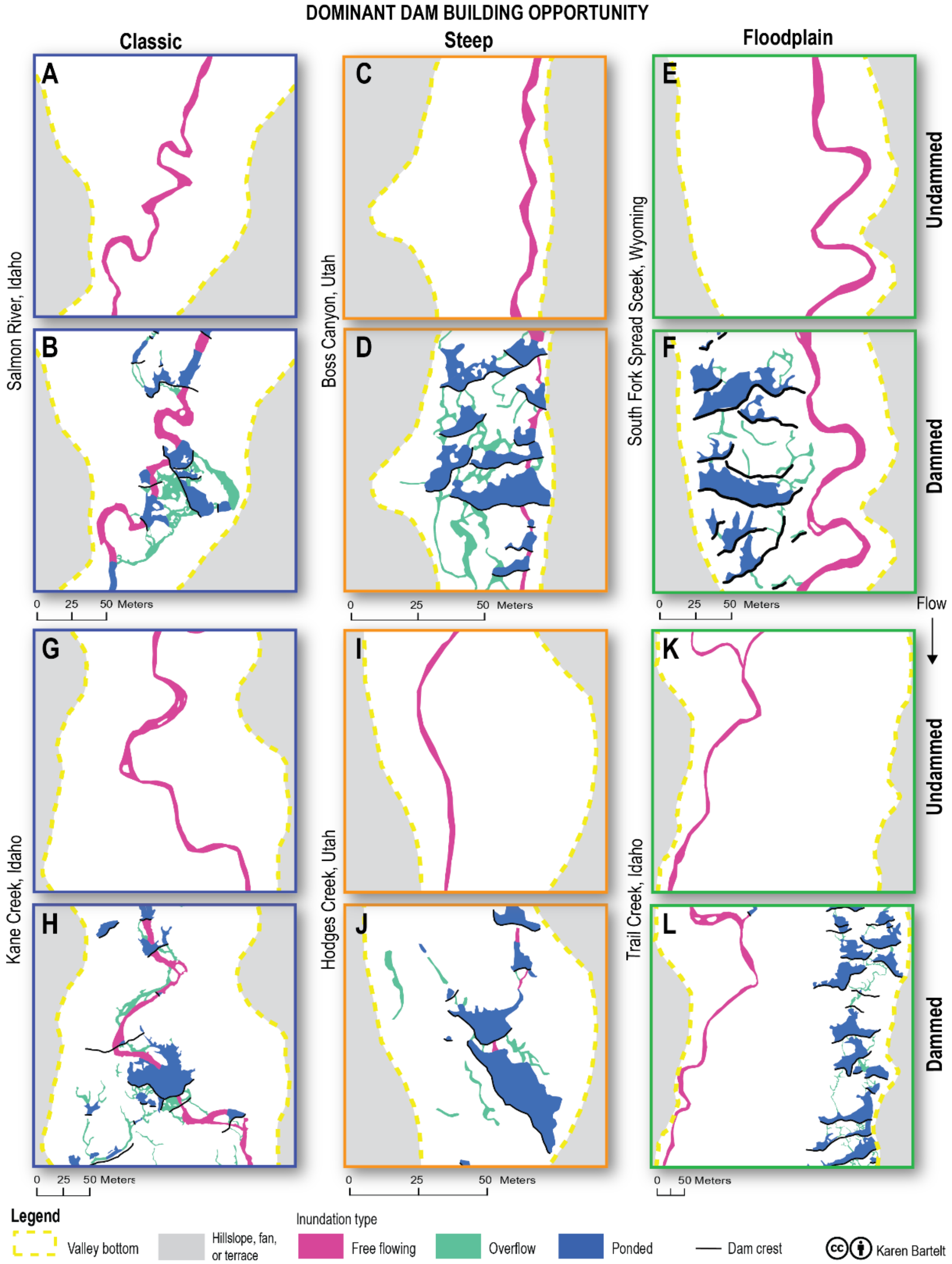

Figure B-4. The previous page shows an example of inundation mapping results across 6 of 37. The columns are organized by dominant dam building opportunity (classic, steep, and floodplain) and the rows alternate showing the undammed and dammed survey from each site. This Figure appears above in the thesis text but is included again here for completeness.

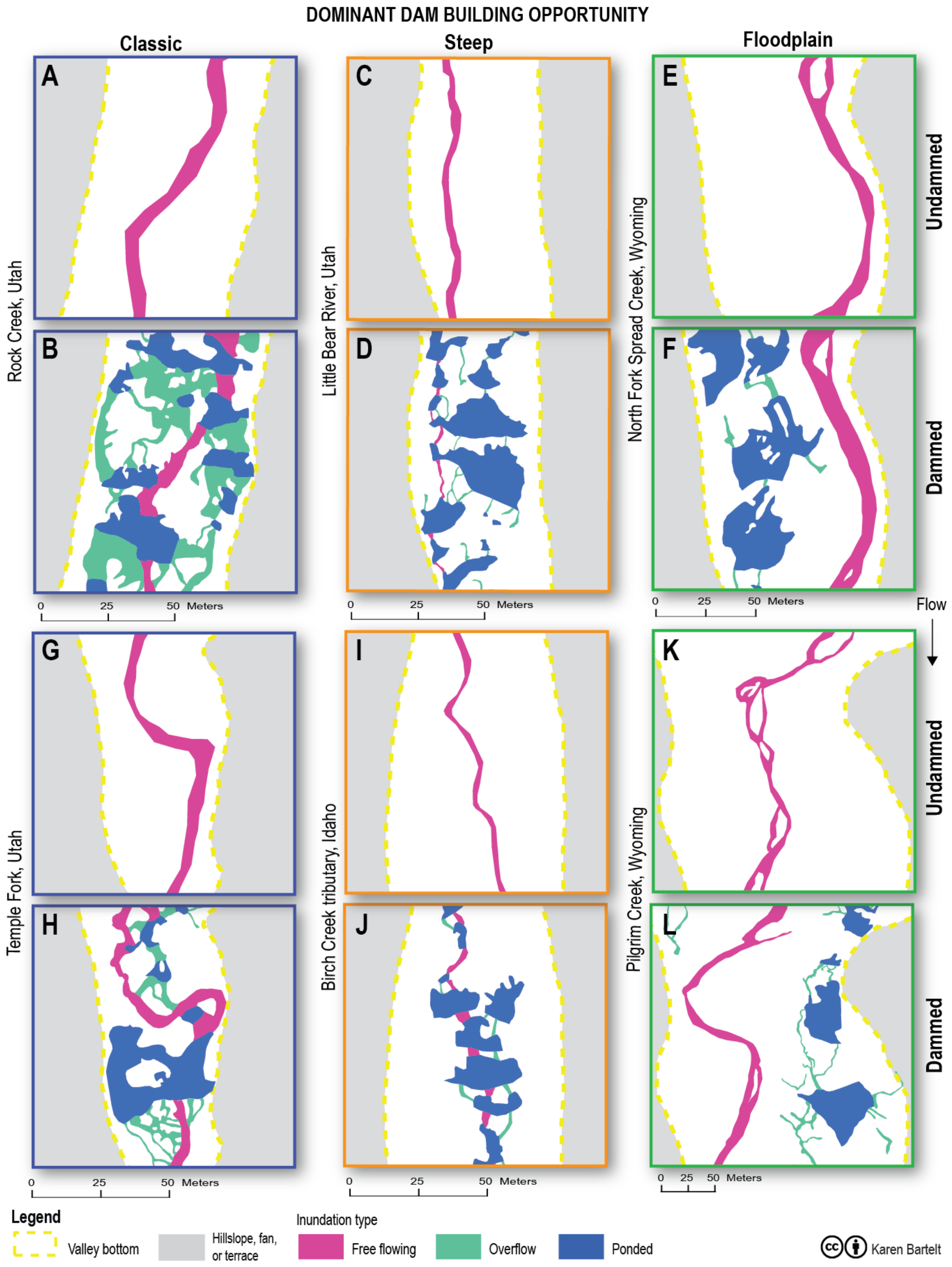

Figure B-5. The previous page shows an example of inundation mapping results across 6 of 37. The columns are organized by dominant dam building opportunity (classic, steep, and floodplain) and the rows alternate showing the undammed and dammed survey from each site. This Figure appears above in the thesis text but is included again here for completeness.

APPENDIX C

SUMMARY RESULTS

Table C-1. The sum, mean, and standard deviation for all metrics from Table 1. The values are organized by the results of the undammed and dammed surveys and grouped by dominant dam building opportunity. The furthest right columns have these summary metrics for undammed and dammed surveys from all sites.

		Classic						Steep						Floodplain						All					
Metric	**Field Name**	**Undammed**			**Dammed**			**Undammed**			**Dammed**			**Undammed**			**Dammed**			**Undammed**			**Dammed**		
Site		Sum	Mean	Standard Deviation	Sum	Mean	Standard Deviation	Sum	Mean	Standard Deviation	Sum	Mean	Standard Deviation	Sum	Mean	Standard Deviation	Sum	Mean	Standard Deviation	Sum	Mean	Standard Deviation	Sum	Mean	Standard Deviation
Valley or Site Area (m^2)	area	525326	30902	24720	525326	30902	24720	79895	7989	5198	79895	7989	5198	914840	91484	96276	914840	91484	96276	1520060	41083	60452	1520060	41083	60452
Hydrogeomorphic																									
Integrated Valley Width (*m*)	intWidth	1310	77	46	1310	77	46	400	40	19	400	40	19	2200	220	124	2200	220	124	3909	106	101	3909	106	101
Upstream Drainage Area (km^2)	iGeo_DA	875	51	80	875	51	80	105	11	9	105	11	9	1021	102	100	1021	102	100	2001	54	81	2001	54	81
Baseflow Discharge (*cfs*)	iHyd_Qlow	105	6	4	105	6	4	62	6	3	62	6	3	77	8	9	77	8	9	244	7	6	244	7	6
2 Year Recurrence Interval Discharge (*cfs*)	iHyd_Q2	1348	79	97	1348	79	97	319	32	22	319	32	22	2024	202	175	2024	202	175	3692	100	128	3692	100	128
Baseflow Stream Power (*watts*)	iHyd_SPLow	920	54	56	920	54	56	1197	120	57	1197	120	57	271	27	30	271	27	30	2388	65	61	2388	65	61
2 Year Recurrence Interval Stream Power (*watts*)	flow_stage	7597	447	381	7597	447	381	5996	600	366	5996	600	366	6860	686	363	6860	686	363	20453	553	376	20453	553	376
Channel Gradient	grad_chan	0.360	0.021	0.015	0.360	0.021	0.015	0.782	0.078	0.029	0.745	0.074	0.027	0.135	0.013	0.008	0.143	0.014	0.011	1.276	0.034	0.033	1.247	0.034	0.031
Channel Length (*m*)	len_chan	7458	439	228	8111	477	262	2126	213	104	2209	221	122	4331	433	183	4659	466	209	13915	376	211	14979	405	241
Valley Gradient	grad_vall	0.419	0.025	0.015	0.419	0.025	0.015	0.801	0.080	0.029	0.801	0.080	0.029	0.173	0.017	0.008	0.173	0.017	0.008	1.394	0.038	0.032	1.394	0.038	0.032
Valley Length or Site Length (*m*)	len_vall	6282	370	186	6282	370	186	2009	201	104	2009	201	104	3455	345	163	3455	345	163	11745	317	173	11745	317	173
Sinuosity - Main Thalweg (calculated as the main thalweg length divided by the valley length)	sinMainTwg	20.08	1.18	0.18	21.65	1.27	0.21	10.69	1.07	0.07	10.92	1.09	0.06	12.85	1.29	0.17	13.69	1.37	0.16	43.63	1.18	0.17	46.26	1.25	0.20
Relative Flow Length (calculated as the total of all thalweg lengths divided by the valley length)	sinAllTwg	20.32	1.20	0.22	51.58	3.03	0.88	11.11	1.11	0.16	23.69	2.37	0.77	17.37	1.74	0.82	42.32	4.23	0.96	48.80	1.32	0.51	117.59	3.18	1.11
Proportion of Total Thalweg Length that is the Main Thalweg (%)	twgPctMain	16.9	1.0	0.0	7.5	0.4	0.1	9.7	1.0	0.1	5.1	0.5	0.2	8.3	0.8	0.2	3.4	0.3	0.1	34.9	0.9	0.1	16.0	0.4	0.1
Structural Forcing																									
Number of Dams	dams_num	0	0	0	342.0	20.1	11.4	0	0	0	138.0	13.8	6.0	0	0	0	121.0	12.1	6.2	0	0	0	601.0	16.2	9.5
Dam Density (*dams/km*)	dam_dens	0	0	0	941.3	55.4	23.8	0	0	0	726.4	72.6	31.4	0	0	0	386.3	38.6	17.0	0	0	0	2054.0	55.5	27.0
Number of Intact Dams	intact_num	0	0	0	158.0	9.3	7.6	0	0	0	110.0	11.0	5.3	0	0	0	74.0	7.4	6.8	0	0	0	342.0	9.2	6.8
Number of Breached Dams	breach_num	0	0	0	153.0	9.0	7.9	0	0	0	25.0	2.5	2.5	0	0	0	40.0	4.0	3.0	0	0	0	218.0	5.9	6.3
Number of Blown out Dams	blown_num	0	0	0	29.0	1.7	1.9	0	0	0	2.0	0.2	0.6	0	0	0	6.0	0.6	1.3	0	0	0	37.0	1.0	1.6
Ratio of Dam Crest Length to the Valley Length (for all dams)	ratio_all	0	0	0	15.80	0.93	0.42	0	0	0	9.40	0.94	0.53	0	0	0	13.10	1.31	0.62	0	0	0	38.30	1.04	0.52
Ratio of Dam Crest Length to the Valley Length (for intact dams)	ratio_act	0	0	0	7.50	0.44	0.34	0	0	0	8.20	0.82	0.48	0	0	0	7.80	0.78	0.51	0	0	0	23.50	0.64	0.45
Ratio of Dam Crest Length to the Valley Length (for active dam crest length)	ratio_int	0	0	0	12.40	0.73	0.36	0	0	0	8.90	0.89	0.50	0	0	0	10.30	1.03	0.38	0	0	0	31.60	0.85	0.42
Percent of Dam Crest Length that is Actively Structurally Forcing Flow (%)	crstPctAct	0	0	0	1343.8	79.0	18.1	0	0	0	960.8	96.1	4.6	0	0	0	817.3	81.7	11.7	0	0	0	3121.9	84.4	15.4
Inundation																									
Integrated Wetted Width (*m*)	intWid_wet	71.3	4.2	1.4	218.6	12.9	5.1	20.8	2.1	0.9	85.0	8.5	2.8	105.6	10.6	11.7	238.2	23.8	11.6	197.7	5.3	6.8	541.8	14.6	9.1
Total Inundated Area (m^2)	tot_area	33276	1957	1408	105924	6231	4621	4308	431	259	17896	1790	936	54524	5452	8027	126413	12641	11468	92107	2489	4556	250233	6763	7693
Total Area of Free Flowing Inundation (m^2)	ff_area	33276	1957	1408	20888	1229	1052	4308	431	259	1749	175	129	54524	5452	8027	57434	5743	8093	92107	2489	4556	80072	2164	4684
Total Area of Ponded Inundation (m^2)	pd_area	0	0	0	59967	3527	3251	0	0	0	13007	1301	801	0	0	0	56291	5629	4669	0	0	0	129265	3494	3593
Total Area of Overflow Inundation (m^2)	ov_area	0	0	0	25069	1475	1322	0	0	0	3139	314	231	0	0	0	12688	1269	962	0	0	0	40896	1105	1126
Percent of Valley Bottom that is Inundated (%)	tot_pct	129.6	7.6	3.2	441.3	26.0	12.8	65.3	6.5	4.7	260.1	26.0	9.4	55.9	5.6	2.5	156.1	15.6	3.5	250.8	6.8	3.5	857.5	23.2	10.9
Minimum Estimated Percent Valley Bottom Inundation when Accounting for Uncertainty	minTot_pct	46.7	2.7	2.8	426.3	25.1	12.5	5.7	0.6	0.7	246.9	24.7	8.8	33.9	3.4	2.8	124.8	12.5	3.5	2.3	2.6		798.0	21.6	11.1
Maximum Estimated Percent Valley Bottom Inundation when Accounting for Uncertainty	maxTot_pct	255.2	15.0	9.2	456.7	26.9	13.1	145.4	14.5	9.8	273.7	27.4	10.0	79.1	7.9	2.4	191.2	19.1	4.5	479.7	13.0	8.5	921.6	24.9	10.9
Percent of Valley Bottom with Free Flowing Inundation (%)	ff_pct	129.6	7.6	3.2	80.5	4.7	2.8	65.3	6.5	4.7	31.8	3.2	3.1	55.9	5.6	2.5	60.2	6.0	2.4	250.8	6.8	3.5	172.5	4.7	2.9
Percent of Valley Bottom with Ponded Inundation (%)	pd_pct	0	0	0	260.5	15.3	9.6	0	0	0	175.5	17.6	4.8	0	0	0	78.4	7.8	3.0	0	0	0	514.4	13.9	8.0
Percent of Valley Bottom with Overflow Inundation (%)	ov_pct	0	0	0	100.2	5.9	3.9	0	0	0	52.9	5.3	5.2	0	0	0	17.6	1.8	0.8	0	0	0	170.7	4.6	4.1
Shannon's Evenness Index Value	SHEI_dry	3.22	0.19	0.06	9.35	0.55	0.17	1.62	0.16	0.09	5.41	0.54	0.16	1.52	0.15	0.05	4.12	0.41	0.07	6.35	0.17	0.07	18.88	0.51	0.16

Table C-2. The result of 15 different linear regression analyses testing the relationship between five measures of the degree of structural forcing (left column) and Percent Valley Bottom Inundated, Shannon Evenness Index, and Relative Flow Length.

Degree of Structural Forcing by Beaver Dams Metric	**Percent Valley Bottom Inundated**		
	R	p	R^2
% of BRAT Estimated Maximum Dam Capacity Realized	-0.089	0.6	0.0079
Ratio of Total Active Dam Crest Length to Riverscape Length	-0.16	0.33	0.027
Linear Dam Density *(dams/km)*	0.1	0.55	0.011
Total Active Dam Crest Length / Riverscape Area	0.56	0.00028	0.32
Dam Density by Area	0.49	0.0019	0.24
	Shannon Evenness Index		
	R	p	R^2
% of BRAT Estimated Maximum Dam Capacity Realized	-0.13	0.46	0.016
Ratio of Total Active Dam Crest Length to Riverscape Length	-0.21	0.21	0.044
Linear Dam Density *(dams/km)*	0.12	0.48	0.014
Total Active Dam Crest Length / Riverscape Area	0.54	0.00064	0.29
Dam Density by Area (dams/km2)	0.53	0.00074	0.28
	Relative Flow Length		
	R	p	R^2
% of BRAT Estimated Maximum Dam Capacity Realized	0.47	0.003	0.22
Ratio of Total Active Dam Crest Length to Riverscape Length	0.19	0.27	0.035
Linear Dam Density *(dams/km)*	-0.049	0.77	0.0024
Total Active Dam Crest Length / Riverscape Area	-0.43	0.0084	0.18
Dam Density by Area (dams/km2)	-0.36	0.029	0.13