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Is the ordinary high water mark ordinarily at bankfull? Applying a weight-of-evidence approach to stream delineation

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Abstract

The ordinary high water mark (OHWM) is a regulatory boundary essential to identifying the lateral jurisdictional limits of rivers and streams in the United States (U.S.). Bankfull is a scientific concept that has been defined and identified in a multitude of ways by scientists. Geomorphologist and hydrologist have long recognized that there can be variability in the identification of bankfull depending on how bankfull is defined. Furthermore, this variability is only increased by the inherent variability in stream characteristics that occurs along a reach of channel. Because of the overlap in the regulatory definition of OHWM and the scientific definitions of bankfull, one of the primary purposes of the study is to apply the definition of OHWM and compare it to bankfull in a variety of channel types in different climatic, hydrologic, and geologic settings. Our results show that there is a clear overlap between the identification of the OHWM and bankfull elevations. Regulatory practitioners are generally not specialized in fluvial geomorphology and yet are tasked with consistently and accurately identifying the OHWM in a variety of stream types throughout the U.S. Therefore, we also present how to apply a weight-of-evidence approach through a clear step-by-step process to potentially improve consistency and accuracy in identification of OHWM and bankfull by both scientists and non-scientists.

KEYWORDS
ordinary high water mark, bankfull, weight of evidence, multivariate regression tree analysis

1 | INTRODUCTION

The ordinary high water mark (OHWM) is a regulatory boundary that was first defined in the United States (U.S.) in the Rivers and Harbors Act of 1899 (33 U.S. Code § 401 et seq.), well before the concept of bankfull was first defined in the geomorphic literature (Williams, 1978; Wohl et al., 2016; Wolman & Leopold, 1957). The federal regulatory definition of the OHWM (33 Code of federal regulation (CFR) 328.3(c)(4), 33 CFR 329.11(a)(1), and USACE Regulatory Guidance Letter No. (RGL) 05-05) states, "The term ordinary high water mark means that line on the shore established by the fluctuations of water and indicated by physical characteristics such as [a] clear, natural line impressed on the

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Research Impact Statement

The ordinary high water mark and bankfull can be delineated at the same elevation in a variety of streams across the country. Applying weight-of-evidence method improves consistency and accuracy in identification.

bank, shelving, changes in the character of soil, destruction of terrestrial vegetation, the presence of litter and debris, or other appropriate means that consider the characteristics of the surrounding areas." Because OHWM is a specific regulatory term used to define the lateral jurisdictional limits of rivers and streams for regulatory purposes within the U.S. and is not necessarily a driver of, predictive factor for, or otherwise informative to geophysical processes, it has not been a point of investigation by the scientific community who instead use scientifically defined concepts such as bankfull to describe the channel morphology of streams (Buffington, 2012; Leopold et al., 1964; Sarker, 2023; Schumm et al., 1984; Thorne et al., 1996; Williams, 1978; Wolman & Leopold, 1957; Wolman & Miller, 1960). However, the OHWM plays an extremely important role nationally because it defines the lateral limits of rivers and streams and is a factor that can inform the jurisdictional status of aquatic resources under the Rivers and Harbors Act of 1899 and the Clean Water Act. The bankfull channel is a concept that is used widely by river scientists and is typically documented using some of the same persistent channel characteristics that are used to identify the OHWM (Table 1). Bankfull is often defined either geomorphically as the incipient flood elevation (Wolman & Leopold, 1957) or hydrologically as the flow that does the most work (dominant discharge) by carrying the most sediment (effective discharge) and therefore is responsible for forming or maintaining the channel (Leopold et al., 1964; Williams, 1978; Wolman & Miller, 1960).

In scientific studies, the elevation of bankfull is characterized to describe the flows responsible for forming the current channel or to understand the magnitude of flows responsible for the movement of sediment. Bankfull discharge is often used as a reference level to be able to analyze variability between sites whether on the same stream system or in comparing systems (Blom et al., 2017; Buraas et al., 2014; Keast & Ellison, 2022; Lindroth et al., 2020; Powell et al., 2006). Despite the breadth of research surrounding the bankfull channel over the past

TABLE 1 Comparison of ordinary high water mark (OHWM) definition from CFR 328.3(c)(7) and Regulatory Guidance Letter (RGL) 05-05 to definition of bankfull in scientific studies.

OHWM definition from 33 CFR 328.3(c)(7)	Additional physical characteristics of OHWM listed in RGL 05-05	Bankfull descriptions with references
"A clear, natural line impressed on the bank, shelving"	Bed and banks; water staining; scour, deposition	The boundary between the active channel and floodplain commonly exists as a clear, natural line impressed on the bank of a river (Wolman & Leopold, 1957) There is usually a topographic break at bankfull. The streambank may change from a sloping bar to a vertical bank. It may change from a vertical bank to a horizontal plane on top of the floodplain. The change in topography may be a subtle as a change in the slope of the bank (Leopold, 1994)
"Changes in the character of soil"	Sediment sorting; scour; deposition	The boundary between the active channel and surrounding floodplain creates hydraulic conditions what will cause a transition between river sediment and soils on an adjacent floodplain (Leopold & Skibitzke, 1967) Bankfull is often registered by a change in the size distribution of materials at the surface, from fine gravel to cobbles, from sand to gravel or even fine gravel material. It can change from fine to coarse or coarse to fine, but a change in common (Leopold, 1994)
"Destruction of terrestrial vegetation"	Vegetation matted down, bent, or absent; change in plant community	Terrestrial vegetation is commonly destroyed by the hydraulic forces associated with frequent flows below bankfull discharge (Leopold & Skibitzke, 1967) The upper limit of the measured depth could be selected not only as the edge of a terrace or bank but also as the lower edge of permanent vegetation and the upper limit of fairly recent deposition or erosion along the sides of the channel (Schumm, 1960) The bankfull level is usually marked by a change in vegetation, such as a change from bare gravel bar to forbs, herbs, or grass (Leopold, 1994)
"The presence of litter and debris"	Leaf litter (LL) disturbed or washed away; wracking	Litter and debris will likely be deposited and persist above bankfull discharge (Leopold & Skibitzke, 1967) Even more subtle are changes in the debris deposited between rocks, such as the amount of leaves, seeds, needles, or organic debris (Leopold, 1994)

60 years, there are still many questions on how best to identify the bankfull elevation in different hydrogeomorphic settings, or in more recent research how best to describe the inherent variability in bankfull elevations along a stream reach (Buraas et al., 2014; Keast & Ellison, 2022; Lindroth et al., 2020; Powell et al., 2006). Williams (1978) outlined 16 different definitions of bankfull that could result in differences in determining bankfull elevation. Bankfull has been described as the elevation of the active floodplain (Wolman & Leopold, 1957) with both geomorphic and ecologic significance because of the transfer and redistribution of organisms, organic matter, and nutrients (Bouwman et al., 2013; Keast & Ellison, 2022). Bankfull has been described as either a "low bench" elevation (Bray, 1972; Schumm, 1960) or, in the case of more incised streams, as a "middle bench" (Woodyer, 1968). Bankfull has also been described as the elevation of the highest surfaces of the channel bars (Lewis & McDonald, 1973), at the lower elevational limit of perennial vegetation (Bray, 1972; Schumm, 1960; Williams, 1978), or the upper limit of sand-sized particles (Leopold & Skibitzke, 1967). In addition to these physical ways of identifying bankfull elevation, there have been attempts to characterize bankfull in quantitative ways using changes in width and depth along a channel cross section by looking at where the ratio becomes a minimum in relation to stage (Johnson & Heil, 1996; Riley, 1972; Wolman, 1955). Using this ratio to identify bankfull assumes that bankfull is at the incipient flood stage; therefore, at the point of bankfull, the cross section will become exceedingly wide and there will be a curve of width-to-depth plotted against stage will have a sharp break. Furthermore, Riley (1972) points out that this estimation of bankfull works best on channels with rectangular cross section shapes, but not as well on channels with a shallow profile and gently sloping banks. Therefore, Riley (1972) proposed a bench index:

$$\mathrm{BI} = \frac{W_i - W_{(i+1)}}{D_i - D_{(i+1)}}, \tag{1}$$

where BI is the bench index, $W_{(i)}$ and $D_{(i)}$ are the width and depth with $i=1, 2, \ldots n-1$. Another quantitative way to characterize bankfull outlined by Williams (1978) is by taking the relationship of area:width against the stage.

These characteristics are all similar to how OHWM is defined both in 33 CFR 328.3 and in RGL 05-05 (Table 1). Despite the clear overlap in the various definitions of bankfull and OHWM, practitioners have sometimes observed that they are not always at the same elevation. In some cases, this may be because study-specific goals can influence which definition of bankfull is most relevant versus the OHWM being defined based on the one regulatory definition. This type of discrepancy in definitions of bankfull can make it difficult to compare results across studies (Navratil et al., 2006). Another complication is the spatial variability in identifying bankfull elevation along a reach of channel. Lindroth et al. (2020) examined variability along a reach of stream and found that the elevation range of mean variability in bankfull stage can influence the shape of developed rating curves. All these studies together suggest that bankfull is not just one single flow, but a range of high flows that then leave behind high flow indicators at a range of elevations (Navratil et al., 2006; Pickup & Rieger, 1979). Because OHWM is a regulatory definition that applies to all non-tidal rivers and streams, practitioners need to be able to consistently identify the correct boundary throughout the U.S., no matter the channel type or hydrogeomorphic setting. Therefore, it is important that there is agreement on the type of stream characteristics that are being identified and what magnitude of flows those are connected too. When identifying the OHWM, practitioners need to be able to document one or more static physical indicators of ordinary high flows. Understanding variability that occurs along the reach of a stream better informs sound regulatory decisions. Few studies investigate this type of variability in the context of OHWM and bankfull, although Williams (1978) outlines 16 definitions for bankfull and shows the variability that can result in bankfull discharge calculations when applying all 16 definitions to a stream reach. Johnson and Heil (1996) used Williams (1978) data to argue the demonstrated variations in bankfull discharge at a site can be attributed to vague definitions of bankfull and the subjective nature of selecting bankfull indicators. Bankfull flows have been found to have recurrence intervals between 1.01 and 5 years in perennial rivers (Castro & Jackson, 2001; Haucke & Clancy, 2011; Leopold et al., 1964; Wolman & Leopold, 1957; Wolman & Miller, 1960) and 1.01 and 20 years in arid systems (Williams, 1978). Redecki-Pawlik (2002) further demonstrates that bankfull discharge should be defined as a range of discharges rather than a deterministic value-specific location. Although recurrence intervals can constrain at what discharge, and therefore elevation, is likely to correspond to the OHWM, it can be problematic to base determinations on a single value throughout the entire nation because (1) recurrence intervals can only be calculated for segments of a stream near a stream gage and (2) a statistical description of streamflow do not account for the variability in elevation of high flow indicators that are often found along stream boundaries.

The weight-of-evidence (WoE) approach, as outlined in this paper, provides practitioners with a clear method to enhance consistency and accuracy in identifying both the OHWM boundary and bankfull elevation. The overarching purpose of this paper is to show that the regulatory definition of OHWM overlaps with various scientific definitions of bankfull, so that practitioners have a better understanding of how to link these two concepts. The WoE approach provides a useful method for organizing high flow stream characteristics as lines of evidence and then sorting through the evidence by determining the relevance, strength, and reliability of each line of evidence to narrow down the location of either bankfull or OHWM and eventually integrate the lines of evidence to draw a final conclusion. This can reduce the subjectivity in identifying bankfull indicators that Johnson and Heil (1996) discuss and improve reproducibility. Practitioners who are not necessarily trained in landscape interpretation at the level of a geomorphologist could benefit from a clear step-by-step process that would help them interpret the individual lines of evidence to more easily conclude the elevation of the OHWM. To trained personnel, there are many locations where the elevation of OHWM and bankfull are obvious, but the WoE approach can be beneficial in areas where identification is challenging. The WoE approach outlines a method of assembling evidence, integrating the evidence by first qualitatively weighting each line of evidence in terms of relevance, strength, and reliability, and then weighing the body of evidence for the final conclusion (David et al., 2022; Linkov et al., 2009; Suter, 2016). This logical process is likely often being applied in simple situations, but so rapidly that the practitioner's may not notice that they are doing it.

In this study, we apply the definition of OHWM and compare it to bankfull in a variety of channel types in different climatic, hydrologic, and geologic settings. We then demonstrate how to apply a WoE approach in all of these different hydrogeomorphic settings to assist in identifying both the OHWM and bankfull in a clear step-by-step process which can help with reproducibility. The objectives of this study are to answer the following three questions: (1) Is the identification of the regulatory boundary of the OHWM the same as the identification of bankfull elevation? (2) What are the linkages between the observed physical characteristics, particularly ones identified as high flow indicators, and flow recurrence intervals in different hydrogeomorphic settings? (3) How can the WoE approach be used to organize and evaluate the observations of physical characteristics to draw a logical conclusion as to the location of the OHWM and bankfull?

Bankfull and OHWM will change over time as stream channels evolve in response to larger scale changes in both land use and climate (Bastola & Diplas, 2023; Buffington, 2012; Bull, 1991; Goudie, 2006; Schumm, 1979; Wohl, 2020; Wolman & Gerson, 1978). Identifying the current bankfull channel is an important factor for restoring rivers that are degraded from past land use and climate changes. For instance, the bankfull elevation needs to be identified before calculating bankfull flows for channel design (Copeland et al., 2001; Rosgen, 2011). Furthermore, the OHWM is assessed by practitioners for permitting based on current conditions; therefore, this paper focuses on identifying the lines of evidence that would lead to evaluating the current elevation of the OHWM and bankfull and not in predicting past or future elevations.

1.1 | Study area

To better understand variability in identification of OHWM based on hydrogeomorphic regions and variability in channel types, sites with differing climatic and land use histories were chosen throughout the United States (Figure 1). Overall, 15 sites were surveyed near USGS streamgages on wadeable reaches throughout the U.S. (Table 2; Figure 1). Streams varied in size and position in the watershed from the 3466 km^2 drainage area (Estrella River, CA) to the 14.1 km^2 drainage area of (Beetree Creek, NC). Land use varied from watersheds with heavy agricultural use versus urban or forested watersheds. Channel types varied between low slope, sand-bed meandering channels (Cobb Creek, OK) to cascading confined mountain streams (Beetree Creek, NC). The San Antonio River is the only braided channel included in the study. Figure 2 shows a photograph of each of the study sites and Table 2 describes the overall characteristics of each site.

2 | METHODS

2.1 | Field data collection

Field data collection consisted of morphological feature-based topographic surveys at 15 sites from differing hydrogeomorphic settings across the nation. The surveys consisted of at least two cross sections extending beyond the active floodplain and a thalweg used to calculate the reach slope. Cross section and longitudinal profile data were collected with a Trimble total station at 10 sites and with a Trimble RTK GPS at five additional sites. Field survey sites were located upstream or downstream of USGS streamgages. Because streamgages are often at bridges, we attempted to move far enough upstream or downstream to reduce variability caused by impacts from road-stream crossing on the site. Vegetation type, vegetation height, sediment, and soil characteristics were recorded at each point along the cross sections surveyed (Table 3). Cross section point density varied between 15 points on small streams to more than 100 in larger systems. The point spacing varied depending on topographic breaks in slope and the locations where there were changes in the channel characteristics. Bed grain size was characterized using a Wolman (1954) pebble count to measure the length along the *b*-axis of 300 pebbles. Pebble counts were not completed at six of the sites, because of time constraints during surveying. Therefore, the bed was characterized visually rather than from a detailed analysis of grain size (Table 2).

To preserve objectivity, the elevation of the OHWM and bankfull for each cross section was determined after the field surveys were completed. Bankfull elevation was determined using three quantitative methods and five methods based on physical indicators (Table 4) (Keast & Ellison, 2022; Navratil et al., 2006; Williams, 1978). In channels that were incised, the bankfull elevation was determined to be at the location of a newly developing floodplain when looking at the morphologic break in slope, but was compared to the higher valley floor elevation when using that definition. The elevation of OHWM was identified by using the regulatory definition, as well as characteristics listed in regulatory guidance letter (RGL 05-05) (USACE, 2005), which includes morphologic and vegetative characteristics, as well as other lines of evidence such as organic litter deposition (Table 1) (David et al., 2022).

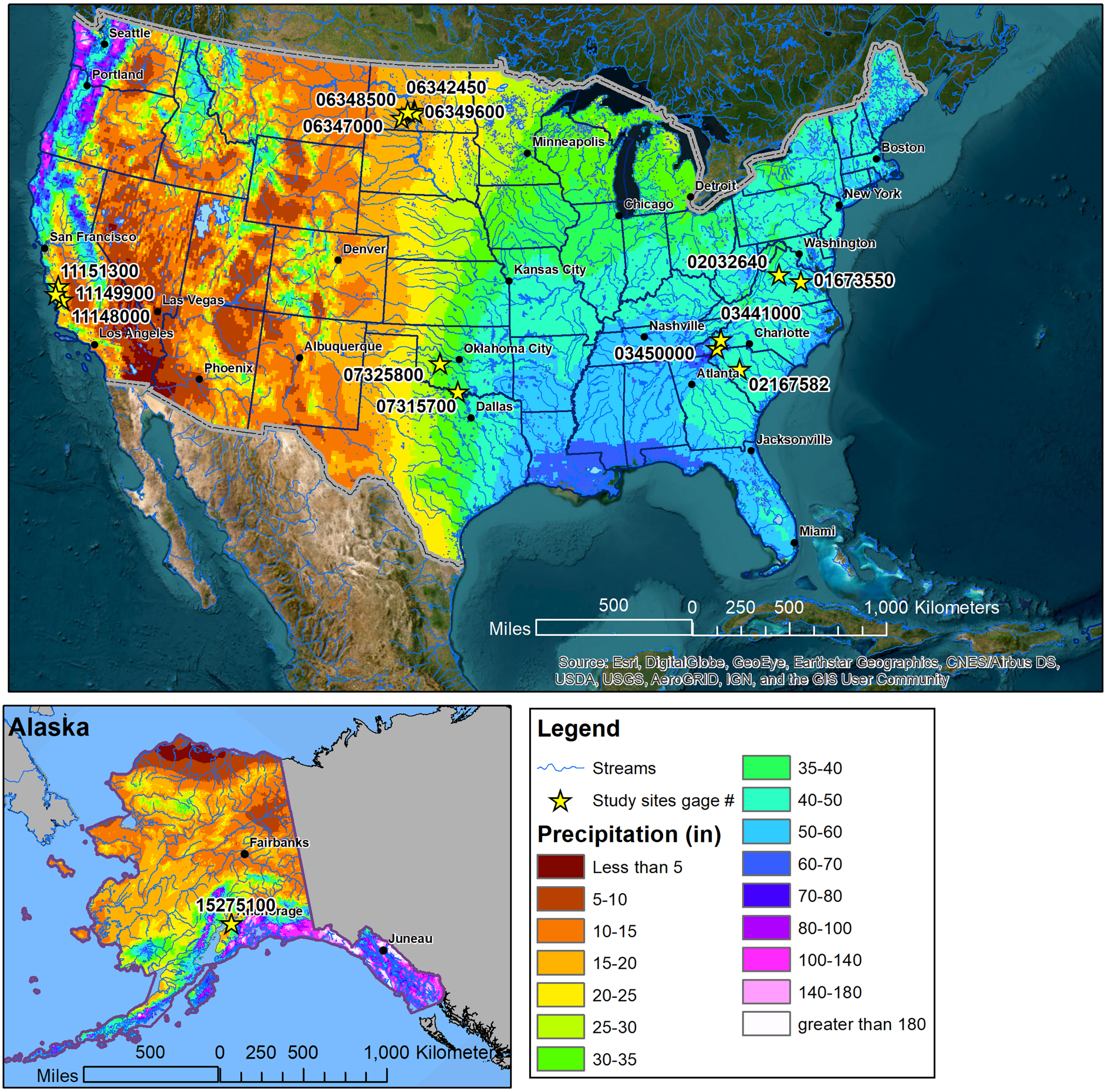

FIGURE 1 Location of study sites in continental United States and Alaska. Each site is shown using the USGS streamgage number.

2.2 | Flow models

One-dimensional steady-state hydraulic models were used to create water surface profiles at each surveyed site (Hamill & David, 2021). The Hydrologic Engineering Center River Analysis System (USACE, 2016) computes one-dimensional steady-state water surface profiles using an iterative solver between equations describing water surface elevations and flow conveyance. The water surface profiles derived from a steady-state hydraulic model provide a way to relate flow magnitude to the elevations of the surveyed indicators. Flow conveyance through a single cross section is computed using Manning's Equation (Chow, 1959; Einstein & Barbarossa, 1952). Water surface elevations between two cross sections are determined using Bernoulli's Equation (Chow, 1959). The program iterates to find a solution that minimizes water surface elevation error across all cross sections in the model.

The georeferenced hydraulic model geometries at each site included a river centerline, bank lines, cross sections at the locations of the surveyed cross sections, and bare-earth digital elevation model (DEM) of the surrounding terrain. The highest resolution DEM was obtained for each site and varied between 1 and 30 m resolution. The field-surveyed points along each cross section were used to provide a more detailed representation of the riverbanks and channel bathymetry by overwriting the topographic elevations directly

TABLE 2 Watershed and channel characteristics for study sites. Median grain size is shown for those sites where pebble counts were conducted.

Region	USGS gage #	Gage name	Survey date and location relative to gage	Geology	Land use	Channel type	Drainage area (km^2)	Reach slope	Mean annual discharge (m^3/s)	Dominant substrate (DS; median grain size (mm), D_{50})
Northeast	01673550	Totopotomoy Creek near Studley, VA	4/10/2017 140 m downstream	Sand and gravel	Urban	Sand-bed	66.6	0.009	0.78	Medium sand (0.34 mm)
	02032640	NF Rivanna River near Earlysville, VA	4/13/2017 200 m downstream	Metamorphic rocks (biotite-gneiss and metabasalt)	Agriculture Forested	Pool-riffle	279.1	0.005	3.8	Fine gravel (4.50 mm)
	03441000	Davidson River near Brevard, NC	3/15/2017 30 m upstream	Metamorphic rocks (biotite-gneiss)	Forested	Pool-riffle	104.3	0.0053	3.63	Cobbles/Gravel (NA)
	03450000	Beetree Creek near Swannanoa, NC	3/16/2017 5 m upstream	Metamorphic rocks (metagraywacke)	Forested	Cascade	14.1	0.0207	0.32	Boulders/Cobbles (NA)
Southeast	02167582	Bush River nr Prosperity, SC	3/13/2017 770 m downstream	Igneous rocks (Granite and metavolcanic rocks)	Agriculture Forested	Pool-riffle	303.3	0.0015	2.53	Sand/Gravel (NA)
Southern Prairies	07325800	Cobb Creek near Eakly, OK	1/30/2017 100 m upstream	Sedimentary rocks (sandstone)	Agriculture	Meandering incised	341.2	0.0007	0.83	Sand bed (NA)
	07315700	Mud Creek near Courtney, OK	2/1/2017 360 m upstream	Sedimentary rocks (shale/sandstone)	Agriculture	Meandering	1488.5	0.0014	5.34	Sand and clay bed with bedrock exposure (NA)
Northern Prairies	06347000	Antelope Creek nr Carson, ND	6/27/2017 At gage	Sedimentary rocks (claystone)	Agriculture	Meandering, incised	614.3	0.0044	0.33	Very large pebbles (51.35 mm)
	06342450	Burnt Creek nr Bismarck, ND	6/29/2017 125 m downstream	Sedimentary rocks (claystone)	Agriculture	Meandering incised	285.7	0.0067	2.30	Very coarse sand (1.77 mm)
	06349600	Hay Creek at Main Avenue in Bismarck, ND	6/26/2017 190 m downstream	Sedimentary rocks (shale)	Urban	Straight	82.4	0.0081	0.17	Fine gravel (3.75 mm)
	06348500	Sweetbriar Creek nr Judson, ND	6/28/2017 260 m downstream	Sedimentary rocks (claystone/siltstone)	Agriculture Forested	Meandering	407.4	0.0129	0.27	Small cobbles (117.99 mm)
Southwest	11148000	Estrella River nr Paso Robles, CA	12/7/2016 100 m upstream	Sedimentary rocks (sandstone)	Forested	Entrenched, meandering	3466.6	0.0004	0.46	Sand bed
	11151300	San Lorenzo C bl Bitterwater C nr King City, CA	12/12/2016 At gage	Sedimentary rocks (sandstone)	Forested	Meandering Sand/gravel bed and bedrock	604.0	0.0044	0.38	Coarse gravel (15.75 mm)
	11149900	San Antonio River nr Lockwood, CA	12/9/2016 75 m upstream	Sedimentary rocks (sandstone)	Forested	Braided	558.1	0.0019	2.85	Medium gravel (9.61 mm)
Alaska	15275100	Chester Creek at Arctic Boulevard at Anchorage, AK	8/14/2017 60 m upstream	Interlayered sedimentary and volcanic rocks	Urban Forested	Straight gravel bed	316.3	0.0097	0.69	Medium gravel (12.45 mm)

FIGURE 2 Photographs looking upstream or downstream at each study site.

extracted from the DEM. A final model terrain was obtained by merging a surface representation of the surveyed cross sections with the surrounding terrain. Initial parameterizations of Manning's at each cross section were obtained based on tabulated values of various morphological characteristics.

The hydraulic models were calibrated using the hydraulic roughness coefficient and the USGS rating curve for the nearest streamflow gage by vertically and horizontally varying the hydraulic roughness to match the modeled and observed rating curves. The boundary conditions for the hydraulic models assumed subcritical flow and a normal depth boundary condition at the downstream cross section.

2.3 | Hydrologic analysis

The hydrologic analysis of OHWM and bankfull involved developing water surface profiles for a range of discharge magnitudes derived from an analytical flow frequency distribution (Figure 3). Hamill and David (2021) developed at-a-site Log Pearson III flow frequency distributions fit to USGS peak flow time series. The number of water surface profiles modeled at each site varied between 11 and 38. Ultimately, the number of water surface profiles at each site depended on how many high flow indicators were surveyed and the shape (skew and standard deviation) of the flow-frequency distributions. The water surface profiles were assigned categorical labels representing the recurrence interval of the non-exceedance probability of each profile. Across site comparisons of bankfull, OHWM, and the locations of high flow indicators were based upon the recurrence interval labels. This provided a means of relating results from sites with large variations in geometry and watershed size.

TABLE 3 Categories and field codes used for data collection at each site. Codes were used as input for the independent variables that are shown below that were then included in the multivariate regression tree analysis (MVRT) analysis.

Feature type	Feature description							
Vegetation type (VT)	0—Bare ground	1—mosses (continuous cover on boulder or bedrock)	2—forbs (saplings included)	3—grasses (both short and tall)	4—shrubs (woody stem, <5 cm dbh)	5–8 deciduous trees 5—small (woody stem, 5–20 cm dbh) 6—medium (20–35 cm dbh) 7—large (35–50 cm dbh) 8—extra large (>50 cm dbh)		9–12 coniferous trees 9—small (5–20 cm dbh) 10—medium (20–35 cm dbh) 11—large (35–50 cm dbh) 12—extra large (>50 cm dbh)
Vegetation height (VH)	0—short (<30 cm)	1 short/medium (30–60 cm)		2 medium (60–90 cm)		3 medium/tall (90–120 cm)	4 tall (120–200 cm, includes grasses)	5—tall >2 m
DS	0—soil	1—silt and clay (0–0.0625 mm)		2—sand (0.0625–2 mm) v. coarse, coarse, medium, fine, v. fine		3—gravel (2–64 mm) v. coarse, coarse, med., fine, v. fine	4—cobble (65–256 mm)	5—boulders 6—bedrock
Soil type (ST)	0—none (bare rock and/or no soil)	1—discontinuous (some soil and/or some bare rock)	2—Thick organic material overlying sediment	3—continuous soil with no distinct horizons	4—Soil with undeveloped A horizon; Can have thin organic layer or humus	5—soil with developed A horizon	6—Soil with thick organic horizon	7—Soil with O horizon and humus
LL	0—none (no litter)	1—discontinuous (litter present in small patches)				2—continuous (continuous litter present)		
Canopy cover (CC)	0—none (full light, no CC)	1—partial shade (under canopy, but receives direct incident light)				2—fully shade (under closed canopy)		3—canopy tree (a canopy dominant tree)

TABLE 4 Bankfull elevation is identified using the following eight methods separated into qualitative and quantitative methods.

Qualitative methods	Quantitative methods
(1) Morphologic bankfull (break in slope on channel bank)	(6) Width-to-depth ratio
(2) Elevation of valley flat	(7) Riley's Bench Index
(3) Upper extent of bar deposit	(8) Area:Width relationship
(4) Change in VT and density	
(5) Change in sediment type and soil development	

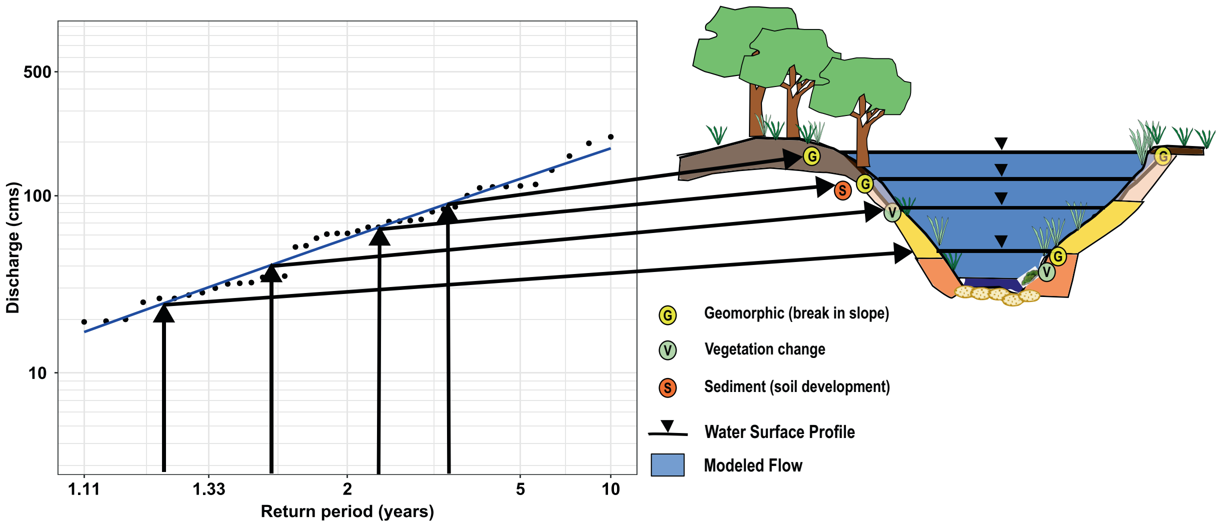

FIGURE 3 Conceptual diagram showing relationships between hydrologic analysis and surveyed field indicators. Statistically defined magnitudes of discharge were used to describe surveyed filed indicators by relating modeled water surface elevations to the indicator elevation.

2.4 | Descriptive flow categorization

The flows were categorized as low, moderate, high, and extreme flows and drawn on each cross section at each site to further examine how streamflow can be used as an additional line of evidence in WoE approach. The descriptive flow categories are based upon multiple statistical flow metrics and hydraulic model derived water surface profiles (Figure 3). The upper elevation of the low-flow category is defined by the water surface elevation associated with mean annual streamflow at each site. The lower elevation of the high flow category is defined using water surface elevation associated with a 1% exceedance probability on a flow duration curve. The upper elevation of the high flow is based on water surface elevation of the flow begins to inundate the floodplain, levee, or terrace. The moderate-flow category is the portion of the channel above the upper bound of the low flows and below the lower bound of high flows. Similarly, extreme flows are any flows larger than the upper boundary of the high flows. The flow categories are used to provide supporting evidence as to the logical location of the OHWM and bankfull, where it is more likely to exist at elevations bounded by the high flow category.

2.5 | Statistical analysis

Cross section data were analyzed together with flow data using a multivariate regression tree analysis (MVRT; De'ath, 2002) in R statistical software (R Core Team, 2023) using the mvpart package (De'ath, 2011). MVRT is an extension of both a univariate and categorical regression trees. The trees are created using a recursively partitioning set of response variables using variable thresholds. A multivariate regression tree minimizes the internal model error using cross-validation algorithms that prioritize predictive power and penalize overly complex trees. Multivariate regression trees have been found to be useful in both ecological studies (Chen et al., 2010; DeVantier et al., 2006; Sheaves et al., 2007; Szalóky et al., 2021) and hydrologic studies (Paez-Trujilo et al., 2023; Pike & Scatena, 2010) because they allow for the evaluation of analysis of complex datasets with complicated interactions that may include nonlinear relationships between variables and missing values (Kim & Lee, 2021).

The use of the MVRT analysis was modeled from Pike and Scatena's (2010) study of streams in Puerto Rico, with a few differences. First, the recurrence intervals are based on an annual maximum flood frequency curve, not a flow duration curve. In this study, the MVRT was used to examine trends of changes in vegetation, soil characteristics, leaf litter, and canopy cover occurring at high flows because low flows do not have a specific recurrence interval that could be applied to it based on a statistical analysis of the annual maximum series. The MVRT is analyzing significant groupings of the data based on flows with recurrence intervals greater than a 1.01 year in each stream. Recurrence intervals were used as the dependent variable with the vegetation, soil characteristics, leaf litter, and canopy cover being used as independent variables (Table 3). The MVRT is missing additional information about the shape of the cross section, that is, significant breaks in slope, organic litter accumulation, large wood accumulation, staining, and any other indicators that can also be used to identify locations of high flow. The MVRT was applied to each channel individually to better understand how the data would be grouped at each site, with data from two to three cross sections being added to the analysis. To increase the sample size, points were interpolated at equal spacing in between the surveyed points. This step was also taken so that the points of transition were not overemphasized in the analysis. The results were tested for normality and log transformed where necessary. In this study, we are interested in understanding what range of flows are related to abrupt changes in the environmental gradient of soil, vegetation, and other physical characteristics along a stream boundary to better evaluate which changes are connected to flows related to the bankfull and OHWM elevation.

3 | RESULTS

3.1 | Research question 1: Bankfull versus OHWM

The first objective of this study is to investigate the relationship between the eight definitions of bankfull described in Table 4 versus the OHWM. All eight bankfull elevations and OHWM elevations are compared in Table 5 with the corresponding discharge for each shown in Figure 4. Our work is building off of findings by Hamill and David (2021), who found that the morphologic bankfull elevation, which is the elevation at the break in slope where the bank slope goes from steep to gentle, and discharge tracked closely with the OHWM. This paper expands on those findings, by investigating eight different quantitative and qualitative methods of identifying bankfull, rather than using only one definition of bankfull. Therefore, Figure 4 shows the data point at the morphologic bankfull discharge, with the range of discharges from the other seven definitions of bankfull shown around it. Table 5 and Figure 4 both demonstrate the close relationship among sites in widely differing hydrogeomorphic landscapes. Furthermore, Table 5 and Figure 4 show the variability found at a site just between two to four cross sections, which is consistent with results found by Johnson and Heil (1996) who demonstrated the variability expected at a site because of differing definitions used for bankfull. Sites with greater variability between cross sections included sites with more complexity, like the braided San Antonio River, or sites with bedrock exposure like Beetree Creek and Mud Creek (Figure 4). Beetree Creek also had added complexity because the stream had just transitioned in gradient from a cascading channel to a pool-riffle and was just upstream of a weir at the location of the USGS streamgage. Similar variability was found between cross sections along a reach whether estimating bankfull elevation or OHWM elevation (Table 5).

Comparison of the resulting elevations from each of these estimations of bankfull shows that all of these methods can be effective at providing a range for bankfull at each site (Table 5). Figure 5 highlights that the average of the bankfull elevations are nearly identical to the OHWM elevation. The sites with the greatest variability in bankfull elevations are sites such as Totopotomoy Creek and Bush River that had clear levees next to the channel, or Chester Creek, which has obviously been altered by urban development. Surprisingly, other sites that were clearly incised did not have as high variability in bankfull elevations as would be expected (Table 5).

Another approach to compare different methods for identifying bankfull versus the OHWM is by calculating the recurrence interval of the flows at the corresponding elevation in the channel (Table 6). Table 6 shows the corresponding recurrence intervals for the OHWM flows and eight methods of calculating bankfull. The recurrence intervals of the flows using these varying methods of estimating bankfull show the wider range of discharges that are being considered depending on the site characteristics. The recurrence intervals for OHWM ranged between 1.2 and 11.01 years. The recurrence intervals for bankfull ranged anywhere from less than 1.01 to upward of 50 years when applying the qualitative methods for estimating bankfull versus 1.18 to over 25 years when using the quantitative methods. The upper ends of these recurrence intervals tend to be in locations where the bankfull definition does not apply (e.g., sites with high levees [Bush River, SC] or that lack a clearly defined break in slope from the channel to the hillslope causing the width:depth ratio to never reach a minimum [Beetree Creek, NC]). Table 6 highlights how much variability there can be between cross sections in discharge calculations and therefore resulting recurrence interval estimates at one location, as well as the variability depending on which definition of bankfull is used. Furthermore, where specific bankfull definitions are not applicable are noted.

3.2 | Research question 2: Linkages between high flow indicators and flow recurrence intervals

The second objective of this study is to evaluate the physical characteristics at each site (Table 3) and connect those characteristics to flows (Table 7). Figures 6 and 7 show boxplots with the trends in dominant substrate and soil type for the combined cross sections based on recurrence intervals of the flows at a selection of the sites. Six sites across different hydrogeomorphic regions were chosen as a subset to show

TABLE 5 OHWM elevation in comparison to eight different methods of calculating bankfull elevation.

		OHWM	Bankfull elevations (m)										
Gage name, USGS gage number	Xsect	elevation (m)	Width:depth	Riley index	Area:width	Morphologic	Valley floor	Bar deposition	Vegetation change	Sediment change	Average Bkfl	Stdev Bkfl	CV Bkfl
Totopotomoy Creek near Studley, VA, 01673550	XS1	12.70	12.73	13.13	13.13	13.07	13.34	11.79	12.42	13.08	12.84	0.51	0.04
	XS2	13.00	13.32	13.73	13.67	13.34	13.67	11.54	13.04	13.32	13.20	0.71	0.05
NF Rivanna River near Earlysville, VA, 02032640	XS1	113.50	115.46	115.52	114.43	114.58	116.51	112.81	113.76	112.81	114.49	1.32	0.012
	XS2	114.10	114.84	115.04	114.84	114.93	116.17	114.54	114.38	114.58	114.92	0.55	0.005
Davidson River near Brevard, NC, 03441000	XS1	646.65	646.67	646.88	646.78	646.85	646.85	NA	645.02	646.65	646.53	0.67	0.001
	XS2	646.61	646.73	647.02	646.33	646.61	648.25	645.36	646.54	645.72	646.57	0.87	0.001
Beetree Creek near Swannanoa, NC, 03450000	XS1	822.60	823.1	822.44	822.46	822.44	NA	822.6	822.59	822.35	822.57	0.25	0.0003
	XS2	822.70	823.41	822.67	823.05	823.10	NA	822.6	823.67	823.17	823.10	0.38	0.001
Bush River nr Prosperity, SC, 02167582	XS1	111.90	111.86	112.94	111.86	113.05	113.43	109.83	111.31	111.65	111.99	1.16	0.01
	XS2	111.90	112.62	113	112.62	113.11	113.4	NA	111.81	113.23	112.83	0.54	0.005
Cobb Creek near Eakly, OK, 07325800	XS1	421.20	420.68	421.67	420.68	421.83	424.46	NA	422.12	422.95	422.06	1.33	0.003
	XS2	421.20	420.69	422.6	420.69	421.85	424.7	422.66	421.85	423.25	422.29	1.33	0.003
	XS3	421.50	422.6	423.44	420.69	421.85	425.14	NA	423.19	424.03	422.99	1.45	0.003
Mud Creek near Courtney, OK, 07315700	XS1	228.90	228.14	226.44	228.14	228.84	228.53	224.91	227.6	229.31	227.74	1.43	0.006
	XS2	229.00	229.34	230.01	229.34	229.34	229.38	224.72	229.3	229.3	228.84	1.68	0.007
Antelope Creek nr Carson, ND, 06347000	XS1	600.71	600.69	601.06	600.69	600.87	602.53	599.64	600.66	599.49	600.70	0.93	0.002
	XS2	601.14	602.06	600.78	600.78	600.96	602.59	600.25	600.54	600.54	601.06	0.82	0.001
Burnt Creek nr Bismarck, ND, 06342450	XS1	516.40	515.45	516.63	515.67	516.50	518.74	NA	516.45	515.77	516.46	1.11	0.002
	XS2	516.50	516.02	516.52	516.02	516.37	518.72	NA	516.52	516.52	516.67	0.93	0.002
Hay Creek at Main Avenue in Bismarck, ND, 06349600	XS1	504.90	504.54	505.26	505.02	504.88	504.86	NA	504.84	504.84	504.89	0.22	0.0004
	XS2	505.00	504.62	505.37	505.21	505.37	505.52	503.63	505.12	505.12	505.00	0.61	0.001
Sweetbriar Creek nr Judson, ND, 06348500	XS1	576.10	NA	575.95	576.11	575.83	575.84	575.47	575.84	575.84	575.84	0.19	0.0003
	XS2	576.10	576.11	576.68	576.4	576.21	576.18	575.43	576.35	575.95	576.16	0.37	0.0006
Estrella River nr Paso Robles, CA, 11148000	XS1	207.90	210.61	208.04	208.04	207.74	207.98	206	207.27	NA	207.95	1.38	0.007
	XS2	207.60	210.64	208.08	206.26	207.87	207.87	206.16	207.87	NA	207.82	1.48	0.007
San Lorenzo C bl Bitterwater C nr King City, CA, 11151300	XS1	133.40	134.06	134.06	133.88	133.74	133.67	132.97	133.67	132.46	133.56	0.56	0.004
	XS2	133.57	133.43	133.98	133.65	133.98	134.01	134.16	133.61	133.03	133.73	0.38	0.003
	XS3	133.50	133.83	133.58	133.58	134.19	134.28	133.58	134.29	133.24	133.82	0.39	0.003
	XS4	133.50	133.62	134.32	133.49	134.16	133.99	133.57	133.99	133.18	133.79	0.38	0.003
San Antonio River nr Lockwood, CA, 11149900	XS1	246.50	245.48	246.14	246.14	246.98	245.86	246.11	245.85	245.85	246.05	0.44	0.002
	XS2	246.80	244.89	246.09	246.09	247.32	247.63	246.63	246.19	246.18	246.38	0.84	0.003
Chester Creek at Arctic Boulevard at Anchorage, AK, 15275100	XS1	6.14	6.4	6.17	6.19	6.12	6.72	5.63	6.23	6.14	6.20	0.30	0.05
	XS2	6.13	6.11	6.13	6.11	6.13	7.28	5.74	6.02	6.19	6.21	0.45	0.07

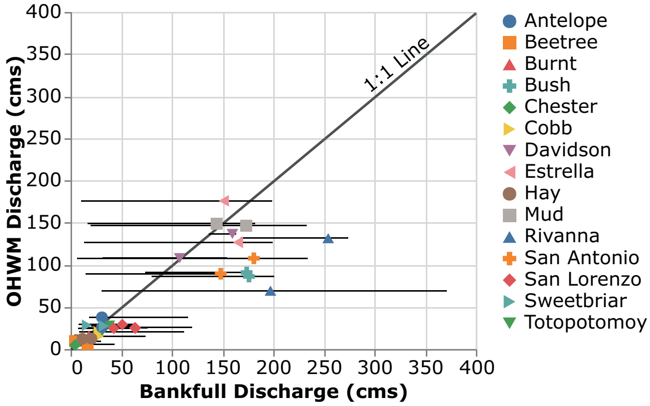

FIGURE 4 Relationship of bankfull discharge to OHWM discharge on a 1:1 plot for all surveyed cross sections. The marker position on the *x*-axis (bankfull discharge) represents the morphologic definitions of bankfull. The range of the *x*-axis error bars show the discharge definitions of the remaining bankfull definitions.

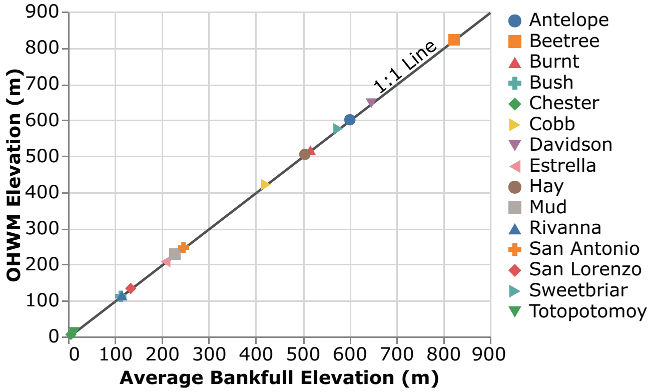

FIGURE 5 Average elevation of bankfull compared to the elevation of the OHWM at each site. The average bankfull elevation is the average using all eight definitions of bankfull.

examples of the relationship between the collected independent variables and recurrence intervals. The range for recurrence intervals of flows associated with the morphologic bankfull and OHWM elevations is overlain on boxplots to show the relationship between these identified flows and physical indicators of flows. Morphologic bankfull elevation was chosen as an example of a bankfull because its definition has the largest overlap with the OHWM regulatory definition. The range of OHWM and bankfull on each boxplot is based on the range found between the two cross sections. At half of the sites, the OHWM and morphological bankfull elevation are just at or below the recurrence intervals (i.e., elevations) where soil is found. Boxplots of soil type are also shown and indicate the more developed the soil the more likely it is found above OHWM and the morphological bankfull elevation.

The trends in vegetation were often more complex at a site or between sites. For instance, Chester Creek in Alaska is in an urban environment and flowing through a park in the location of the survey, with actively maintained grass found on both sides of the channel. At this location, the height of the vegetation was obviously influenced by lawn care and not related to channel processes. Antelope Creek is an agricultural setting in the prairies in North Dakota where cattle grazing was evident. Therefore, short grass was also common at the upper elevations away from the channel. Both vegetation height and type were found in almost every model, indicating that there is some usefulness in understanding how both are influenced by flows in different climatic environments. A number of vegetative characteristics were not accounted for in this method because of the need to simplify data collection as much as possible between differing hydrogeomorphic regions. Therefore, other variables such as vegetation density and more specific species identification were noted during surveying and included in the overall interpretation of the site, but not included in the MVRT analysis. The MVRT created groupings along each of the branches that included both soil, vegetation, and other physical characteristics that assisted with understanding which characteristics were most prominent at the elevation of both the OHWM and bankfull. Figure 8 shows an example of how the results of the MVRT can be interpreted at one site (Antelope Creek in North Dakota). The vegetation and sediment characteristics are distinctly different above the location of the morphologic bankfull and OHWM. The results at Antelope Creek generally show the main difference being that there is no or little soil development below the OHWM and bankfull, but there is soil formation above the OHWM and bankfull.

TABLE 6 Comparison of flow recurrence intervals found for flows at the elevation of OHWM versus each of the differing measures of bankfull. The range shows the difference estimates of OHWM and bankfull between the two to four cross sections (depending on the site).

	Flow recurrence intervals (years)								
Gage name, USGS gage number	**OHWM**	**Morphologic bankfull**	**Bankfull recurrence interval based on W:D**	**Riley's Bench Index**	**Area:Width relationship**	**Valley flat**	**Bar deposit**	**Vegetation change**	**Sediment change**
Totopotomoy Creek near Studley, VA, 01673550	3.12–4.29	1.43–5.12	4–5	6.67–10 year	5–10	6.67 (overtopped levee 5 year still below levee)	<1.01 flow (bars below this level)	1.67–3.33 (woody veg.)	5–10 (change in sediment characteristics)
NF Rivanna River near Earlysville, VA, 02032640	1.23–1.41	2.61–2.7	2.5–7	3–9	1.5–2.5	3–7.5 year (2 benches)	1.05–2	1.5–1.8 (woody veg.)	1.05–2
Davidson River near Brevard, NC, 03441000	3.75–7.54	3.75–7.54	3.33–10	20	3.33–10	13	1.8	1.2–5 year (woody shrubs); 10 years deciduous trees	1.05 (gravel to sand) to 1.8 year (sand to soil)
Beetree Creek near Swannanoa, NC, 03450000	1.74–2.89	1.43–8.42	25 (minimum not reached)	1.33–1.67 (peaks a few times with even higher values at 20–25 year)	1.54–6.67	NA (confined channel)	1.18–1.82	4–25 (woody veg.)	1.33–6.67 (soil development)
Bush River nr Prosperity, SC, 02167582	3.27–3.57	10.09–10.14	6.67–10	20	3.33–10	20–50 (top of levee)	<1.01	1.67–2.86 (woody veg.)	2.5–20 (sand deposits)
Cobb Creek near Eakly, OK, 07325800	1.2–1.4	1.2–1.4	1.2–2.5	1.4–2.86	1.3–1.4	>5 year	1.9	1.5–2.9 (woody veg)	2.5–4 (soil development)
Mud Creek near Courtney, OK, 07315700	1.78–1.85	1.5–2	1.5–2	1.8–2.5	1.5–2	1.5–1.9	<1.1 (bars submerged well below this level)	1.3–1.9 (woody veg)	1.8–2 year (soil development)
Antelope Creek nr Carson, ND, 06347000	2.72–2.97	2.33–2.72	2.5–6.67	2.5–4	2–2.5	10 year	1.5–2.5	2–2.86 (woody shrubs and deciduous trees)	1.5–2.22 (gravel and sand to clay loam)
Burnt Creek nr Bismarck, ND, 06342450	1.95–2.00	1.60–1.73	1.33–1.54	2–2.5	1.33–1.54	>25 year	Not applicable (bars well below 1.01 year)	2–2.22 year (change in density and distribution)	2 year (upper extent of sand deposit)
Hay Creek at Main Avenue in Bismarck, ND, 06349600	2.01–2.39	2.01–6.53	1.4	3–10	3–4	>11 year	Not applicable (bars well below 1.01)	2 year (grass to herbaceous veg); 2–11 year woody veg	2–3 year (upper extent of sand deposition)
Sweetbriar Creek nr Judson, ND, 06348500	2.97	2.44–3.35	2–3	2.5–5.5	3–4	3.5–4	1.54–2	2.5 (woody veg) to 4.5	2.5 (upper extent of sand deposition); 4–6 year soil development

(Continues)

TABLE 6 (Continued)

Gage name, USGS gage number	Flow recurrence intervals (years)								
	OHWM	Morphologic bankfull	Bankfull recurrence interval based on W:D	Riley's Bench Index	Area:Width relationship	Valley flat	Bar deposit	Vegetation change	Sediment change
Estrella River nr Paso Robles, CA, 11148000	7.64–11.01	11.53–11.73	29	6.64	10	1.54–1.82	6	5 (deciduous trees)	All sand
San Lorenzo C bl Bitterwater C nr King City, CA, 11151300	1.73–2.42	1.69–1.75	1.67–3.33	1.82–4	1.67–2.86	2–3.33	1.25–1.67	1.8–3.33 (change in type and density of woody vegetation)	1.25–1.54 (fine sandy loam soil development)
San Antonio River nr Lockwood, CA, 11149900	1.7–1.81	1.93–2.8	1.18–1.25	1.33–1.43	1.33–1.67	1.82–3.33	1.43–1.67	1.33–1.67 (change in type and density of woody veg)	1.33–1.82 (soil development)
Chester Creek at Arctic Boulevard at Anchorage, AK, 15275100	1.6	1.6–1.7	1.33–4	1.538–4	1.33–1.538 year	1.538 (first bench)	No substantial bars	1.4–5 year (woody veg.)	1.2 (soils)–2.5 year (sand deposition)

TABLE 7 Multivariate regression tree analysis results. First split is which independent variables had their first branch of the tree and at what value they split based on the values shown in Table 3. The other branches are subsequent branches for each tree and the value where they split. Log transformation was done on the analysis to meet underlying assumptions of the analysis for some of the sites.

	Multivariate regression tree analysis			
Gage name	**First split**	**Other branches**	**Transformations**	R^2
Totopotomoy Creek near Studley, VA 01673550	DS (soil/no soil)	VT (1.5); VT (5.5); VT (4.5); VT (2.5); LL (1.5); VH (0.5)	Log transformed	0.68
NF Rivanna River near Earlysville, VA 02032640	CC (partial shade/ complete)	LL (0.5); VH (0.5); VH (3.5); VT (1.5)	No transformation	0.48
Davidson River near Brevard, NC 03441000	VT (mosses/forbs)	VH (2.5)	Log transformed	0.57
Beetree Creek near Swannanoa, NC 03450000	DS (clay/silt vs. sand)	LL (1.5); VT (1.5); VT (3.5)	Log transformed; SoilT excluded	0.51
Bush River nr Prosperity, SC 02167582	LL (discontinuous/ continuous)	DS (1.5); VT (4.5); VH (2.5); VH (1.5); VH (4.5); VH (0.5); VT (3.5); VT (1.5)	No transformation	0.68
Cobb Creek near Eakly, OK 07325800	ST (discontinuous/ organic material over sediment)	VT (2); DS (1.5); CC (0.5); VH (0.5); LL (1.5)	No transformation	0.69
Mud Creek near Courtney, OK 07315700	CC (none/partial shade)	ST (0.5); CC (1.5); DS (1.5); CC (1.5); ST (3); VT (2.5)	No transformation	0.81
Antelope Creek nr Carson, ND 06347000	ST (undeveloped/ developed)	VH (0.5); VT (3.5); LL (0.5); VT (2.5)	Log transformed	0.72
Burnt Creek nr Bismarck, ND 06342450	ST (soil with organic horizon/soil O horizon)	VH (0.5); ST (2); VT (1.5); CC (0.5)	Log transformed	0.83
Hay Creek at Main Avenue in Bismarck, ND 06349600	DS (soil/no soil)	VH (1.5)	Log transformed	0.53
Sweetbriar Creek nr Judson, ND 06348500	DS (soil/no soil)	VH (0.5); VT (3.5); VH (1.5)	Log transformed; SoilT excluded	0.51
Estrella River nr Paso Robles, CA 11148000	VH (short/medium)	CC (0.5)	No transformation	0.23
San Lorenzo C bl Bitterwater C nr King City, CA 11151300	VH (medium/ medium–tall)	VH (0.5); ST (2.5); ST (3.5); VT (1.5); DS (0.5)	No transformation	0.43
San Antonio River nr Lockwood, CA 11149900	DS (soil/no soil)	LL (0.5); VH (0.5); LL (1.5); VH (0.5)	Log transformed	0.66
Chester Creek at Arctic Boulevard at Anchorage, AK 15275100	VH (short/medium)	VH (0.5); VT (3.5)	Log transformed	0.65

The MVRT of each site revealed some commonalities among sites (Table 7). About half the sites had an initial split based on either soil type or dominant substrate. The transition from no soil to soil appears to be one of the most consistent transitions to observe for OHWM and bankfull identification, although some sites had much greater complexity in the floodplain because of natural levees composed of sand that were adjacent to channels such as Totopotomoy Creek in Virginia and Bush River in South Carolina. Therefore, understanding both the substrate characteristics, the underlying stratigraphy, and combining that understanding with geomorphology of the landscape is essential for using the substrate characteristics as an indicator of OHWM along streambank, levees, and floodplain. At some locations, a thick organic soil was found above a certain elevation, whereas at others, there may only be organic matter, such as leaf litter, small wood, or pieces of plant material deposited thickly over sand, or, in some cases, sand and gravel in the floodplain. Often, the transition from no deposition of organic material to a thick deposition of organic material, including thick deposits of leaf litter, assisted in identifying the most probable location of the OHWM and bankfull.

There were limitations to the applicability of the MVRT analysis, most notably where the R^2 values ended up being low such as in the Estrella River in California ($R^2 = 0.23$). The Estrella River was in a large, extremely dry, watershed. The channel had obviously been altered by humans and had a distinct trapezoidal shape. Agricultural fields adjacent to the channel were obvious input of water in the floodplain, causing a shift in vegetation that was related to these anthropogenic impacts rather than from forces related to channel flow. Therefore, it is unsurprising that so few variables worked for this site in the MVRT analysis, with only two branches found to be significant related to vegetation height and canopy cover. Even though the results of this analysis were not statistically significant, it emphasizes the need to have a logical approach, such as the WoE method, for identifying OHWM and bankfull. The relevance, strength, and reliability of the vegetation data can be sorted out based on the landscape context using the WoE method.

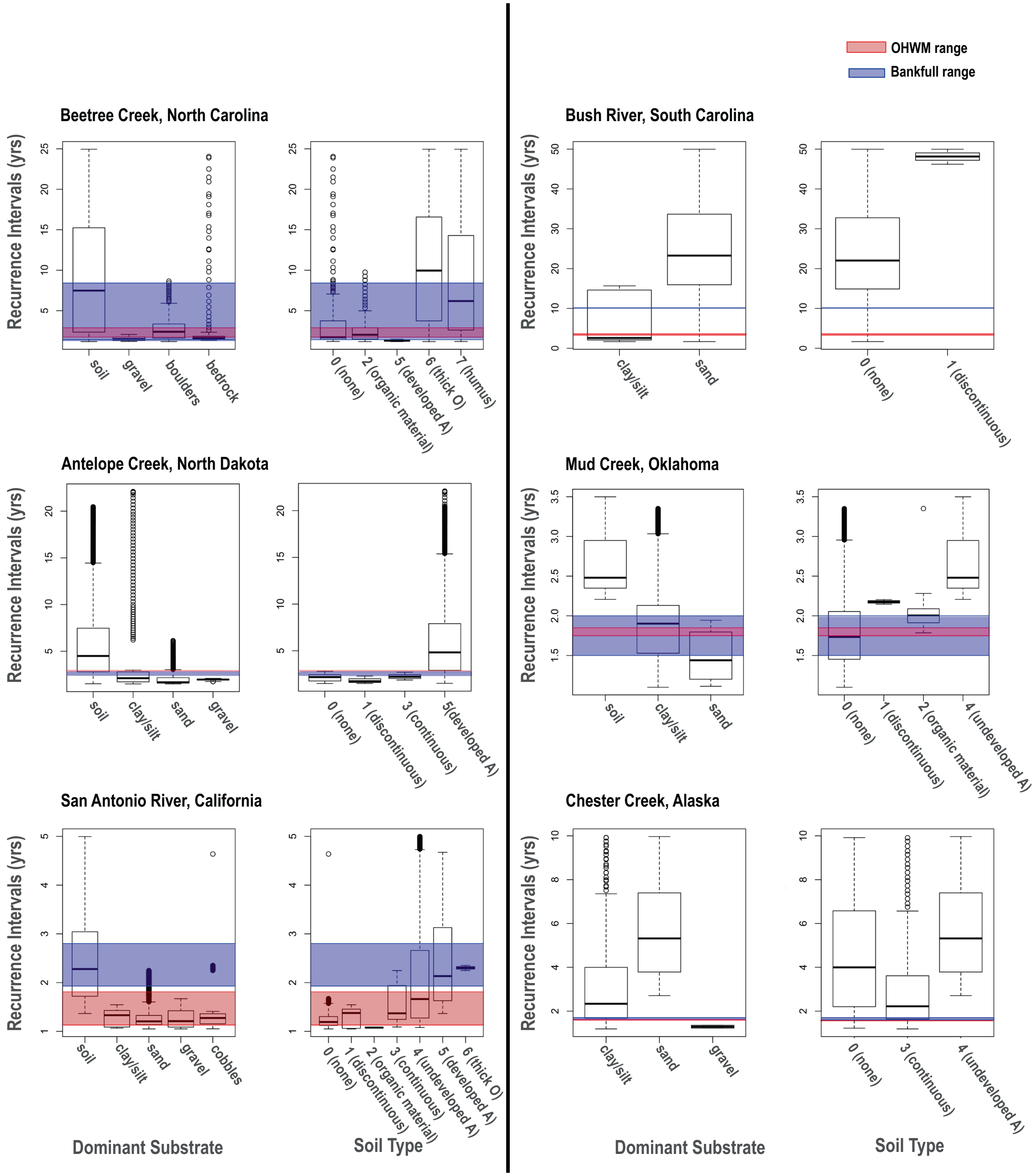

FIGURE 6 Boxplots of DS and STs versus flow recurrence intervals for streams from different hydrogeomorphic regions of the country. Boxplots for each stream include the data from two cross sections, with Cobb Creek including three cross sections and San Lorenzo including four. The DS and ST were noted at each surveyed point along the cross section. Full descriptions of each are in Table 3. The red lines show the location of OHWM for each cross section and the blue shows the morphologic bankfull recurrence intervals, with the filled in portion showing the range between the two–four cross sections. At some sites, there was much greater variability in recurrence intervals between cross sections than at others, so some sites show just a single line, versus a filled in box.

3.3 | Research question 3: Applying WoE approach to streams

The third objective of this study is to evaluate how to apply the WoE approach to draw a logical conclusion as to the location of the OHWM and bankfull (Figures 9–11). Indicators of high flow included in this study are the morphologic break in slope, changes in vegetation type and

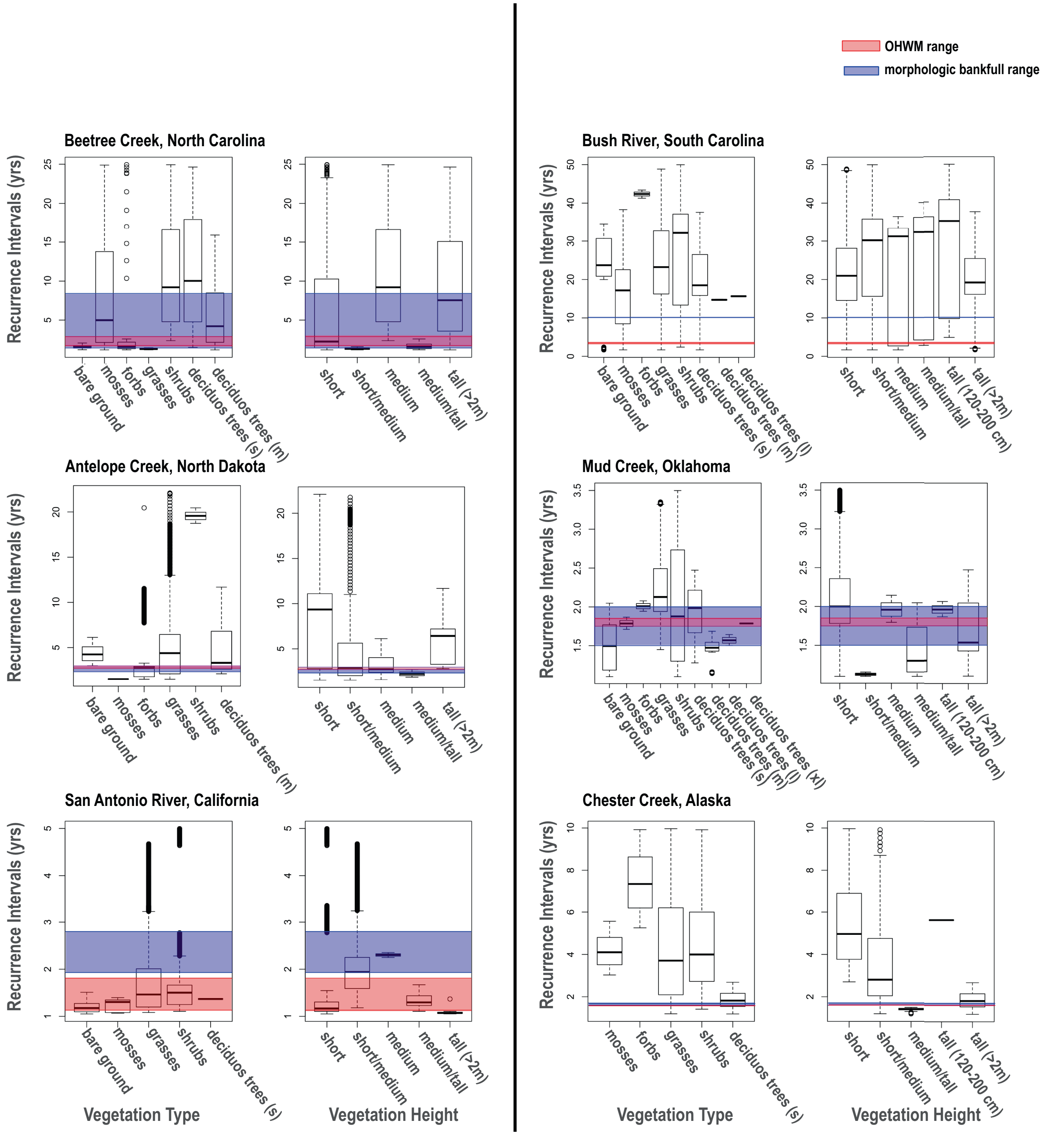

FIGURE 7 Boxplot of VT and VH versus flow recurrence interval for different hydrogeomorphic regions of the country. Data were collected at each surveyed point along the cross section and paired with flow recurrence intervals using the Hydrologic Engineering Center River Analysis System flow models.

density, changes in soil characteristics, upper elevation of sand-sized sediment deposition, changes in sediment characteristics, organic litter deposition, large wood deposition, upper elevation of channel bars. Table 8 shows these flow characteristics organized into four categories of geomorphic, vegetation, sediment, and other physical indicators. Observations in relation to bankfull for each of these indicators are well established in the literature (Bray, 1972; Leopold, 1994; Leopold & Skibitzke, 1967; Redecki-Pawlik, 2002; Schumm, 1960; Williams, 1978; Wolman & Leopold, 1957; Woodyer, 1968). Therefore, the below discusses applying the WoE in identification of OHWM, but the clear overlap with bankfull has already been established throughout this paper.

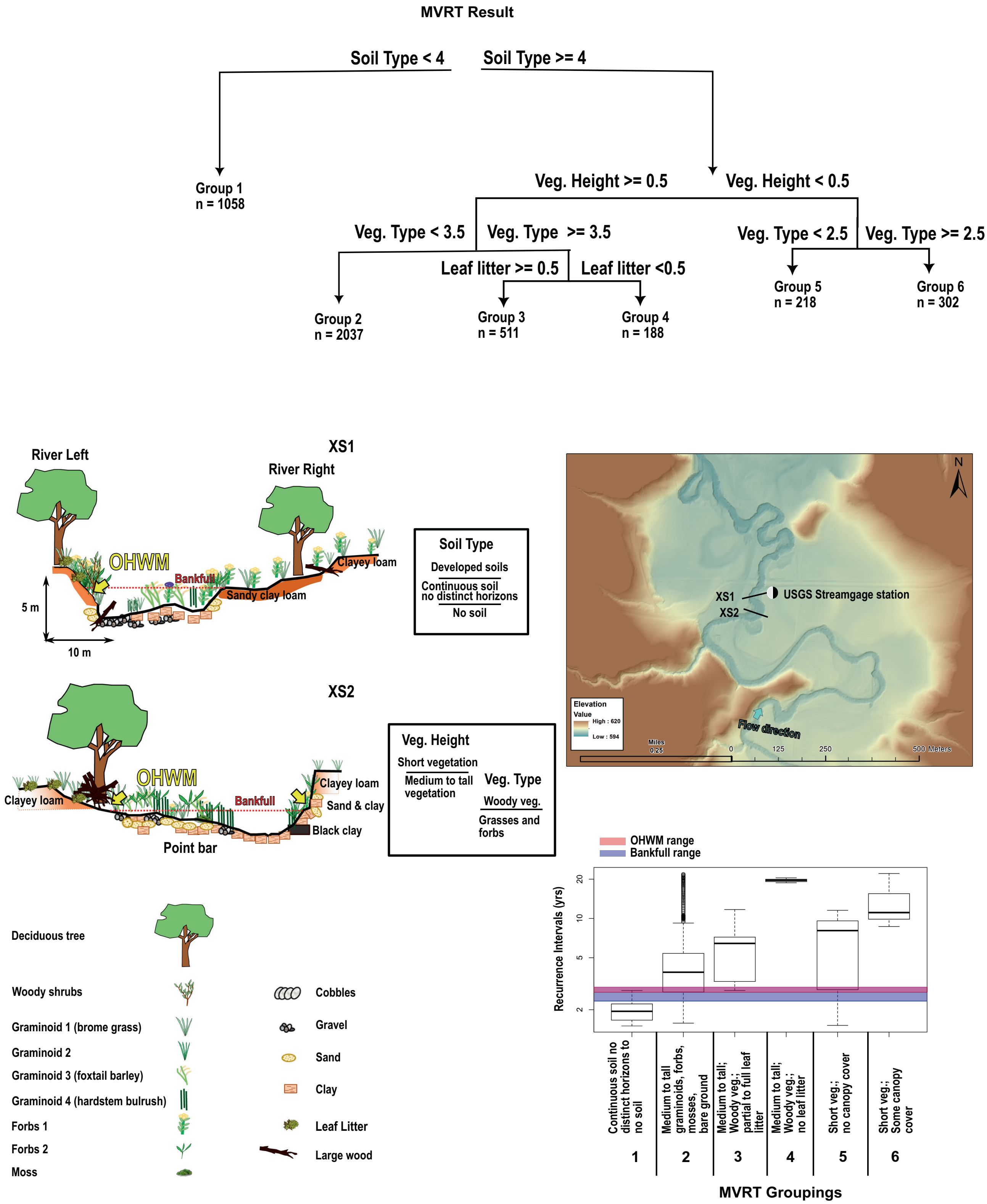

FIGURE 8 Example of MVRT results at one site (Antelope Creek). The top figure shows the results of the tree after inputting data from the two cross sections on Antelope creek as independent variables and the flow recurrence interval as dependent. A schematic of each cross section is shown with vegetation and sediment showing at what elevations there are changes in soil and VH and type. The boxplot at the bottom then shows the boxplot of flow recurrence intervals for each group under the MVRT result tree. Overlain on that is the range of recurrence intervals for the OHWM and bankfull. The explanation under each boxplot is the combination of physical parameters that are represented by that box.

TABLE 8 Indicators of high flow separated into four categories of geomorphic, vegetation, sediment, and other physical indicators.

Category	Flow indicator
Geomorphic	Break in slope
	Shelving
	Channel bar
	Instream bedforms and other bed load transport evidence
	Secondary channels
Vegetation	Change in VT and/or density
	Vegetation matted down and/or bent
	Exposed roots below intact soil layer
Sediment	Soil development
	Changes in character of soil
	Mudcracks
	Changes in particle-sized distribution
Other physical indicators	Wracking/presence of organic litter
	Presence of large wood
	LL disturbed or washed away
	Water staining
	Weathered clasts or bedrock

Table 9 demonstrates the steps included in the WoE methodology and how to apply those steps to stream systems. The first step in applying the WoE approach is to assemble the lines of evidence. Figure 9 provides an example of assembled evidence from Cobb Creek by plotting the spatial distribution of high water indicators along a cross section schematic, longitudinal profile, and overlain on a satellite image of the site.

The next step in applying the WoE approach is to weigh the evidence by evaluating the relevance, strength, and reliability of the flow indicators (Table 9). Figure 10 shows the portion of the cross section that experiences high flows on Cobb Creek to help visualize which flow indicators are most likely related to high flows. Some of the changes in vegetation type, for instance from bare ground to graminoids or moss to graminoids, occur at a moderate flow level. Therefore, these are not relevant, because we are focused on indicators of high flow. Similarly, there are some topographic breaks that occur more at an extreme flow level. These would also be considered not relevant for the current investigation. The strength of an indicator is based on how persistent it is across the landscape. For instance, Figure 9 shows that breaks in slope and organic litter deposition are persistent up- and downstream. Similarly, the elevation of tree establishment is also a persistent indicator. Lastly, the reliability should be considered. Reliability is whether the indicator would persist over time. Topographic breaks in slope would be more likely to persist over longer time periods than organic litter deposition, since organic litter may be moved out of the system during a large flood or could eventually decompose. The elevation that woody vegetation establishes is also much more persistent over time than graminoids and forbs that grow quickly in the summer or spring and may not be present in the fall and winter. Soil development may also be a persistent indicator over time because of the long time scales over which soils develop, and may be a reliable indicator.

The last step in the WoE approach is to weigh the body of evidence (Table 9). This step involves qualitatively combining weights for indicators that are relevant, strong, and reliable, especially where flow indicators co-occur. Figure 11 shows the zones in which specific indicators occurred on Cobb Creek. In this example, the OHWM is placed at the edge of where woody shrubs are establishing, which overlaps some of the topographic breaks in slope along the cross sections and the area that organic litter and large wood is being deposited from high flows (Figure 11). There is no organic litter deposition above a certain elevation and soil development is at the upper break in slope, therefore that is considered to be above the OHWM. The lower break in slope appears to coincide with sand/clay sedimentological layering in the banks; therefore, this is not considered to be as significant a break for determining the OHWM. Also, the flow modeling showed that this break was closer to the lower end of high flows. Therefore, the elevation of the woody vegetation establishment was determined to be a more reasonable location for the OHWM after weighing the body of evidence.

4 | DISCUSSION

4.1 | Research question 1: Bankfull versus OHWM

The overall purpose of this study was to understand the connection between OHWM and bankfull in different stream types found in a variety of hydrogeomorphic regions across the U.S. We demonstrated the overlap between OHWM and bankfull using both qualitative and

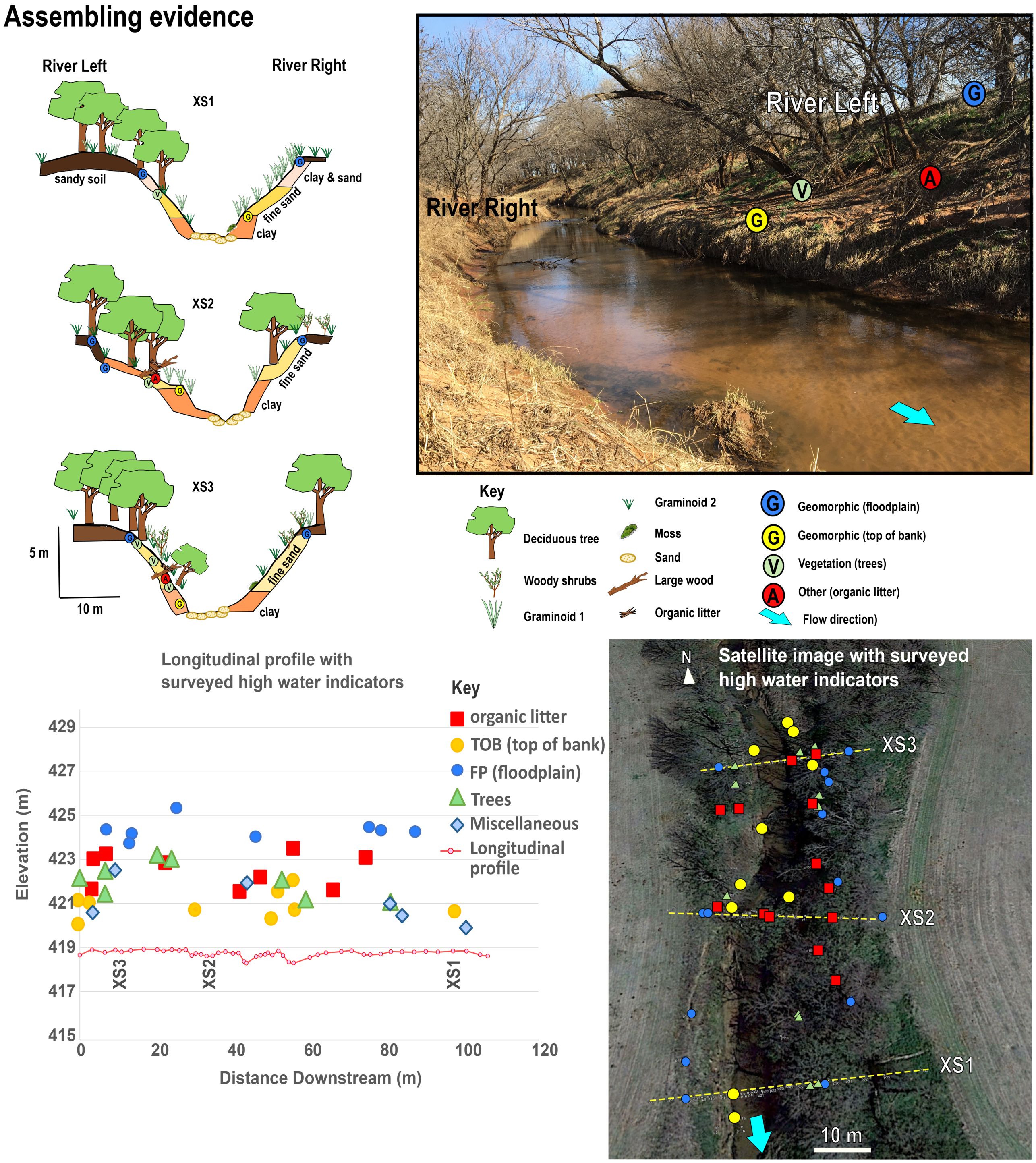

FIGURE 9 Cross section and longitudinal profile showing locations of flow observations. The longitudinal profile shows the elevation relative to the thalweg elevation of the flow observations. The cross sections show the observations in terms of the four categories. The two geomorphic observations are the break in slope on the top of bank and the break in slope at the floodplain elevation. The vegetation is the transition from graminoids to trees. The ancillary indicators are the locations of organic litter and large wood deposition.

quantitative methods for defining bankfull. The average elevation of all of the definitions of bankfull presented in this paper was found to be strongly correlated to OHWM with remarkably negligible differences between the two (Figure 5). This demonstrates how applying multiple definitions for bankfull can help constrain where the OHWM is located within a variety of channel types across the nation. Researchers are more likely to use a combination of the break in slope, vegetation transitions, and sediment changes to identify bankfull, which are all characteristics used to identify the OHWM. Therefore, it is encouraging that the average of all these definitions of bankfull overlaps with the OHWM

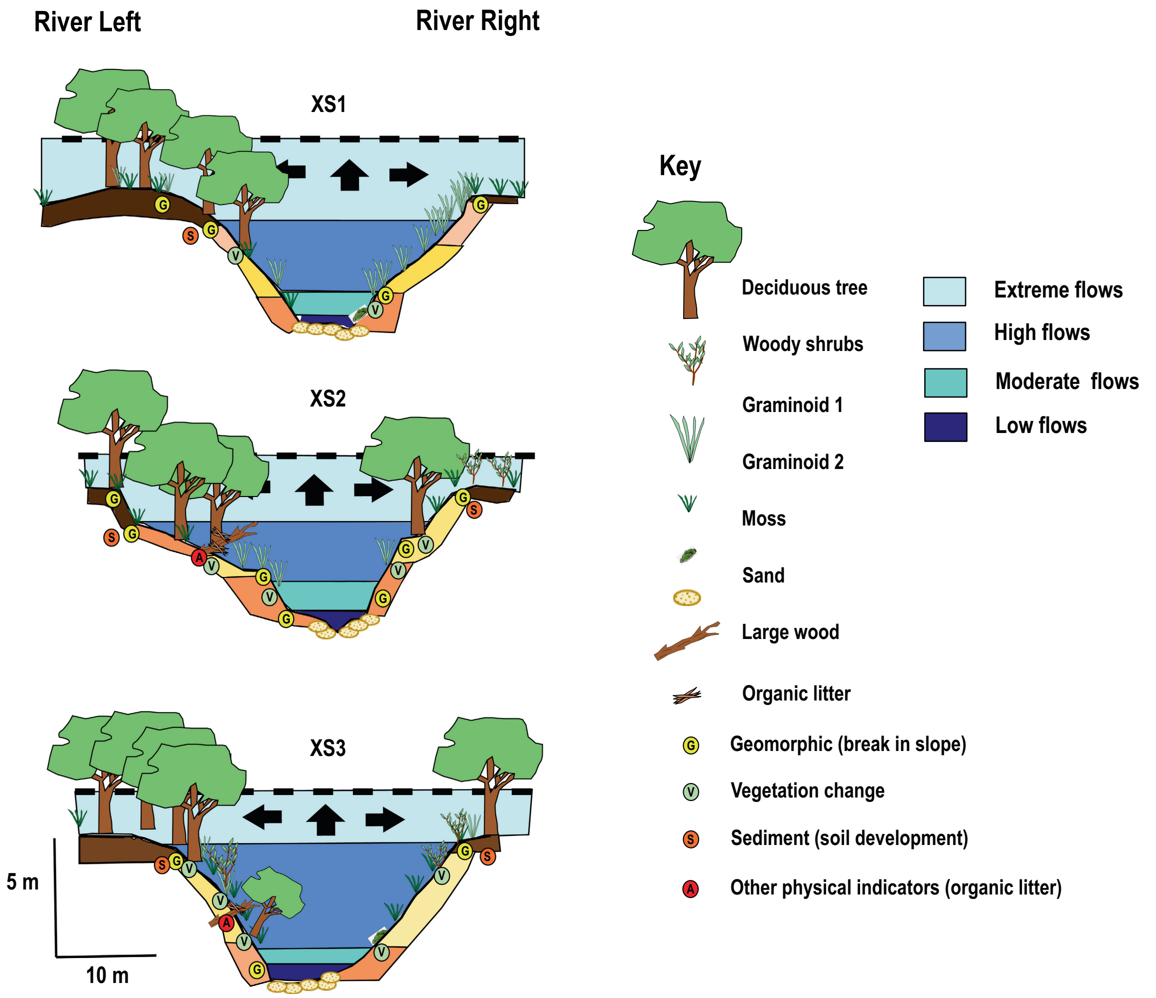

FIGURE 10 Cross sections showing flow levels and location of geomorphic, vegetation, sediment, and other physical indicators.

and that the two would most likely be identified in the same location. The observed relationship between OHWM and bankfull is noteworthy, given that OHWM was established in 1899, predating the concept of the bankfull channel introduced in the 1950s.

This provides evidence that the regulatory boundary being investigated as the OHWM overlaps with the scientific concept of bankfull. There may be variability between the two concepts depending on how a particular researcher is defining bankfull, which can depend on the goals of the scientific study being conducted (Redecki-Pawlik, 2002). Complicated systems, either because of anthropogenic influences or natural climatic and topographic influences, tended to have higher variability in bankfull when applying all eight definitions (Tables 5 and 6). The variability in bankfull was likely related to hydrogeomorphic setting as well as land use changes. Interestingly, incised channels in the southern part of the country (Totopotomoy Creek, VA; Rivanna River, VA; Bush River, SC) had some of the greatest variability in bankfull elevations, whereas other incised systems such as Burnt Creek and Antelope Creek in ND and Cobb Creek in OK did not (Table 5). These results may be related to the length of time since the incision-inducing impacts and how the streams are recovering (Brunsden & Thorne, 1979; Schumm, 1979). The ND and OK streams all had the beginnings of inset floodplains where there were multiple lines of evidence for OHWM and bankfull, which resulted in many of the bankfull elevations being closer together. The VA and SC streams had steeper banks leading into the channel and high levees, which resulted in the bankfull elevations being more spread out depending on which definition of bankfull was being applied. Figure 12 provides examples of two of these incised channels (Bush River, SC and Burnt Creek, ND) and how the differing definitions of bankfull would result in different bankfull elevations. The OHWM is found within the same range and bank area where bankfull is identified and in both examples overlaps with at least one of the bankfull elevations.

Bankfull and OHWM are both found where there is transition along the channel margins. Attempts have been made to define bankfull in a more quantitative ways, which each have been found to have their pros and cons (Keast & Ellison, 2022; Riley, 1972; Wolman, 1955). We found that these quantitative methods worked at some sites, but not all the sites sometimes depending on characteristics of individual cross sections (Table 6). Likewise, Keast and Ellison (2022) found that each of these quantitative methods did not work necessarily on their own, but provided a suitable means of approximating bankfull. Similar to other studies, they found that bankfull had a high variability on a reach-scale

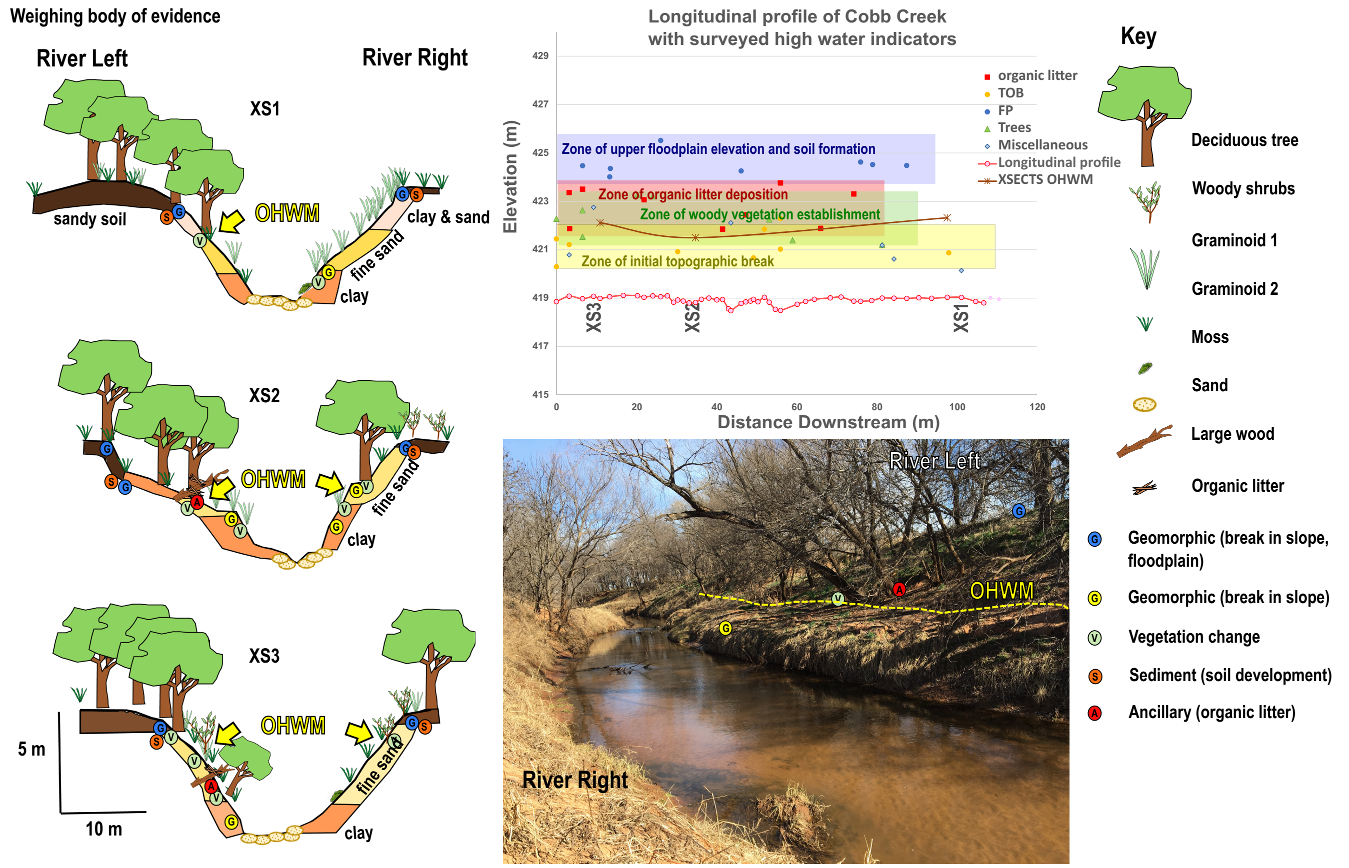

FIGURE 11 Weighing the body of evidence. The morphologic break in slope that was identified as the bankfull would be slightly below the OHWM at this site. This initial break in slope was explained by the underlying stratigraphic layering of sand and clay at the site, with the clay being much more cohesive and not as easily eroded.

TABLE 9 The step-by-step process for applying the WoE approach to identifying OHWM or bankfull in a stream.

Steps	Definition	Questions	Tasks	Questions related to tasks
Assemble evidence	Gather evidence at the site	What are the surrounding landscape characteristics that may influence both observations and interpretations of flow indicators?	Site condition: land use	Consider the surrounding land use. What land use impacts could affect ability to observe indicators?
			Site condition: flow	What are the flow conditions? Do the current flow conditions affect ability to observe high flow indicators?
			List field observations	What physical indicators of flow are observed at this location?
Weight the evidence	Assign relative importance to evidence	Which stream characteristics are reliable high-flow indicators?	Relevance	Is this indicator left by low, high, or extreme flows?
			Strength	Is this indicator persistent on the landscape both up- and downstream, as well as across the channel? Does this indicator occur at the same elevation as other indicators?
			Reliability	Is this indicator persistent on the landscape over time? Will this indicator persist across different seasons?
Weigh body of evidence	Arrive at final decision	What combination of high-flow indicators represent the OHWM?	Combine weights	Integrate the lines of evidence. Where do the high-flow indicators co-occur (at what elevation)?
			Interpret bodies of evidence	Explain why the combination of high-flow indicators represent the OHWM or bankfull elevation
			Explain ambiguities and discrepancies	If there are multiple possibility for the OHWM or bankfull, explain why there are two (or more) possibilities. Include any relevant discussion on why specific indicators were not included in the final decision

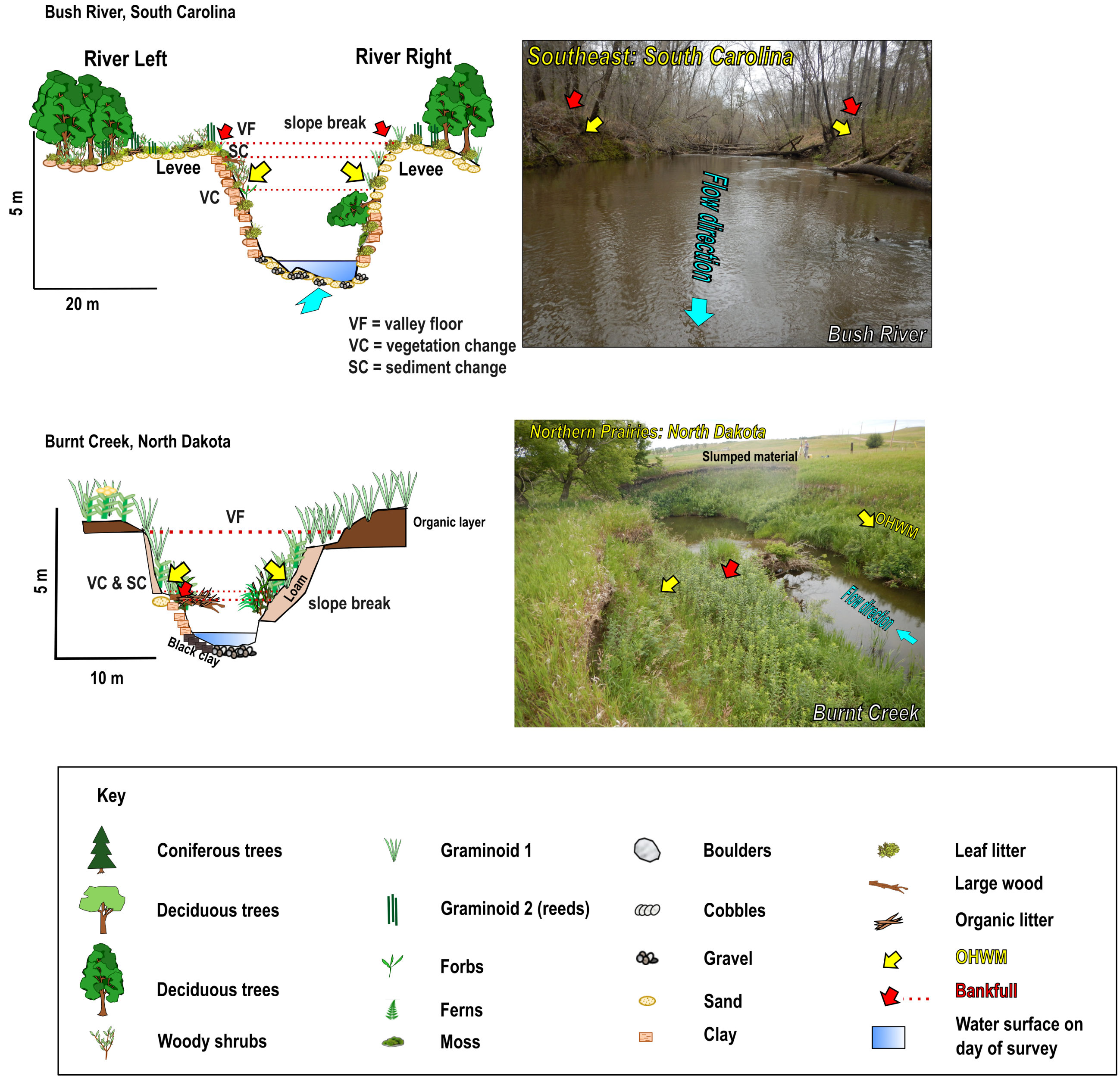

FIGURE 12 Comparison of bankfull versus OHWM elevation for incised streams. Bankfull is shown based on elevation of valley floor, break in slope, vegetation change, and sediment change along each cross section.

and therefore should be presented as a range of values with confidence intervals rather than as a single finite result. Our study came to a similar conclusion that the range of definitions used to identify bankfull, whether quantitative or qualitative, allowed researchers to then constrain the location of bankfull. Furthermore, the complication when investigating a stream reach is that these transitions may not occur at the same elevation even along a short reach (Figure 3) (Harman et al., 2008; Keast & Ellison, 2022; Leopold, 1994; Williams, 1978). Channel geometry is not a product of a single discharge, but a range of flows for a multitude of reasons (Navratil et al., 2006; Pickup & Rieger, 1979). First, the water surface at high flows would not likely flow as a flat surface, particularly when there are roughness elements in the water or channel bends. Second, there could be influences from the hyporheic zone and groundwater on vegetation patterns as well as from the surface water. Third, underlying geology can also have a big influence on topographic breaks, shelving, and soil development, which can then influence groundwater inputs and other elements like vegetation growth including both type and density.

4.2 | Research question 2: Linkages between high flow indicators and flow recurrence intervals

The flow models, hydrologic analysis, and MVRT analysis provide support for understanding the physical and vegetative characteristics and their connection to frequency of high flows. The MVRT analysis highlights that both substrate characteristics and soil development can be an important initial characteristic to look for at a site (Table 7). Figure 6 shows that sites tended to have clearer trends between these substrate and soil characteristics and flow recurrence intervals than the vegetation (Figure 7), which soils tending to be found at higher recurrence interval flows. Johnson and Heil (1996) point out that using the vegetation and sediment characteristics tends to be more subjective than applying what can sometimes be a more reliable definition like the active floodplain. Alternatively, our results highlight that applying the substrate type and soil development can both be important indicators for bankfull and OHWM identification along with the vegetation (Table 7). Overall, the OHWM was most often identified below where the soil becomes well developed at each of the sites, meaning the elevation just below where soil is developing is an appropriate place to look around for other lines of evidence, such as changes in vegetation characteristics, for both the OHWM and bankfull.

In some locations, the stream may cut into some more developed soils, so topographic breaks could still be at the soil layer, but often at these sites sand and small gravel would be deposited on top of the soil indicating the presence of overbank deposition. Figures 6 and 7 show how the morphologic bankfull location does not always clearly line up with soil transitions or vegetation transitions, likely due to variability between cross sections and site-specific controls. For example, sites such as Beetree Creek and Mud Creek contained bedrock exposed in the channel, making the channel form more likely connected to extreme events rather than high flow events. The San Antonio River also had high variability in the elevation of the morphological bankfull between cross sections, which was unsurprising for a complex braided system that was partially confined by a steep hillslope at the upstream cross section. These observations demonstrate the importance of understanding the site-specific contingencies that interact with channel form and processes.

It is well understood that riparian community patterns are influenced by the periodic disturbance that occurs adjacent to a stream channel from relatively frequent flooding (Hupp et al., 2016; Hupp & Osterkamp, 1985; Naiman et al., 1993; Nilsson et al., 1989). Vegetation distribution and density is controlled by duration of inundation, hydraulic stress, and the susceptibility of the plant species to flooding (Hupp et al., 2016). Lumping the variety of vegetation species into the categories of mosses, forbs, graminoids, shrubs, deciduous trees, and coniferous trees provided a means to do an overall analysis of shifts in many dominant types of vegetation but misses some of the complexity in the floodplains for each of these sites, which may be why vegetation was rarely the first split in the MVRT analysis. For instance, mosses are found at a variety of elevations, but the type of moss and growth form would vary greatly where the moss grows near the channel boundary versus on the forest floor. Vegetation at Antelope Creek shows that graminoids and deciduous trees overlap with forbs in the zone of the OHWM, and then become dominant above this zone (Figure 8). The woody vegetation for the San Antonio River seems to mainly be at the elevation of the OHWM (Figure 13), but the cross sections did not necessarily capture the spatial extent of the vegetative characteristics. For instance, there was a clear zone of growth for tall deciduous trees that was above the elevation of the OHWM. What the analysis reveals is that some vegetation can end up dominating over a very narrow zone that often overlaps with the elevation of the OHWM.

Vegetation height did not provide many clear trends, although the MVRT revealed that it can be useful when other variables are first considered. Many of the sites included the division between short vegetation and short/medium or taller as second or third branch on the MVRT. The reasoning for short vegetation would vary based on the region and history of the site. For instance, short grasses were found along Chester Creek, because the channel is in a park in an urban setting. Short grasses were found along the terraces around Antelope Creek either because of cattle grazing or the arid environment. In Antelope Creek, vegetation height and type were both branches that helped categorize areas above the OHWM and bankfull flows (Figure 5).

The specific type and density of vegetation found at the OHWM and bankfull, as well as the transitions between type and density are all site specific based on the hydrogeomorphic characteristics of the region and local channel processes. Vegetation can have a complex relationship with channel width, depending on other factors such as sediment characteristics, slope, and overall size of channel. Török and Parker (2022) show that channels with fine-grained material ($D_{50} < 2$ mm) tend to be wider when woody vegetation density increases versus channels with coarser grained material ($D_{50} > 16$ mm). This is seen as a balance between woody vegetation roots and rooting depth increasing cohesion of banks versus the woody vegetation increasing weight on the banks and causing bank failure. Overall, in arid environments, vegetation tends to be thicker and taller close to the channel, whereas in wetter climates such as the northeast and southeast, there is less of a trend of changes in vegetation height with flow recurrence intervals because larger trees can often be found along the banks being undercut by the streams. Depending on the width, depositional environment, and vegetation, some channels in wet environments will have a clear trend of graminoids and forbs growing next to the channel and woody vegetation being set back, because of inundation frequency (Appollonio et al., 2021; Merritt et al., 2010).

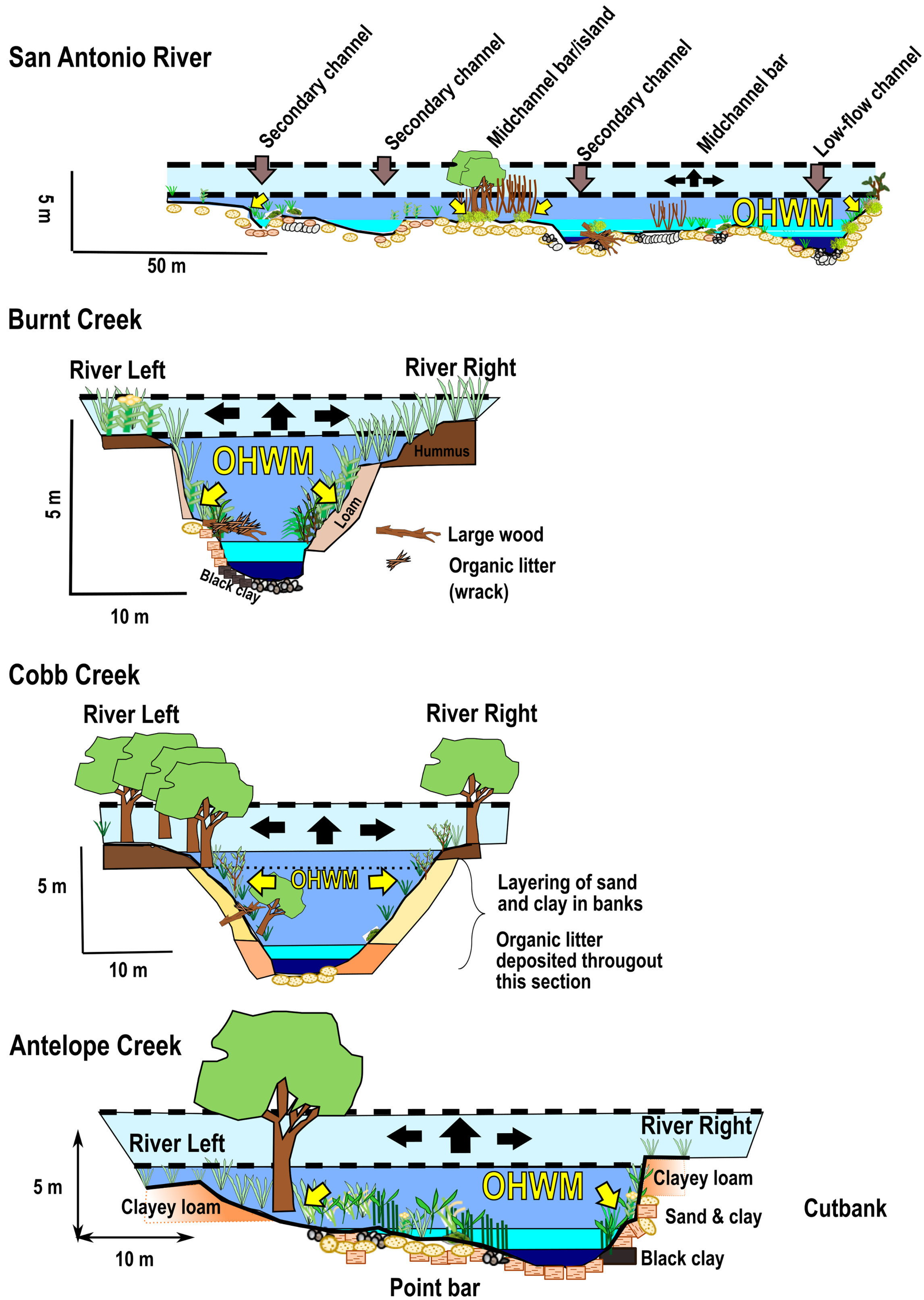

FIGURE 13 Cross sections with low, moderate, and high flow zones in different channel types and hydroclimatic regions of the country.

4.3 | Research question 3: WoE

Despite the breadth of research on bankfull stage, it remains a challenge for scientists and practitioners to identify bankfull elevations on all stream systems (Leopold, 1994; Navratil et al., 2006; Schumm et al., 1984; Thorne et al., 1996; Williams, 1978), yet practitioners are required to identify the OHWM in any channel where a permit is needed. Streams are dynamic systems that vary greatly in geomorphic, hydrologic, and vegetative characteristics depending on the climatic, topographic, geologic position in the watershed. Additionally, both natural and anthropogenic disturbances can mask or alter the characteristics used to identify bankfull and OHWM. A WoE approach can be applied to any stream reach to gather lines of evidence, qualitatively assess the relevance, strength, and reliability of each line of evidence, and determine the OHWM and bankfull elevation by combining that information and weighing the body of evidence (Table 9). This type of logical process is the backbone of the geomorphic tradition of reading the landscape through collection and interpretation of geomorphic field data (Brierley & Fryirs, 2014), and understanding the importance of both contingency and patterns to understanding geomorphic form and processes (Wohl, 2013). Training practitioners without a geomorphic background on how to "read the landscape" can be difficult. Even experienced geomorphologist, as noted by Leopold (1994), "will often be able to specify the bankfull elevation by mere inspection, but even they are sometimes in error. It is best not to depend on primary indicators at just one location or just one cross section. Even reliable evidence may lie at somewhat inconsistent elevations, so the best procedure is to use as many local indicators as can be found in a short reach." Outlining and applying a step-by-step WoE approach provides a process for inexperienced practitioners to apply while they gain more experience and a better understanding of landscape and fluvial processes. Applying the WoE approach can allow both inexperienced and experienced practitioners to come to a consistent and accurate conclusion as to the most likely location of the OHWM and bankfull.

Cobb Creek in Oklahoma provides an example of a low-gradient incised sand-bed channel in a heavy agricultural region. Applying the WoE approach to this channel type allowed a detailed investigation of the high flow indicators. The flow models that we developed were an additional line of evidence that later showed that many of the observed indicators identified as relevant were within the range of high flows that influence the channel form. The flow model helped with putting the site and flows in context, but, even without this model, there was clear overlap of strong, reliable, and relevant indicators at a certain elevation that could be used together to identify the OHWM and bankfull elevation (Figures 9–11).

It is not just a single discharge that is responsible for any given stream characteristic, but the variability in flow at each site that results in specific vegetative, sediment, and geomorphic characteristics (Hupp et al., 2016; Pike & Scatena, 2010). The range of high flows that influence a stream cross section are shown in Figure 13 for different streams in different hydroclimatic regions of the country. The WoE approach allows for a method of investigating the high-flow indicators that can be observed along these cross sections and applying a step-by-step process of assembling and weighting each line of evidence and then weighing the body of evidence. The overlap of these indicators provide a clear, consistent location for the OHWM, or in other terms where flow is leaving persistent marks on the landscape that can reliably be identified over space and time and identified as the OHWM.

Over larger time scales, both OHWM and bankfull are likely to change in stream systems because of both climatic and land use changes in the watershed (Bastola & Diplas, 2023; Buffington, 2012; Bull, 1991; Goudie, 2006; Schumm, 1979; Wohl, 2020; Wolman & Gerson, 1978). Future changes to the climate are likely to change flood drivers such as duration of extreme rainfall events, extent of drought periods, and timing of snowmelt and size of snowpack (Hodgkins et al., 2019; Yu et al., 2020). Therefore, flow statistics such as flow recurrence intervals and flow duration curves can change over time, but the directions of streamflow change are difficult to predict and scientific consensus is limited because some of the drivers could increase flooding while others could cause less flooding (Archfield et al., 2016; Hodgkins et al., 2019; Ivancic & Shaw, 2015; Yu et al., 2020). Nevertheless, the WoE approach allows for a step-by-step process that can be applied again when a site needs to be re-evaluated in the future to find either the new bankfull elevation or OHWM boundary. Furthermore, application of this method can be an essential step in identifying the current bankfull elevation in a degraded river prior to implementing river restoration activities.

5 | CONCLUSION

Practitioners are required to identify the location of the OHWM in a manner that others can understand and also replicate. The question posed by this paper, "is the ordinary high water mark ordinarily at bankfull?" is clearly answered by the remarkably close relationship shown between the OHWM and average bankfull elevations within a variety of channel types across the nation (Figure 5). Applying a WoE approach in a step-by-step process provides a logical method that can be used to identify either the OHWM or bankfull. Application of this WoE approach is described further in the OHWM national field delineation manual (David et al., 2022). This technical manual also provides a method and data sheet that can be utilized by practitioners who are not trained geomorphologists. It is important though that scientists and practitioners identify commonalities in what they are identifying. When using a multitude of definitions of bankfull, there is a clear relationship between bankfull and OHWM elevations. The application of a WoE approach was demonstrated on a reach to show how evidence can be assembled, weighted, and the body of evidence weighed to draw a conclusion as to the most practicable location of the OHWM. Overall, the WoE approach helps assemble and sort through the observations of changes in vegetation, sediment, and geomorphic characteristics along a stream reach and evaluate the most likely location of the OHWM. Application of this method can support decision-making of both scientists and regulatory practitioners to potentially increase consistency and repeatability in the identification of the OHWM as well as identification of bankfull.

AUTHOR CONTRIBUTIONS

Gabrielle C. L. David: Conceptualization; data curation; formal analysis; funding acquisition; investigation; methodology; project administration; supervision; validation; visualization; writing – original draft; writing – review and editing. **Daniel Hamill:** Formal analysis; methodology; validation; writing – review and editing.

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CONFLICT OF INTEREST STATEMENT

The authors have no conflicts of interest.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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