MAPPING FLUVIAL GEOMORPHIC HAZARDS IN VALLEY MARGINS: THE FLUVIAL HAZARD BUFFER

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Abstract

Fluvial geomorphic hazards resulting from valley bottom fluvial process such as channel migration or the erosion and deposition of sediment and debris can impact valley margins adjacent to and well above the active geomorphic floodplain. Valley margin and hillslope impacts due to toe erosion, hillslope failure, and mass wasting events are typically not considered in riverine flood hazard assessments or floodplain inundation mapping. Fluvial geomorphic processes can impact property and structures well above a mapped floodplain as is evidenced by the high percentage of flood insurance claims in the United States that come from properties located outside of mapped floodplains. We present a method and framework for evaluating and mapping valley margin hazards, what we call the fluvial hazard buffer, to fill in this gap of flood and riverine hazard analysis. Using pre- and post-flood digital elevation models as well as aerial imagery, we analyzed valley margin erosion as a result of flood events and from gradual channel movement over time in streams and rivers representing a variety of flood climatologies and geomorphologies in Colorado, U.S. With this analysis we develop numeric guidance for mapping the fluvial hazard buffer beyond the margin of the geomorphic floodplain. This buffer is a factor of stream or valley bottom width depending on the stream type. Though the regional dataset informing these guidelines may be specific to Colorado, the framework for mapping the fluvial hazard buffer may be applied elsewhere.

Introduction

Globally, efforts to characterize and map fluvial (i.e., riverine) flood hazards within a floodplain or stream corridor primarily focus on the inundation hazard: what gets wet, at what frequency, and where (Merwade et al., 2008). Inundation hazard maps rarely account for the possibility of channel movement, which can occur either dramatically during an extreme flood event or incrementally over many low to moderate flood events (FEMA, 1999). Inundation hazard mapping also ignores the possibility of fluvial floods impacting human development located on erodible valley margins well above the elevation of the mapped inundation extent (Figure 1). Considered “high and dry”, property owners in these zones adjacent to the floodplain may not be prepared for flood-related erosion and mass-wasting possible in certain stream corridors. Land use planners and floodplain managers may want to communicate these fluvial geomorphic hazards to landowners as well as avoid or mitigate development in these hazardous floodplain-adjacent areas. Mapping fluvial geomorphic hazards associated with the erosion, transport, and storage of sediment and debris within an active, geomorphic floodplain expands our understanding of hazards within a river corridor (ASFPM, 2016; Blazewicz et al., 2020) and provides the flood management community with better information to manage land use, plan and design infrastructure, and protect aquatic and riparian ecosystems within a stream corridor (Malavoi et al. 1998, Piegay et al. 2005, Sholtes et al. 2018).

Methods for mapping fluvial geomorphic hazards within a valley bottom or active stream corridor has been discussed elsewhere (FEMA 1999, Piégay et al., 2005, Kline and Cahoon, 2010; Olson et al., 2014, Buffin-Bélanger et al., 2015). As defined for this study, active stream corridor encompasses the lands shaped by fluvial erosion and deposition under the prevailing flow and sediment regimes (i.e., the modern or active geomorphic floodplain) (Blazewicz et al., 2020). Dominant geomorphic processes within this boundary are lateral and downstream channel migration, avulsions, and scour and deposition of sediment and woody material within the channel and floodplain.

The lateral extent beyond a floodplain that may be impacted directly from channel scour into an erodible valley margin or hillslope failure following oversteepening is referred to herein as the fluvial hazard buffer or FHB (Figure 1, Blazewicz et al., 2020). The FHB width is a function of various parameters related to the erosivity of the stream corridor and the erodibility of the margins (Figure 2).

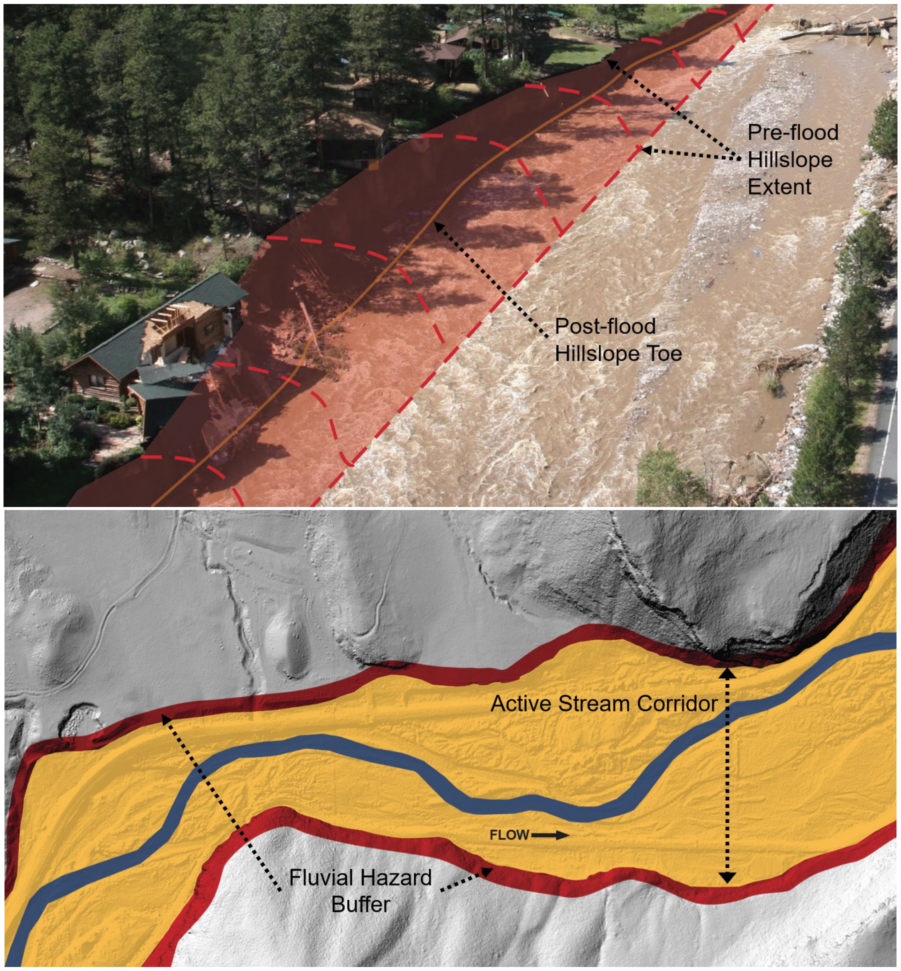

Figure 1. Example of fluvial geomorphic hazards in valley margins on the Big Thompson River, (top) and mapped along the South St. Vrain Creek (bottom).

Some fluvial geomorphic hazard mapping methods include a mapping component that identifies the potential for valley margin erosion or mass wasting beyond the active stream corridor (Rapp and Abbe 2003, Olson et al, 2014, Blazewicz et al., 2020). Other methods estimate or model a hillslope angle of repose after steepening has occurred from hillslope toe score or channel incision (Ayers and Associates, 2004; Travis and Wahlin, 2011). Boyd and Thatcher (2016) quantify valley margin erosion from historical aerial mapping and extrapolate erosion into the valley margin for a defined period into the future for some Montana, U.S. streams. However, to the authors' knowledge, studies quantifying the potential for and extent of stream-caused lateral erosion and mass wasting into valley margins over large scales (10's of km) have not been published.

Lateral migration or incision of a stream channel and the subsequent impact of erosion and mass wasting of the valley margin because of a flood can be highly variable and difficult to predict as not all of the factors influencing this are easily evaluated (Surian et al., 2016, Yochum et al., 2017, Sholtes et al., 2018). As such, numeric guidelines are necessarily region specific or require site-scale data collection (Travis and Wahlin, 2011). To facilitate the mapping of the FHB for a fluvial geomorphic hazard zone mapping program developed for the State of Colorado, U.S. (Blazewicz et al. 2020) a series of observational studies on the phenomenon was conducted across a variety of stream types in the state. We present the results of these studies and apply them to a quantitative framework for mapping the width of the FHB into valley margins beyond the active stream corridor.

FLUVIAL HAZARD BUFFERS: VALLEY MARGIN EROSION

Valley margins are defined as the transition from the active stream corridor (geomorphic floodplain) to valley margins comprised of bedrock, regolith, alluvium, and soils (Fryirs et al., 2016). Our definition of valley margin also includes what Fryirs et al. (2016) term the valley bottom margin, or landforms within the broader valley bottom that, due to their mass, effectively serve to confine a stream, such as terraces or fans. In our study areas, we observed valley margins ranging from very resistant (crystalline bedrock), moderately resistant (sedimentary bedrock, regolith, and colluvium), somewhat erodible (vegetated soil over regolith with moderate to mild slopes), to erodible (vegetated and unvegetated soil with mild to steep slopes and unconsolidated material such as fans, alluvium, and aeolian deposits).

A conceptual diagram describing the factors that influence the erosivity of the stream corridor and the erodibility of the valley margin, both of which contribute to the width of the FHB, is provided in Figure 2, adapted from Olson et al. (2014). Intuitively, the FHB width will increase with greater erodibility of the valley margin. In addition to erosion from fluvial scour, mass wasting events along valley margins may be triggered by toe erosion of a slope or channel incision, leading to hillslope instability from over-steepening. High soil moisture content likely contributed to some mass wasting events along valley margins in Colorado during a catastrophic 2013 flood event (Coe et al., 2013). Streambanks and hillslopes may also become saturated from high water levels during and after flood events, increasing the potential for hillslope failure (Travis and Wahlin, 2011). The greater the height and slope of a valley margin, the greater the potential FHB width will be as an angle of repose is established through mass wasting after oversteepening from fluvial scour (van Beek et al., 2008).

Stream corridor erosivity is influenced by flood intensity and duration (i.e., hydrologic setting or flood climatography) as well as its slope and degree of channel confinement. Flood hydrology is

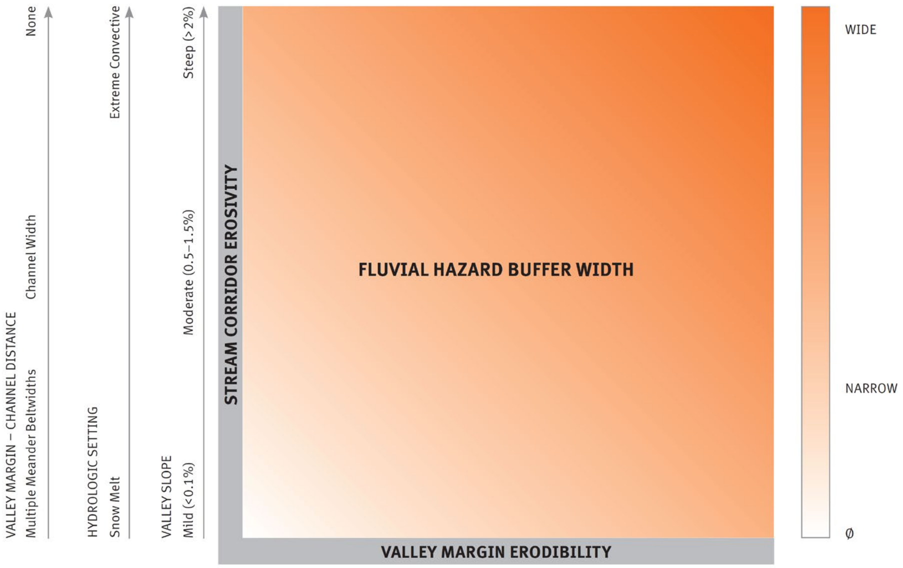

Figure 2. Qualitative relationships between Fluvial Hazard Buffer width (relative to stream width) and factors influencing this width, including the erosivity of the stream corridor (i.e., the power of flood waters and likelihood of the channel and flood waters coming into contact with the valley margin), as well as the erodibility and stability of the valley margin. Valley Margin - Channel Distance refers to the level of channel confinement by valley margin. Flood intensity refers to how likely valley filling flood events occur. Valley margin material refers to the level of erodibility of the valley margin. Floodplain fill (i.e., roadway embankments) is akin to unconsolidated fill in terms of erodibility. Adapted from Olson et al. (2014).

influenced by the flood generating mechanisms within a stream's watershed. Smaller and steeper basins tend to have more intense floods compared with flatter, larger basins (Leopold and Dunne, 1978). Basins whose flooding is driven by convective precipitation will have more intense flooding compared to snowmelt dominated systems (Jarrett and Costa, 1988). Valley slope and stream confinement influence unit stream power and, hence, stream corridor erosivity (Thompson and Croke, 2013). Finally, the likelihood that a stream channel will encounter a hillslope influences the erosivity of the stream corridor. This may be expressed as a factor of stream channel proximity to a valley margin or the rate of migration of the stream within the active stream corridor. For example, single-thread, meandering streams with lower hydrologic variability may migrate more slowly than streams with greater sediment loads closer to the braided spectrum of channel morphology and with greater flow variability (Schumm, 2007).

STUDY AREA

Bisected by the Rocky Mountains, Colorado contains a multitude of surficial geologies, slopes, valley types, and hydroclimatologies. We performed three empirical studies to provide numerical guidance for determining the width of the FHB across three disparate stream corridor settings. The first study investigated the width of lateral loss of valley margins along the Colorado Front Range as a result of the catastrophic 2013 Colorado Flood (Figure 3). Lateral loss width is defined as the width or distance, as measured in planview, of valley margin material lost due to direct fluvial scour or mass wasting (hillslope failure). Streams in this study are typically perennial due to watersheds that incorporate alpine regions with significant snow accumulation. However, monsoonal precipitation events drive extreme flooding in this region (Doesken et al., 2003).

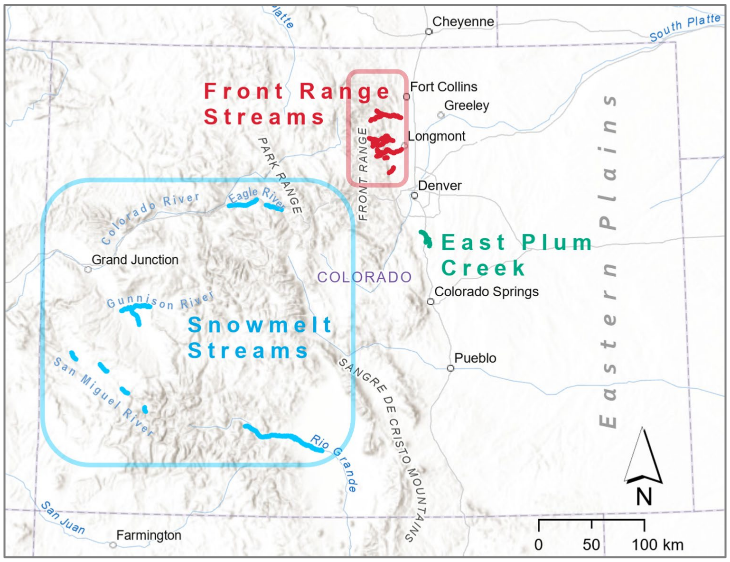

Figure 3. Overview map showing locations of study reaches across the three fluvial hazard buffer studies.

Flood magnitudes from the 2013 Colorado Flood ranged in annual exceedance probabilities of approximately 3% to less than 0.5% (Yochum et al., 2017). Lateral losses of valley margins as a result of lateral channel movement and mass wasting occurred within the canyons and valleys of the foothills and piedmont regions of the Colorado Front Range. Valleys in the canyons of the foothills are predominantly confined with a valley width to channel width ratio less than five: $W_{val}/W_{ch} < 5$. These areas are dominated by granitic and metamorphic rock (colluvium and bedrock) along with some alluvium (as well as road fill), and debris fans (Colton, 1978). Downstream of these canyons, the Front Range study area transitions to the piedmont where valley margins are composed of sedimentary rock and shalestone in the hogback region, then primarily alluvium in the form of terraces further downstream. These reaches are typically partially confined ($5 \leq W_{val}/W_{ch} < 12$) to unconfined ($12 \leq W_{val}/W_{ch}$). These numerical intervals for channel-valley confinement categories were defined subjectively and assigned based on the geographic distribution of confinement categories across the study area (Sholtes et al., 2018).

The second study involved analysis of valley margin lateral loss along East Plum Creek near Castle Rock, Colorado (Figure 3) as a result of a catastrophic regional flood event that occurred in 1965. This study area represents streams with high intensity flooding and highly erodible valley margins. Streams in this region are typically ephemeral and intermittent because their headwaters are located within lower elevation zones where snow does not accumulate. East Plum Creek and others like it within the Colorado piedmont and plains physiographic regions flow through erodible geologic units including poorly consolidated to unconsolidated sedimentary, alluvial, and aeolian formations (Thorson, 2004). These streams experience extreme rainfall and runoff episodically, which can result in dramatic shifts of the channel and impacts to erodible valley margins (Friedman and Lee, 2002). As a result of the 1965 flood event, dramatic valley margin lateral loss and wholesale valley movement occurred on East Plum Creek.

The first two studies focused on two different stream types located within the Colorado Front Range piedmont and plains. We conducted a third study focusing on the width of lateral loss associated with valley margin erosion along perennial, snow-melt driven streams in larger watersheds (>250 km^2) within the Rocky Mountains. The flood hydrology of these streams is dominated by spring snowmelt runoff. These larger drainages within the Western Slope and in the southern region of the Colorado Rocky Mountains are typically not susceptible to flooding from intense precipitation events as these events occur over smaller scales (Doesken et al., 1995). Study reaches were evaluated on the Eagle, Rio Grande, San Miguel, Gunnison, and Uncompahgre Rivers at locations where erosion into valley margins had occurred over a decadal timeframe (Figure 3). Though far from comprehensive, these three studies encompass measurements of lateral loss width into valley margins along streams with a wide variety of valley types, flood hydroclimatologies, and surficial geologies.

DATA AND METHODS

FRONT RANGE STUDY

Using LiDAR-derived digital elevation models (DEMs) of the Colorado Front Range collected before (2011) and after the 2013 Colorado Flood, we created DEMS-of-difference (DoDs) to investigate lateral loss width from valley margin erosion and mass wasting on over 158 km of stream corridor (Figure 3). Methods and data sources for the DoDs are described in Sholtes et al. (2018). To determine the lateral loss width, lines were manually traced (heads-up digitization) using ESRI's ArcMap (ArcGIS Desktop, v10.5.1) along the top crest of a channel bank (top of bank) or hillslope using the pre-flood hillshade raster with 1x1 m resolution as guidance at a scale of 1:1000.

This line defined the location of the pre-flood valley or bank margin (green line in Figure 4c). Lines were also drawn along the upper margin of lateral loss up to where the DoD indicated significant negative topographic change. This was defined as a value of less than or equal to -0.25 m, an average value for significant loss at the $\alpha = 0.05$ level represented in the DoDs generated for this study area (Sholtes et al., 2018). This line (yellow in Figure 4c) represented the outer extent of lateral loss. To calculate the distance between these two sets of lines delineating the margins of lateral loss we generated points with 3 m spacing on each line and used the "Near" tool in ArcMap to calculate the distance between pairs of points across these two lines. For each discrete lateral loss site, we chose the 95th percentile value of loss width between the pre- and post-flood valley margin lines to represent the extremal value of lateral loss. Lateral loss width measurements using this method compared well with a sample of manual (digitized by hand) lateral loss width measurements.

For comparison among different drainages, we normalized this loss width by the reach-averaged stream width. Reaches and reach-scale geomorphic parameters, including valley-stream confinement and reach-averaged stream width, were measured by and defined in Sholtes et al. (2018). Observations of lateral loss widths as a result of the 2013 flood event and adjacent channel and valley properties were made for 494 discrete lateral loss events within the study area over 158 km of stream length. These included lateral losses within hillslope material, fan material, as well as bank erosion within the active stream corridor.

To investigate relationships between lateral loss width and physical setting, we examined four potential variables hypothesized to influence lateral loss width: the slope of the adjacent hillside, the geologic class of the underlying material, the location of lateral loss relative to the curvature of the valley, and valley confinement. The slope of the valley margin at the location of the lateral loss event was evaluated as the mean slope value calculated from a slope raster created from the pre-flood DEM and sampled along the upper margin of hillslope failure. Valley margin geologic

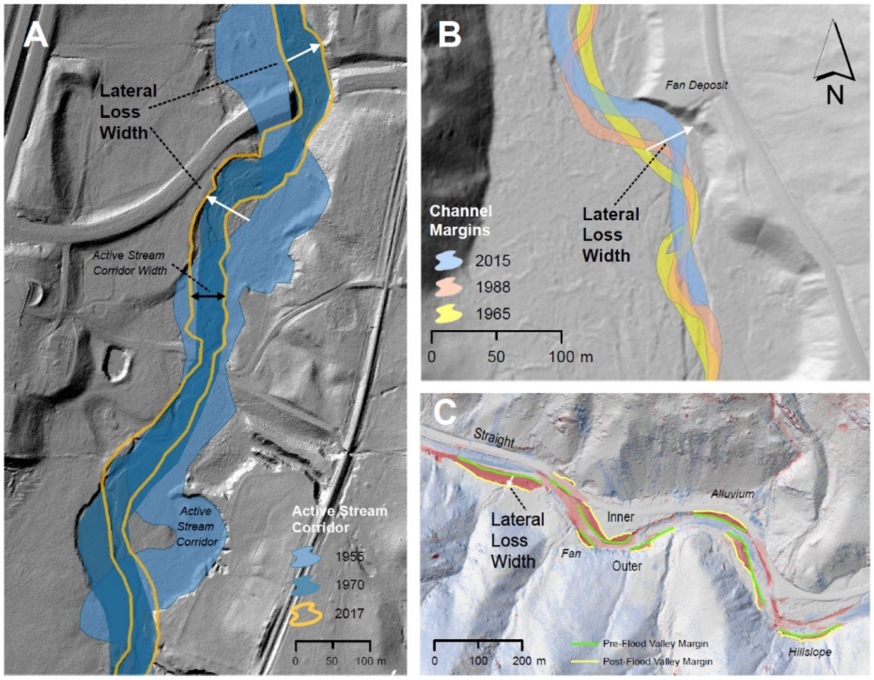

Figure 4. Illustrations of lateral loss widths across the three studies. White arrows indicate lateral loss width in each example. (A) Valley-wide channel migration and valley margin erosion on East Plum Creek. Shaded polygons demark the active stream corridor (channel and active stream corridor) for each year. The active stream corridor migrated 10s to over 100 meters as a result of the 1965 flood (1955 to 1970). Since this event (1970-2017), several moderate-sized flood events have occurred resulting in gradual erosion of valley margins. (B) Example of maximum lateral loss width measurement for snow-melt driven stream. Lateral loss width was measured from the outer margin of the oldest channel margin mapped to the toe of the adjacent hillslope. This example is of the South Fork of the San Miguel River where the stream channel has eroded into alluvial fan material comprising the valley margin. (C) Example of measurement of lateral loss width using DEM-of-difference before and after the 2013 Colorado Flood along the Big Thompson River. Green lines indicate location of original bank or hillslope toe and yellow lines indicate the outer extent of lateral loss as identified in the DEM-of-difference. Margins types are denoted as well as location of failure event relative to channel curvature.

class was evaluated using digitized 1:24,000 and 1:100,000 geological maps for the Colorado Front Range available through the U.S. Geologic Survey National Geologic Map Database (https://ngmdb.usgs.gov). Lateral loss location was categorized as either inside or outside of a bend or along a relatively straight reach. Valley confinement was defined as the ratio of the reach-averaged active stream corridor width to the top-of-bank stream width (W_{val}/W_{ch}). Active stream corridor widths were measured in ArcMap along reaches defined by Sholtes et al. (2018) using LiDAR-derived, pre-flood, hillshade rasters. Geological classifications, typically based off of 1:24,000 scale maps, did not provide adequate detail to determine the type of landforms impacted by the 2013 flood event (i.e., alluvium, fan, hillslope). Therefore, we assigned "material" categories to each instance of lateral loss. This allowed us to identify if the event occurred within floodplain alluvium or fill (i.e., roadways), alluvial or debris fan material, or hillslope valley margins.

EAST PLUM CREEK STUDY

The East Plum Creek study involved analysis of valley margin movement in response to the 1965 flood that impacted the Colorado Front Range in the drainages within Denver, Colorado and to the south and east, including East Plum Creek. Using georeferenced pre- and post-flood aerial imagery, assisted with contemporary LiDAR-derived hillshade imagery, we manually delineated valley margins for the years 1955 and 1970 in ESRI's ArcMap (Figure 4a). Georeferenced digital aerial imagery for this study area was obtained from Douglas County (2018). Valley margins were delineated at a 1:1000 scale.

Utilizing the Planform Statistics tool, an ESRI ArcMap add-in developed for the Stream Restoration Toolbox (Cantelli et al., 2007), active stream corridor width and valley margin lateral loss width between these two photographic sets were calculated. This tool calculates distances between two lines at a specified interval (note that this tool was not utilized in the Front Range study described previously because it was overly cumbersome to implement on over 400 sites). The East Plum Creek study area totals 21.5 km of stream length over which active stream corridor width and the translational distance of the valley centerline and right and left valley margin lines were evaluated at 30 m intervals. Outward lateral movement of each valley margin was then calculated and normalized by the median active stream corridor width of each reach based on the 1955 (pre-flood) conditions. Active stream corridor width was used as the normalization factor in this study because stream width within the study area and region is highly dynamic. Rather than maintaining a relatively stable average value over time as is observed in the perennial streams of the Front Range study, stream width in these systems is a function of time since the last major flood as described by Friedman and Lee (2002).

SNOW MELT STREAMS STUDY

We measured lateral loss widths of valley margins along approximately 250 km of stream corridor within the following rivers: the Eagle, the Rio Grande, the San Miguel, the Gunnison, and the Uncompahgre. Maximum lateral loss widths were measured manually at a 1:1000 scale within ESRI's ArcMap. Lateral loss width was measured from the outer margin of the oldest stream margin mapped to the toe of the adjacent hillslope where lateral loss was observed (Figure 4b). Lateral loss width was normalized by average width of the contemporary stream in the vicinity of the lateral loss. This study follows similar studies done in Montana, U.S. (c.f., Boyd and Thatcher, 2016).

We used historical aerial imagery to delineate stream margins dating back to the 1950s and 1960s and acquired from the U.S. Geologic Survey's Earth Explorer imagery repository up to aerial imagery collected in 2015 to 2017 (USGS, 2018). This resulted in imagery datasets covering 50 to 60 years of channel migration. Aerial images were georeferenced in ArcMAP using its georeferencing tools. Non-georeferenced images were referenced to georeferenced 2015 and 2017 National Agriculture Imagery Program aerial imagery (USDA, 2017). A minimum of six reference points were obtained per image. Images were scaled and transformed using a first order polynomial. In total, 166 measurements of lateral loss were made within the study reaches of which only 14 were observed to occur within valley margins.

RESULTS

FRONT RANGE STUDY

Only 21% of study reaches (by length) did not experience some mappable lateral loss over the 158 km of streams evaluated in the Front Range study as a result of the 2103 flood event. Valley margin slopes that exhibited lateral loss because of the flood were typically less steep in areas mapped as alluvial material and steeper for those in areas mapped as crystalline and sedimentary rock. These geologic classes were primarily located within the canyons of the foothills where reaches were confined by valley margins and/or where contact with the stream and the valley margin was more likely to occur. Lateral loss (normalized by reach-averaged stream width) was not strongly influenced by the slope of the valley margin though greater median values of lateral loss occur for slopes greater than 10°.

Table 1. Summary statistics of relative lateral loss width for the three study areas.

Study Area	Material	Confinement Category	n	min	mean	q50	q75	q90	q95	max
Front Range	alluvium	Confined	120	0.1	1.0	0.9	1.3	1.9	2.4	3.7
	alluvium	Partially Conf.	69	0.2	1.3	1.0	1.4	2.2	3.6	6.3
	alluvium	Unconfined	48	0.3	1.7	1.2	2.1	3.4	4.9	8.5
	hillslope	Confined	189	0.2	1.8	1.5	2.3	3.4	4.2	7.4
	hillslope	Partially Conf.	49	0.3	1.4	1.2	1.8	2.5	2.6	2.8
East Plum Creek	**Location**									
	Center		695	0.0	0.6	0.5	0.8	1.4	2.0	3.1
	Outer		1317	0.0	0.9	0.7	1.3	1.9	2.2	4.1
Snow Melt	All Lateral Loss		166	0.2	1.2	0.9	1.7	2.5	2.8	7.9
	Valley Margin Lateral Loss		14	0.2	0.7	0.4	0.7	1.0	1.8	3.2

NOTE: Front Range study organized by valley confinement category and affected material category (top section) with lateral loss widths normalized by reach-averaged stream width. The “hillslope” material category includes fans. Lateral loss width normalized by active stream corridor width for the East Plum Creek study. Center indicates the lateral movement of the active stream corridor centerline and outer indicates the lateral movement of the active stream corridor margin. Column headers such as “q95” denote the value quantile associated with that number (i.e. 95th quantile).

The relative width of the lateral loss event was not a strong function of its location relative to the channel planform (Figure 4c), though events occurring along an inner bend have a central tendency that is less than those on outer bends and along straight reaches. For hazard mapping purposes we do not recommend adjusting the width of the FHB at the sub-reach scale (i.e., wider FHB on the outside vs. inside bend) as stochastic nature of flood events can rapidly shift channel configurations.

Channel confinement did influence the relative lateral loss width (Table 1). In confined channels ($W_{val}/W_{ch} < 5$), the median value of normalized lateral loss width is 1.4 stream widths (95th percentile = 3.7), in partially-confined channels ($5 \leq W_{val}/W_{ch} < 12$) the median value is slightly lower at 1.2 stream widths (95th percentile = 2.6).

By defining unconfined channels as those with $W_{val}/W_{ch} \geq 12$, no lateral loss observations in hillslope material were documented in this confinement category. We present summary statistics of normalized lateral loss widths by hillslope material and confinement categories in Table 1. Rather than compare central tendencies of normalized lateral loss widths across confinement categories (i.e., medians or means), we utilize the 95th percentile values to inform numerical guidance for FHB widths. This is because we are interested in mapping relatively extreme responses to the infrequent, high magnitude events experienced in the study area for floodplain planning and management purposes. The statistical significance and correlation between independent variables such as valley and stream geomorphology and flood peak hydraulic metrics and fluvial geomorphic response dependent variables (e.g., lateral loss width) for the 2013 Colorado Front Range flood event can be found in Gartner et al. (2016), Yochum et al. (2107), and Sholtes et al. (2018).

EAST PLUM CREEK STUDY

Dramatic change of the valley margin was observed in many areas within the East Plum Creek study reaches. Where the channel and valley margin terraces displayed sinuosity prior to the 1965 flood, the flood caused the channel and its active stream corridor to flip sides across the meander belt centerline resulting in up to 100 m of lateral movement into terraces forming the valley margins (Figure 4a). The active channel widened dramatically after the 1965 flood going from a single thread to multiple threads and sometimes taking on a braided form that spanned the width of the active stream corridor. In some straighter reaches where a bend in the valley did not exist, the valley margins expanded. Comparison of the width and location of the valley margin of 2017 indicates that down-valley migration of the channel and erosion into valley margins has continued to occur as a result of low to moderate intensity flood events, though at a more gradual rate. Comparing historical aerial imagery to terrace elevations in the 2017 DEM reveal that the channel and its active stream corridor have incised by 1.5 to 3.0 meters since 1970. As a result, the contemporary active stream corridor is narrower and entrenched within the active stream corridor footprint observed in 1970 following the flood event (Figure 4a).

Using the 1965 flood as an example of an extreme event resulting in fluvial geomorphic hazards, we calculate summary statistics of valley margin lateral movement (i.e., lateral loss width) normalized by the pre-flood active stream corridor width (Table 1). Active stream corridor width along the main stem of East Plum Creek averaged 90 m and median lateral loss width along the outer margin of the active stream corridor was 0.7 active stream corridor widths (2.2 for the 95th percentile). Results are reported for the movement of the valley centerline from 1955 to 1970 (center) as well as the outward or distal movement of the valley margin line away from the valley center (outer).

SNOW MELT STREAMS STUDY

The median value of lateral loss width over 166 discrete observations along snowmelt rivers was approximately one (1) stream width (Table 1). However, this value primarily reflects meander migration within the active stream corridor rather than lateral loss of the valley margins. Observations of lateral loss widths into valley margins only were relatively infrequent (n = 14) with a median value of 0.4 stream widths. The majority of observations of lateral loss into the valley margin along these rivers occurred in relatively erodible material including alluvial and debris fan deposits (San Miguel and Eagle Rivers) and bluffs comprised of poorly consolidated material (e.g., Mancos Shale, Uncompahgre River). Additionally, lateral loss of valley margins primarily occurred within confined to partially confined reaches. Though not impossible, we did not observe lateral loss of valley margins comprised of more resistant geologic material at the scale and resolution or over the time frame (approximately 60 years) of this analysis for these larger, snowmelt rivers.

DISCUSSION AND APPLICATION

Utilizing the results of lateral loss width within valley margins across the three studies presented here, we created a framework for delineating the FHB. Three approaches to mapping the FHB, or “types”, are presented with associated guidance. The Front Range study of observed lateral loss width is used to inform guidelines for the fluvial hazard buffer on most streams across Colorado with high intensity flood hydrology (convective and monsoonal) and relatively resistant to moderately resistant valley margins (Type I). The Type I FHB width is based on the categories of reach-averaged confinement ratio using factors of reach-averaged stream width. The East Plum Creek study was used to inform FHB guidelines based on factors of active stream corridor width (rather than stream width) for streams with high intensity flood hydrology and with moderately to highly erodible valley margins (Type II) such as those located on the central and southern Colorado Front Range piedmont and Eastern Plains. In larger watersheds with snowmelt driven flood hydrology (Type III), a simple stream width factor is recommended for the FHB width. Type III streams and rivers are located in the Rocky Mountains and Colorado Plateau and typically have drainage areas greater than 250 km^2. A review of Colorado flood hydroclimatology, considerations for climate change, and associated topics can be found in Blazewicz et al. (2020). Specific guidance is not provided for determining reach-averaged stream or corridor width – typically those variables can be determined within a GIS using remotely-sensed data and professional judgement.

TYPE I STREAMS

The Type I FHB mapping protocol applies to streams with high intensity flood hydrology including streams with small drainages (< 250 km^2) statewide, streams in the Colorado Front Range foothills and piedmont, and streams in the Colorado Plateau in the western portion of the state. Type I stream corridors should have relatively resistant valley margins similar to the crystalline and sedimentary bedrock and colluvial or soil mantled bedrock materials found in the Front Range study area. To set numeric guidelines on FHB width factors for Type I streams, we utilized 95th percentile values of lateral loss width by reach confinement category (Table 1).

In confined settings where the ratio of the valley width to stream width is less than five ($W_{val}/W_{ch} < 5$), the recommended FHB width is four (4) stream widths beyond the margin of the active stream corridor. In partially-confined settings ($5 \leq W_{val}/W_{ch} < 12$) the recommended FHB width is three (3) stream widths. In unconfined settings valley ($12 \leq W_{val}/W_{ch}$) where the valley margin is proximal to the channel (within the meander belt width or within six stream widths), the recommended FHB width is two (2) stream widths. Finally, in unconfined settings where the valley margins are greater than six stream widths or outside of the meander belt width of the channel, the minimum recommended FHB is one (1) stream width. Where the valley margin has been deemed to be competent bedrock, the FHB may be reduced or eliminated.

We illustrate these FHB width factors as a function of confinement and channel proximity to the valley margin in Figure 5. The FHB width factor decreases with increasing confinement ratio as the likelihood of the channel coming into contact with the valley margin decreases. Additional guidelines are presented in Table 3.

TYPE II STREAMS

The Type II FHB mapping protocol applies to streams with high intensity flood hydrology and moderate to highly erodible valley margins such as those located in the Colorado Front Range piedmont (e.g., Colorado Palmer Divide region), Colorado's eastern plains, and the Colorado Plateau on the western side of the Colorado Rockies. These typically ephemeral and intermittent streams have the potential to dramatically alter their valley margins. Stream width for these systems is dynamic and may vary with time since the last major flood (Friedman and Lee, 2002). Therefore, under these conditions, the FHB is delineated as a factor of the active stream corridor width (1.25 to 2.0 active stream corridor widths) rather than the stream width. Additionally, the FHB is buffered from the valley centerline rather than the margin of the active stream corridor. This is due to the possibility of wholesale valley margin migration as a result of

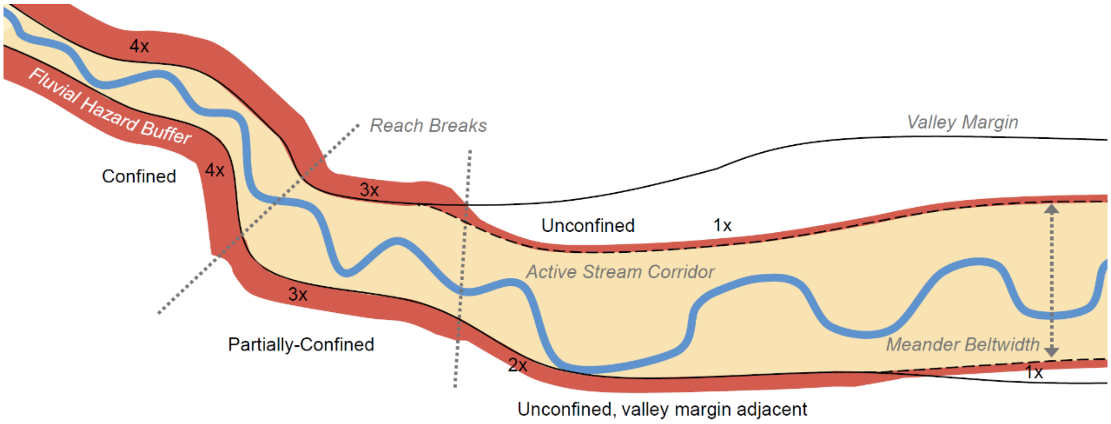

Figure 5. An example of fluvial hazard buffer width factors applied to the outside of the active stream corridor for a Type I stream following numeric guidance in Table 1. The active stream corridor is shaded in beige and the fluvial hazard buffer is shaded in orange.

a major flood event on these streams. The FHB should extend 0.25 to 0.5 active stream corridor widths from the contemporary active stream corridor margin. Guidelines for mapping the FHB in these streams is presented in Blazewicz et al. (2020).

TYPE III STREAMS

The Type III FHB mapping protocol applies to perennial streams with snow melt dominated hydrology, larger drainage areas (> 25 to 250 km^2), and milder valley slopes (< 0.5%) located in the Colorado Rocky Mountains. This excludes the streams located on the Colorado Front Range below approximately 2,500 m above mean sea level where intense precipitation is more likely to occur (Jarett and Costa, 1988). A factor of 0.5 to 1.0 stream widths is recommended as a minimum FHB value for Type III streams. A narrower FHB factor applies to partially or unconfined stream reaches with more resistant valley margins and a wider FHB factor may apply to more confined reaches or reaches with channels more proximal to valley margins that are more erodible. Note that most observations of channel erosion of the valley margin along these rivers occurred in relatively erodible material including fan deposits and bluffs comprised of poorly consolidated sedimentary material such as shale and mudstone. As such, the geology of valley margins should be considered when delineating the FHB.

Intense, watershed-scale rainfall events driving catastrophic geomorphic change typically do not impact streams with large drainage areas in the Rocky Mountains that fall under the Type III FHB guidelines (with some exceptions). However, streams with smaller drainages within the Rocky Mountains may indeed experience watershed-scale rainfall events resulting in precipitation dominated flood hydrology (Doesken et al., 1995). Coupled with the steeper slopes and narrower valleys of many of these streams, this results in the potential for greater unit stream power and therefore greater potential for fluvial geomorphic work to be done during a flood (Yochum et al., 2017, Sholtes et al., 2018). As such, it is recommended that the Type I guidelines be used for delineating the FHB for these smaller streams outside of the Colorado Front Range (Table 1)

LIMITATIONS AND INTERPRETATION

The fluvial hazard buffer factors presented herein, based on reach-averaged reference stream and active stream corridor widths, are rounded values generated from measurements of lateral loss from DoDs and georeferenced aerial imagery in addition to the measured reference widths themselves. All these measurements are subject to georeferencing, digitization, and scale error. As such, the scale and precision of FHB delineations should be limited to approximately 1:1000 and +/- 10 m based on the resolution of the underlying geospatial data and georeferencing. As discussed in the Colorado Fluvial Hazard Zone mapping protocol (Blazewicz et al. 2020), fluvial geomorphic hazard maps based on these methods are intended for reach (1 to 10 km) to segment scale (10 to 100 km) land use planning and floodplain management. Site scale studies of valley margins (100 to 1000 m) are required where higher resolution delineation is needed, such as for site development plans. The numeric guidelines are therefore not intended for site-scale planning.

These FHB guidelines serve as first order estimates of the potential lateral loss a valley margin might experience under different stream corridor contexts. The FHB mapping team must use their own professional judgement based on a thorough analysis of reach context and setting, stressors, valley bottom and margin characteristics, and geomorphic processes to determine an expected response and thus inform FHB type. As shown in Figure 2, many factors integrate to influence the potential width of the FHB.

The observations used to inform FHB width factors for Type I and Type II stream corridors come from single extreme flood events and are therefore presumed to be event-based FHBs. The observations for Type III stream corridors integrate valley margin lateral loss over many decades. As such, FHBs delineated within these stream corridors are assumed to have time horizons of approximately 50 years. Following major flood events, any mapping of fluvial geomorphic hazards should be reviewed and updated if deemed necessary.

Where a continuous, steep hillslope extends beyond an FHB, a geotechnical flag may be incorporated in a fluvial hazard zone map (Rap and Abbe 2003, Blazewicz et al. 2020). This flag is used to identify where hillslope failure or mass wasting triggered by fluvial scour or incision may extend beyond the FHB. Surficial geology and slope steepness along with field observations can inform where such a flag should be incorporated. Further guidance for modifying FHB boundaries – particularly in relation to fans and observed bedrock outcrops – as well as delineation of FHBs as part of a complete fluvial geomorphic hazard map are discussed in the Colorado Fluvial Hazard Zone Mapping Delineation Protocol (Blazewicz et al., 2020).

CONCLUSION

The lateral distance associated with erosion and mass wasting of the valley margins, referred to as “lateral loss width”, was evaluated in support of delineating the region of influence from fluvial geomorphic hazards within the valley margin, known as the Fluvial Hazard Buffer (FHB). This work was conducted as part of the Colorado Fluvial Hazard Zone Delineation Protocol (Blazewicz et al., 2020). These studies considered lateral loss width as a result of two major flood events on the Colorado Front Range, U.S. (2013 and 1965) as well as some 60+ years of lateral loss occurring within Rocky Mountain stream corridors where snowmelt drives the flood hydrology. In total, lateral loss width of valley margins was evaluated on nearly 430 km of streams in Colorado. In the streams within the lower elevations of the Colorado Front Range whose valley margins are more resistant to erosion, as well as higher elevation stream with smaller drainage areas (< 25 km^2), stream width buffer factors (1 to 4 stream widths) based on the valley to stream width confinement ratio are recommended for delineating the FHB (Type I FHB). In streams along the Colorado Front Range and Western Slope that are subject to intense rainfall and whose margins are more erodible, we present a methodology based on factors of the active stream corridor width (Type II FHB). Finally, for streams with larger drainage areas whose flood hydrology is dominated by less intense snow melt runoff, we recommend an FHB factor of 0.5 to 1.0 average stream widths based on valley confinement and valley margin material (Type III FHB).

The FHB is used to delineate hazardous areas within valley margins adjacent to stream corridors. The framework for delineating the FHB presented here may be applied over stream reach to segment scales (1 to 100 km) using both remotely sensed data and synoptic field observations. It should not be interpreted beyond a scale of 1:1,000 with a horizontal resolution of +/- 10 m nor should it be used for site scale development planning (100 to 1,000 m). Though the numeric guidelines presented here are based on lateral loss observations within Colorado, U.S., the general framework and approaches may be applied elsewhere.

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