The geography of fluvial geomorphic hazards in river corridors

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Abstract

The natural and human-influenced river processes of avulsion, erosion, and deposition change the boundaries of a river, its valley margins, and its floodplain. These fluvial geomorphic processes, which may occur gradually over time or abruptly during a flood, become hazards when they interact with human infrastructure located within stream corridors. Fluvial geomorphic hazards can lead to unexpected and unmitigated flood impacts that traditional floodplain mapping ignores. From deposition of sediment at alluvial fans, to scour of hillslopes in steep mountain streams, to braiding of wandering sand bed rivers, a wide variety of fluvial geomorphic hazards exist across Colorado and within the western United States. We provide an overview of how streams and rivers move, influence the river corridor, and identify the geographic settings where they are most severe. This geography of fluvial geomorphic hazards can inform floodplain management in hope of avoiding future damages and improving resilience to natural disasters within our communities.

Introduction

Floodplain management in the U.S. has characterized hazards within a river or stream corridor by mapping zones of potential inundation from a flood (i.e., the flood insurance rate map, FIRM, FEMA, 2019). These are federally and locally regulated maps that inform the need for and cost of flood insurance and as well as land use planning within stream corridors. Since 1978, approximately 40% of all National Flood Insurance Program claims in Colorado have come from insurance policies written outside the high-risk area depicted on the Federal Emergency Management Agency (FEMA) FIRMs (i.e., the 1% annual chance flood or 100-year floodplain, Matthew Buddie, FEMA Region 8, personal communication, October 25, 2017). This is may be due to inaccuracies or (unpublished) uncertainties in the hydrology and hydraulics associated with this inundation mapping (Merwade et al., 2008), the occurrence of floods with annual chances smaller than 1%, as well as lack of representation of dynamic stream processes occurring gradually over time and associated with flood events (FEMA 1999). Because they only identify inundation hazards and assume that the stream channel and floodplain are topographically static, FIRM maps fall short of characterizing all hazards associated with stream corridors, defined as the stream, its floodplain, and adjacent valley margins.

Stream corridors are naturally dynamic environments. Fluvial geomorphic processes are those created by moving water that involve the erosion, transport, and deposition of sediment and organic matter. These physical processes, which may occur gradually over time or abruptly during a flood, become hazards when they interact with human infrastructure located within stream corridors. These interactions may include damage beyond simple wetting associated with inundation flooding and as previously mentioned may extend beyond the mapped and regulated
floodplain areas designated in FEMA FIRMs. Because of these issues, the State of Colorado’s Water Conservation Board (a state agency located within the Department of Natural Resources) is developing a protocol for mapping the Fluvial Hazard Zone (FHZ), defined as the area a stream has occupied in recent history, may occupy, or may physically influence as the stream stores and transports water, sediment and debris.

The process for mapping FHZs in Colorado is built on a body of work and developed in other regions in the U.S. including the States of Washington (Olson et al., 2014, Rapp and Abbe 2004), Vermont (VT DNR 2017), Montana (MT ARS, 2017), as well as arid and semi-arid municipalities such as Maricopa County (Maricopa County, AZ 2013). A review of these methodologies was conducted for the State of Colorado FHZ program by Jagt et al. (2015).

In this paper, we discuss the physiographic contexts – geologic, hydrologic, and geomorphic – that drive fluvial geomorphic hazards from the watershed to reach scales and inform the spatial character, or geography, of fluvial geomorphic hazards. Evaluating the physiographic context of a study area sets up a framework and context for describing and ultimately mapping fluvial geomorphic hazards. Geologic context can inform valley form and slope, erodibility of valley margins, and sediment supply. Climatic context informs flow regime variability, fire regime, and vegetation type and prevalence. Finally, geomorphic context integrates these other contexts to inform how a river corridor has evolved over human time scales, inform how it responds to flood events, and to predict the trajectory of its form and sensitivity to change over the decades to come.

We first describe how these various contexts influence fluvial geomorphic processes, and hence hazards, over a range of temporal and spatial scales. We then integrate these contexts to create a framework for describing the geography of fluvial geomorphic hazards. Finally, we apply this framework to a case study on East Plum Creek, Douglas County, CO.

**Physiographic Context**

The physiographic context is defined by the dominant geologic, topographic, and climatic conditions which influence its form, associated physical processes, and magnitude and frequency of dynamism. Physiographic regions have been defined by Fenneman and Johnson (1946) and since refined and expanded upon (e.g., NRCS, 2006). These regions (Figure 1) delineate areas within which geology and climate are relatively homogenous.

The entirety of a study area will not necessarily lie within the same physiographic setting. Longer reaches of streams may span two or more regions or subregions. Examples of this are many streams on the Colorado Front Range that begin in the Southern Rocky Mountains region and flow into the Colorado Piedmont and Great Plains regions. Major rivers such as the Yampa, Gunnison, Arkansas, and Colorado also flow through two or more physiographic regions from their headwaters to their mainstems.

**Geologic Context**

The geologic context controls a suite of variables pertinent to geomorphic response of stream systems ranging from sediment supply, valley confinement, erodibility of channel and valley margins, vegetation, and hydrology (Brierley and Fryirs, 2005). This geologic setting will inform the watershed- to reach-scale geomorphic context of the study area. For example, many basins in Colorado’s Rocky Mountains were glaciated or influenced by glacial events. As glaciers retreated, they produced meltwater flows and sediment loads exceeding contemporary flows and
sediment loads (Church and Ryder, 1972). Along the Colorado Front Range Piedmont, and in other areas such as the piedmont of the Sangre de Cristo Mountains in the San Luis Valley, deposits formed from glacial outwash material, sometimes creating alluvial fans (McCalpin, 1982). The glaciers also deposited terminal and lateral moraines with which contemporary stream corridors interact. Headwater streams located within or downstream of glaciated valleys may be considered “underfit” if the existing stream is not responsible for forming the broad valley or corridor within which the present stream now resides (Drury, 1964).

![Figure 1. Physiographic regions of Colorado (from Colorado Geologic Survey, 2019)](image)

During the present inter-glacial period, many of these former depositional environments are now degradational eroding into glacial outwash deposits and forming alluvial terraces as they abandon former floodplains. These terraces may comprise the valley margins of these streams. In many regions within the Colorado Piedmont, terraces margins comprised of glacial outwash are composed of sand and gravel and are highly erodible. In other cases, such as along the Eagle River, headwater tributary to the Colorado River, alluvial terraces comprised of cobble- and boulder-sized material may be less erodible (Lidke, 2002).

Other geologic features that may be important to the geologic context are the presence of faults, dykes, and kickzones, which may provide local topographic and valley morphology controls. Aeolian deposits (i.e., loess) and sand dunes may represent more erodible material present within a river corridor. Ultimately, as these examples indicate, the identification of the regional geologic context is important to identify and understand.

To characterize the geologic context, surficial geology maps can be used to identify geologic formations within a study area and along study reaches (Figure 2). Other geologic studies may also be available including local geologic hazard reports. Available surficial geology maps are posted to the National Geologic Map Database (U.S.G.S. 2019). The 1:24,000 scale of the most detailed geologic maps limits their accuracy at smaller scales (i.e., < 1:1000). They may also not account for fill material imported into the floodplain from recent development. Finally, because a geologic map designates a particular surface as a type of bedrock unit, this does not necessarily mean that a bedrock outcrop exists along the entire mapped unit. Rather, erodible mantles
comprised of colluvium or a soil may exist. As such, field verification is required to ground truth surficial geology.

![Figure 2](image.jpg)

Figure 2. Example of 1:24,000 scale geologic map (Castle Rock South quadrangle, Thorson, 2004). Presence of “Q” units within the East Plum Creek corridor indicate alluvial deposits of varying ages and a highly erodible corridor. In some cases, approximate ages of different “Q” units provided within geologic maps can be used to differentiate between active floodplain and terrace features. The Dawson Formation is represented by units labeled “TKda”.

Surficial geologic maps can be useful for identifying erodible units such as Holocene or Pleistocene alluvial, colluvial or aeolian deposits (Morse, 1976; Crifasi, 1992) or those created in lacustrine environments such as within the Roan Plateau on the Western Slope (Hail, 1992). These erodible sedimentary formations are typically composed of sandstones and claystones along with conglomerates. The Dawson Formation, located around Castle Rock and the Palmer Divide area, is an example of this type unit (Figure 2, Thorson, 2004). Composed of weakly consolidated sandstone, claystone, and conglomerate, the Dawson Formation is particularly prone to gullying and constitutes a large upland sediment supply to streams in this area.

**Hydrologic Context**

The timing and magnitude of runoff as a result of a precipitation event is complex. It can be related to the slope and size of the contributing watershed (Dunne and Leopold, 1978), density of the upstream channel network (Gregory and Walling, 1968), the infiltration capacity and antecedent soil moisture conditions surfaces within the watershed, wildfires or development in the watershed (Holman-Dodds et al., 2003; Ebel and Moody, 2013), as well as rate and timing of precipitation or snowmelt (Berghuijs et al., 2018).

Topography, including regional orographic effects, elevation, and local conditions such as slope and aspect, plays a large role in climatology and flood meteorology (Doesken et al., 2003). Colorado straddles the continental divide and hosts a diverse topography over a wide range of elevations. Because precipitation quantity and intensity are influenced in part by elevation as well as by which side of the continental divide a study area’s watershed lies (Capesius and Stephens, 2009), the flood climatology of Colorado is quite variable across the state. Colorado flood geography has been summarized by the United States Geological Survey (USGS) in their regional flood frequency analyses (Capesious and Stephens, 2009; and Cohn et al., 2016). It has also been summarized by the Colorado Dam Safety Office in a related study of regions within
which flood-producing precipitation events are relatively homogenous in terms of their magnitude (duration, intensity, and depth) and scale (Figure 3, Colorado Dam Safety, 2018).

Flooding in Colorado occurs primarily as a result of intense and persistent rainfall events from small to large scales (Doesken et al., 2003). In an analysis of flood peak intensity, defined as a high ratio of annual maximum peak discharge to average annual maximum peak discharge, the majority of intense floods have been observed along the Colorado Piedmont (Front Range) and along the Arkansas and Purgatorie Rivers (Figure 3). Smaller-scale flooding from intense rainfall has been observed along the Roan Plateau and in the southwest of Colorado. Snowmelt driven floods also occur in years of heavy snow pack. Snowmelt floods are typically less intense but can have very long durations resulting in significant geomorphic work on the channel and floodplain. Rainfall over an existing snowpack can rapidly melt snow recruiting greater quantities of runoff for a flood on top of a spring snowmelt hydrograph resulting in relatively large flood magnitudes. In a review of trends for “rain-on-snow” events in the western U.S. (McCabe et al., 2007), significant positive temporal trends in their frequency were found at higher elevation sites (> 6,500 ft) and significant negative trends where found at lower elevation sites (< 6,500 ft). Rain-on-snow events decrease with warmer temperatures up to a certain elevation: under hotter conditions, there is less snow on the ground and therefore less opportunity for rain-on-snow events. However, rain-on-snow events may be increasing for higher elevation sites where snowpack is expected to remain (McCabe et al., 2007).

At watershed to sub-watershed scales, the hydrologic context of a study stream is important to evaluate as changes in hydrology—as a result of land use change or flow regulation—can disrupt the water-sediment balance in stream systems thus informing fluvial processes and trajectories. Enhanced stormwater runoff from development, for example, may increase the volume and peak runoff rate of stormflow leading to erosion, incision, and channel widening, particularly in smaller drainage areas (Vietz et al., 2016). Similarly, wildfire may significantly increase the volume and amount of water and sediment delivered to a channel and change the
timing of runoff (Pierson et al., 2001).

Conversely, reductions in flow either from diversions or impoundment can cause a stream to narrow over time as vegetation encroaches and sediment accumulates (Church, 1995). This in turn may lead to increased channel erosion and bank failure during large flood events when diversions and impoundments are bypassed, and the channel regains its latent footprint. In fact many of Colorado’s streams have flow regimes that are moderately to severely impacted by regulation from dams. This flow regulation typically results in the reduction of peak flows as compared to the hydrograph prior to regulation. Flow regulation may reduce the migration rate of a stream downstream (i.e., Shields et al., 2000). It may also result in channel narrowing as vegetation encroaches on surfaces that are no longer disturbed by semi-frequent floods events (Surian, 1999; Grams and Schmidt, 2002). The existence of a dam upstream of a study area does not preclude the possibility of geomorphically-significant flow events downstream. Indeed, runoff upstream of a reservoir can exceed that reservoir’s capacity resulting in spillway or outlet works releases exceeding the channel capacity. The 2013 Colorado Front Range flood overwhelmed several reservoirs in the affected region resulting in uncontrolled spillway releases, such as on the St. Vrain Creek upstream of Lyons. Another recent example, the Oroville Dam in 2017 on the Feather River in California, resulted in widespread geomorphic change to the receiving channel and banks downstream.

Many sources of data exist to aid in evaluating the hydrologic context of a study area. A regional analysis of stream gage data (i.e., annual maximum floods) can inform the level of intensity of flooding in a region of interest. Hydrologic studies associated with floodplain mapping within or nearby the study area can also provide useful information. The National Oceanic and Atmospheric Administration maintains an atlas of extreme precipitation depths for the nation (NOAA Atlas 14, i.e., Bonnin et al, 2011). The USGS’ StreamStats (2019) online tool can be used to provide reach-scale drainage area and flood frequency estimates based on regional regression equations. Finally, descriptions of the geographic distribution of extreme precipitation across a state may be available (e.g., Capesious and Stephens, 2009, Colorado Dam Safety Office, 2018).

**Geomorphic Context and Trajectory**

The geomorphic context integrates physiographic factors (geology, hydrology, biology) and human factors and considers these in the existing morphology (i.e., form) of the reach. These factors may include land use history at the reach to watershed scale, floodplain development, channel modifications, biotic factors such as riparian vegetation, beaver, large wood, and alterations to the flow regime. Analysis of the geomorphic context provides a better understanding of what fluvial processes are actively working on the channel and its margins as well as the types of flood responses and hazards that exist within the study area.

Geomorphic trajectory refers to how channel and floodplain form and process may evolve in the future based on current and past states, active processes and external stressors. Geomorphic history is important to understanding trajectory as it can provide context to understanding contemporary geomorphic processes and their influence on channel evolution and flood response. The combination of these spatial and temporal characteristics creates a geomorphic context that governs the contemporary form of the active river corridor and the mechanisms and rate at which fluvial processes occur (Wohl, 2018).
**Temporal Scale**

The concept of a stream’s slope and cross-sectional shape in equilibrium with its flow regime and sediment supply has been a theoretical foundation of fluvial geomorphology (Gilbert, 1914; Mackin, 1948). However, contemporary investigators have found that in many cases, the streams may never truly achieve equilibrium (Graf, 1983; Pizzuto, 1986) but rather they perpetually adjust in response to short and long terms forcing. Streams may be adjusting to changes in flow or sediment regimes over the short (1’s to 10’s of years) or long (100’s to 1,000’s of years) term. They may also be adjusting from past flood events (i.e., Friedman and Jones, 2000) or human interventions such as channel straightening and armoring, constrictions and fill, and floodplain disconnection. Examples of short-term adjustment are channel widening then narrowing in response to a flood, channel widening and braiding from augmented mainstem sediment supply from a forest fire, and channel incision and widening in response to urbanization.

Examples of long-term adjustment include the net denudation of the Rocky Mountains and up-canyon knickpoint migration along the Front Range (Anderson et al., 2006), net erosion of glacial outwash alluvium in mountain piedmont settings (Church and Ryder, 1972), and channel and valley response to floodplain encroachment by alluvial or debris fans (Lancaster and Casebeer, 2007). Long-term adjustments typically occur over larger scales and influence channel and floodplain processes over tens to hundreds of miles (Montgomery and Buffington, 1997). The context of the watershed and its history may illuminate these various adjustment scenarios. An objective assessment of the next phases of channel and landscape evolution, given potentially altered hydrologic characteristics due to development, transbasin diversions, wildfire, and climate change, may be influential on geomorphic processes in the coming decades. However, the hydro-geomorphic regime of the geologic past sets the stage for these processes to play out. Consultation with geologists can bring appropriate perspective to this question.

Geomorphic form and process are influenced by and occur within a framework of nested scales (Brierly and Fryirs, 2005). The following is a discussion of how the mediators of fluvial geomorphic hazards, such as geology, hydrology, land use, and landforms, play out at the landscape, valley, and reach scales. These scales should be delineated and classified to inform the geomorphic context of the study area.

**Landscape Spatial Scale**

A watershed of interest may be divided into “landscape units” broadly defined by their position within a watershed and the prevailing sediment transport processes of net erosion, transfer, or accumulation (Brierley and Fryirs, 2005; Figure 4). In mountains to plains settings, such as on the Colorado Front Range, landscape units might be grouped as steep headwater channels (sediment source or net erosional streams); canyon reaches (transport and erosional reaches); foothills reaches (transport / response reaches), and plains reaches (transport and depositional reaches). Within each landscape unit, prevailing sediment transport processes influences the types of channel response to floods. Source or erosional units will most likely respond to floods through channel incision, and hillslope failure. Transport dominated zones will respond with channel widening, some incision and hillslope failure, as well as lateral meander migration. Net transfer, or accumulation zones will exhibit some channel widening, but lateral migration and avulsion will likely dominate stream response.
**Valley Spatial Scale**

Valley setting is the next level of classification nested within each landscape unit. At this scale one considers the slope of the valley, the amount of room that exists between the stream channel(s) and the confining valley margins, as well as the proportion of valley length stream channels are in contact with valley margins (Fryirs et al., 2016). Confined valleys have walls that extend down to the stream banks or have only narrow floodplain benches. Partially-confined channels have valley walls set back from the channel and a continuous floodplain may exist. Unconfined channels have wide valleys, or no valley margins at all, allowing for ample meander room. Valley confinement ratios (valley floor width: average channel width) associated with confinement classifications are not firm and may vary depending on the stream system.

Valley margin steepness and erodibility may also be an important factor to consider particularly when the channel is coupled with that feature (Whiting and Bradley, 1993). Hillslope channel-coupling means that debris flows or hillslope failures can introduce coarse sediment into the channel. This excess material may cause a geomorphic response locally as a valley constriction and as punctuated sediment supply that can create local and downstream hazards.

![Figure 4](image)

**Figure 4.** Example of landscape units and dominant flood response within a watershed from mountain headwaters to plains. A) A confined reach in the canyons of the Colorado Front Range Foothills responds to a flood with incision and widening, though braiding and deposition can occur at smaller scales in floodplain pockets. B) A partially confined reach at the transition from canyons to plains responds with lateral migration and braiding. C) An unconfined reach in the plains responds with bank erosion and avulsion. Here the light blue line designates the main channel and the yellow dashed line the avulsion pathway. Adapted from Brierley and Fryirs (2005).

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**Reach Spatial Scale**
Stream reaches are geomorphically homogeneous lengths of stream within landscape units and valley settings. Channel and floodplain geomorphology (e.g., stream width, depth, slope, and sinuosity) may vary from year to year over mean values but maintain a dynamic equilibrium over time given a stable flow regime and sediment supply (Leopold, 1994). For example, a meandering stream may gradually migrate down valley via erosion of the outer bank. Concomitant deposition on point bars maintains a stable width during this process. Outward meandering and an increase in sinuosity (reduction in channel slope) are balanced with meander cutoffs, which shorten the reach length, reduce sinuosity, and increase slope. A disturbance, such as a flood event, may temporarily alter this dynamic equilibrium, but channel form adjusts towards pre-disturbance conditions over time as dictated by the geomorphic context. The relaxation time, the time required to return to equilibrium conditions after a disturbance, may be longer or shorter than the average frequency of disturbances, dictating if and how long a system may achieve dynamic equilibrium (Wolman and Gearson, 1978).

Changes in sediment supply from a tributary or valley confinement or valley slope that may occur from reach to reach can influence geomorphic response to floods. Longitudinal variation in reach-scale properties, anthropogenic influences such as undersized crossings that act as sediment and debris traps, natural debris jams, and other factors can influence geomorphic responses to floods on the reach-scale basis. For example, reaches located at a trough or at the toe of a longitudinal profile of unit stream power at the peak of the 2013 flood exhibited wider widths of fluvial disturbance than other reaches studied along the Front Range (Sholtes et al., 2018). Troughs or toes in units stream power may occur at the valley to landscape scales along where milder slopes and/or wider valley bottoms occur downstream of steeper slopes and/or narrower valley bottoms. In these cases, upstream reach properties can influence downstream response at the reach scale.

**Framework for Mapping Fluvial Geomorphic Hazards**

The physiographic and geomorphic contexts can be synthesized to identify the type and magnitude of fluvial geomorphic hazards to characterize in a study area as is further explored in the fluvial hazard mapping protocol developed for the State of Colorado (CWCB, 2019). Under this protocol, the fluvial hazard zone is defined as the active river corridor (ARC) (i.e., the geomorphic floodplain) with an adjoining fluvial hazard buffer. The active river corridor is land adjacent to a stream that has been shaped by stream erosion and deposition under the prevailing flow and sediment regimes. The fluvial hazard buffer accounts for erosion prone land located beyond the ARC, such as hillslopes and terraces, that may be susceptible to failure as a result of toe erosion. Auxiliary FHZ units include the avulsion hazard zone, which identifies pathways a channel might occupy during a flood event outside of the ARC. Alluvial and debris fans within the stream corridor are also identified; however, hazards within a fan are not explicitly characterized.

The ARC represents the primary component of the FHZ. In steep to moderately sloped streams (3% to 0.1%) that are confined to partially confined and have developed (though potentially discontinuous) floodplains, the ARC is delineated by identifying topographic signatures of active fluvial geomorphic processes in the stream corridor using LiDAR-derived topographic data, aerial photographs, and geologic maps. This method follows in part what is outlined by the State of Washington (WA Department of Ecology, 2014). In meandering rivers and streams in broad, mild-sloped valleys that are unconfined (valley margins are beyond the meander belt), the ARC may be delineated as a buffer from a meander centerline closely following methods developed by the State of Vermont (VT ANR, 2017). Finally, special considerations are taken when
delineating the ARC in urbanized areas where floodplain fill, channel straightening, and bank revetment all may affect a stream’s response to floods and in headwater streams where fluvial signatures have not yet formed.

A study of hillslope erosion and mass wasting as a result of past flood events was conducted in support of the creation of this FHZ mapping protocol. Buffer widths, appended to the outside of ARCs, are typically factors of channel or floodplain width and are a decreasing function of the ratio of valley to channel width: more confinement (a smaller ratio) results in a wider buffer.

**Case Study: East Plum Creek, Douglas County, Colorado**

East Plum Creek (EPC), a tributary to the South Platte River, drains the north side of the Palmer Divide along the southern border of the Denver Metropolitan region along the Front Range of the Colorado Rocky Mountains. The study reach runs through the Town of Castle Rock, which has experienced rapid growth over the last 20 years, some of which has occurred adjacent to the stream corridor. Streams in this region are typically sand bedded and entrenched within valley margins composed of alluvial material as well as the weakly consolidated sandstone, claystone, and conglomerate of the Dawson formation (Figure 2, Thorson, 2004). Ongoing development on alluvial terraces adjacent to the stream corridor may be susceptible to fluvial hazards associated with hillslope failures due to channel migration and channel widening. As such, the Town of Castle Rock volunteered to participate in a pilot fluvial hazard mapping program with the Colorado Water Conservation Board.

**Physio-Geographic and Geologic Setting**

East Plum Creek, our case study stream, lies within the Colorado Piedmont subregion within the Great Plains physiographic region (Figure 1). The evolution of the Great Plains of Colorado begins during the Laramide orogeny when the uplifting Rocky Mountains resulted in downwarped structural basins east of the mountain front. As uplift continued though the Cretaceous and Eocene, packages of synorogenic clastic sediments accumulated in these basins. The end of the Laramide orogeny was followed by a period of low sedimentation during the Oligocene and early Miocene. During the late Eocene, the Rocky Mountains and Great Plains were again uplifted, possibly by the East Pacific Rise to the west. This resulted in a gentle, eastward-dipping surface on which sediments of the Miocene Ogallala Formation were deposited (High Plains). Later incision and transport of sediment by the South Platte and Arkansas rivers and their tributaries removed the Miocene and younger sediments resulting in an eroded region called the Colorado Piedmont (CWCB, 2019).

![Figure 5. East Plum Creek and Sellers Gulch (eastern tributary) fluvial hazard zone mapping study area with location relative to the State of Colorado in inset map (red area).](image-url)
The East Plum Creek watershed is bounded by the Palmer Divide (a caprock escarpment) to the south and drains to the north joining West Plum Creek then the South Platte river at Chatfield Reservoir. Interstate 25 runs along the length of its corridor to the west (Figure 5). The maximum basin elevation is 9370’ above sea level and the mean basin elevation is 7045’. Annual precipitation is approximately 15 inches resulting in a semi-arid climate with sparse shrubby vegetation in the uplands and willow and cottonwood along the riparian corridor. The drainage area across the study area ranges from 85 mi² to 115 mi².

The valley bottom and margins along the study reaches are primarily composed of unconsolidated alluvial deposits (Morgan et al., 2004). This alluvial material contains sediment with size classes that include silt, sand, and gravel. Alluvium in the terraces that comprise the valley margins was generally deposited by streams flowing east from the Rockies during late-glacial and interglacial periods dating back to the early to middle Pleistocene epoch. Other alluvial deposits include more recent debris fan deposits with similar grain sizes as well as pediment gravel deposits, which contain coarser material in the gravel to cobble size range.

The study reaches have since incised within this alluvial material (Figure 6) likely as a combined result of large flood events, historic extirpation of beavers from the system, channel straightening and floodplain fill, and changes in the hydrology of the contributing watersheds (specifically as a result of urbanization). Sporadic outcrops of conglomerate and interbedded sandstone material are mapped along the river corridor but are discontinuous and were not observed to provide grade or valley margin control along the study reaches. Anthropogenic fill material has been introduced into the stream corridor to provide for development along its margins. It is assumed that this fill material has a similar erodibility as native material.

**Figure 6.** (Left) East Plum Creek with alluvial terrace edges highlighted. Terrace material, which forms valley margins, is highly erodible. (Right) Planview of hillshade image of East Plum Creek with approximate dates of when terrace margins formed (i.e., when river incised and abandoned these surfaces as floodplains) based on historic aerial imagery analysis. Channel has incised approximately 12 feet since 1930 in this area.

**Hydrologic Context**

Colorado’s most intense large-scale rainfall events occur over the Great Plains Region, especially along the Colorado Piedmont (Doesken et al., 2003). Precipitation in the Colorado Piedmont averages 15 inches annually, most of which falls as snow in the early spring and rainfall during
the summer months. As such, natural vegetation is limited to grass, shrubs, and evergreen trees in upland areas with deciduous riparian vegetation such as cottonwood and willow in stream corridors (Hansen, 1978). Here small-scale, short duration to regional-scale, long duration extreme precipitation events occur in the late summer and early fall as moisture is forced to uplift along the Front Range (i.e., Gochis et al., 2014). This extreme rainfall along with the alluvial deposits that form much of the Colorado Piedmont, as well as the aeolian deposits further east, result in highly dynamic stream systems.

East Plum Creek is primarily intermittent, flowing seasonally with low-elevation snow melt and in response to summer and fall rainstorms. Portions are perennial where waste water treatment plant effluent outflows contribute. Monsoons and convective rainfalls occurring in the summer and fall are responsible for the most extreme floods in the region (Jarrett and Costa 1988, Pitlick 1994, Mahoney et al., 2015, and Figure 3, above). Regional-scale heavy rainfall over extended durations was responsible for the 1965 and 2013 floods along the Front Range and Eastern Plains, both of which resulted in catastrophic damage over large areas (i.e., multiple HUC-8 basins). Smaller-scale convective rainfall events that result in localized flood damages are more common. These floods typically influence one or more smaller basins (HUC-14) or a single larger basin (HUC-8). Runoff from rainfall events can augment the small to nonexistent baseflow to 1000’s of ft³/s. The 1% annual exceedance flood for East Plum Creek along the study reach is 16,650 ft³/s (UDFCD 2016). The propensity for such large extremes in flood flows and history of extreme rain events in this region led to the construction of Chatfield Reservoir downstream of the study reach by the U.S. Army Corps of Engineers following the 1965 flood that impacted this watershed and others in the region.

**Geomorphic Context**

Both the East Plum Creek and Sellers Gulch are primarily comprised of sinuous sand and gravel bedded reaches of moderate slopes (0.5-2.5%). Some reaches are comprised of wide valleys with multi-threaded, willow-dominated, wetland-like zones where no dominant channel exists. Evidence of beaver activity has been observed in these reaches. Other reaches have sinuous and wandering channels entrenched within alluvial terraces ranging from 10 to 30 feet, increasing in height downstream. The reaches of the study area are partially to fully confined. Estimating an average width of the channel proves challenging as it is highly variable longitudinally and is also a strong function of time since the last major flood (i.e., Friedman and Jones, 2000). As discussed under the previous sections, a combination of high sediment supply, erodible valley margins, and flashy hydrology results in East Plum Creek being geomorphically dynamic, especially under floods.

The East Plum Creek watershed has experienced several extreme flood events over the last 100 years that have reconfigured the channel, floodplain, and valley resulting in a broad braided channel post flood. Aerial photo analysis, confirmed with gauge data, indicate that the 1965 flood was the most recent of these significant floodplain-altering events for the mainstem of East Plum Creek. Since then, vegetation in the active river corridor of the study area has largely re-established and the post-flood braided channels have narrowed back into a small single-thread channel. Due to the highly erodible nature of the valley margin, large flood events may result in hillslope retreat on the order of 10’s to 100’s of feet (Figure 7).

Analysis of historic aerial imagery coupled with contemporary digital elevation models indicates that East Plum Creek has been incising over at least the last century and perhaps longer (Figures 6 and 7). Beaver extirpation from the Front Range during the mid-1800s may have aided in channel incision (Goldfarb, 2018). Since 1930, the channel has incised up to 12 feet in some locations resulting in a series of alluvial terraces (Figure 6). The presence of erodible sands and
gravels of alluvial terrace margins along with the lack of the bedrock to provide natural grade control has resulted in a net export of sediment from these study reaches and a continual lowering of the channel bed and floodplain over time. Changes in land cover from historic ranching to urbanization in the watershed may have also exacerbated channel incision and sediment loads to the study area. However, the ranching itself may have contributed to this. Gullying can be observed throughout the study area along ephemeral side drainages (Figure 6).

Incisional processes in East Plum Creek compounds geomorphic hazards associated with valley margins, which are prone to mass-wasting as a result of direct fluvial scour and over-steepening. Urbanization along the center of the study area has led to moderate and heavily alteration to the stream corridor including increased constriction of the channel by floodplain fill. Therefore, in addition to lateral hillslope erosion during floods, chronic channel incision and floodplain fill may contribute to geomorphic hazards associated with the instability of valley margin terraces. The geomorphic trajectory of the East Plum Creek study area is likely continued channel incision along with episodic, valley-scale widening as a result of low-frequency, extreme flood events.

**Figure 7.** Illustration of valley-wide channel migration and valley margin erosion on East Plum Creek, north of the Town of Castle Rock. Shaded polygons demark the active river corridor (channel and geomorphic floodplain) for each year. Since this event (1970-1996), several moderate-sized flood events have occurred resulting in gradual (tens of feet) erosion of valley margins.

**Mapping Fluvial Geomorphic Hazards on East Plum Creek**

Mapping fluvial geomorphic hazards along East Plum Creek begins with defining the active geomorphic floodplain, also known as the active river corridor (CWCB, 2019). Based on historic evidence of valley-wide expansion of the creek during extreme flood events, the ARC was typically delineated from toe to toe of the valley margin. Given the multiple incisional events that have occurred over the past century and the numerous terrace margins bordering the active river corridor at different elevations, defining the valley margin proved to be a non-trivial task (Figure 7). Use of a LiDAR-derived relative elevation models coupled with hillshade imagery allowed for initial active river corridor delineation, later refined with field observations used to verify which terraces could be within the ARC.

A wide fluvial hazard buffer, extending from the edge of the ARC to some distance into the valley margins, was deemed necessary based on observations of dramatic lateral erosion into valley margins. Median values for the width of lateral erosion into valley margins as a result of the 1965 flood event averaged one half of the width of the ARC (100 ft) (CWCB, 2019). However, as noted above, East Plum Creek has incised over ten feet in the last century resulting in much higher terrace valley margins in many locations. A flood event of similar magnitude as the 1965 flood in
the contemporary stream corridor may not accomplish such wide margins of erosion given its greater degree of entrenchment. To delineate the FHB, a buffer of two ARC widths was made on either side of the valley centerline. The FHB was defined as the area of the buffer extending beyond the ARC. A minimum of one channel width from the ARC defines the FHB where the ARC intersects this meander centerline buffer (Figure 8). Site-scale geologic or geotechnical studies may be used to validate the width of this buffer and determine if some valley margins are more competent than assumed in this delineation.

The fluvial hazard zone, then is defined as the sum of the active river corridor and the fluvial hazard buffer. Fans identified within the stream corridor along with potential avulsion pathways are identified as auxiliary hazard units.

Figure 8. In a highly erosive system like East Plum Creek the fluvial hazard buffer is determined by delineating a buffer (orange polygon) of two ARC widths on either side of the valley centerline.

Summary and Conclusions

In this paper we have described the various components of the physiographic and geomorphic contexts that influence fluvial geomorphic hazards along stream corridors. This context is important in understanding the geomorphic trajectory of the stream corridor and its sensitivity to disturbances. This in turn informs how a fluvial hazard zone can be mapped to delineate existing fluvial geomorphic hazards. We provide a case study on East Plum Creek in the Colorado Front Range Piedmont region in which we define the physiographic and geomorphic contexts and apply them to a fluvial hazard zone delineation. We are grateful for the contributions of Matthew Morgan and Kevin McCoy of the Colorado Geologic Survey and for the support and funding of the Colorado Water Conservation Board.

References


