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Ruarri J. Day-Stirrat, State Geologist

OPEN-FILE REPORT O-24-09

CHANNEL MIGRATION ZONE MAPS FOR THE ZIGZAG RIVER, CLACKAMAS COUNTY, OREGON

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WHAT'S IN THIS REPORT?

This report describes the methods and results of channel migration zone mapping for the Zigzag River in Clackamas County, Oregon. This information can help communities plan and prepare for natural disasters.

Cover photograph: View of Zigzag River, Oregon near the Road 31 bridge, looking east, upstream (45.3085, -121.8595 WGS geographic coordinates). Photo credit: Christina Appleby, 2023

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Clackamas_Co_CMZ.gdb

Feature dataset: Zigzag_River_CMZ

Feature classes:

Zigzag_River_AC; Zigzag_River_AHA; Zigzag_River_CMZ; Zigzag_River_EHA_Low; Zigzag_River_EHA_Medium; Zigzag_River_EHA_High; Zigzag_River Flag; Zigzag_River HMA; Zigzag_River_Study_Area

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EXECUTIVE SUMMARY

This study provides Oregon communities with new information about the natural hazards associated with channel migration. During 2023 and 2024, the Oregon Department of Geology and Mineral Industries (DOGAMI) produced channel migration zone (CMZ) maps for the Zigzag River in Clackamas County. These maps are the first of their kind published for this river.

CMZ maps define the area in which a given stream is likely to move laterally and change its channel course within the next 30 and 100 years. In this study, we mapped CMZs along the lower 7.8 mi (12.5 km) of the Zigzag River. The components of these CMZ maps are the active channel; historical migration area; 30-year high, 30-year medium, and 100-year low erosion hazard areas; avulsion hazard area; and flagged streambanks. The method we used was primarily based on the interpretation of historical aerial photographs, high-resolution lidar topography, geologic maps, and flood inundation maps.

Overall, our results show that the Zigzag River is a highly dynamic system; all of the segments in the study area experienced some degree of lateral migration during the last 66 years and remain vulnerable to future channel migration. During the catastrophic December 1964 flood, the Zigzag River underwent widespread, accelerated change during which the banks and floodplain were heavily eroded, and the channel avulsed to new locations in several areas. The maximum erosion rates within each river segment ranged from 8.9 to 40.4 ft/yr (2.7 to 12.3 m/yr). After the 1960s, lateral migration has continued, but at a more modest pace and smaller extent; between 1995 and 2022, the majority of the channel migration occurred in the lower 1.4 mi (2.3 km) of the river.

From a broader geologic perspective, the Zigzag River is located within the Mount Hood region; this area has been heavily impacted by multiple hazards and the interactions between these hazards can be complex. While the purpose of this study is to examine the channel migration hazard, the history of volcanism, landslides, and debris flows must also be recognized. The next time a volcanic eruption or very large debris flow fills the river channel or valley with sediment, the Zigzag River may take decades, if not centuries or longer, to reestablish a channel and floodplain. Even a series of smaller events, such as multiple years with large debris flows, can cause significant damage and major changes to the floodplain. Channel migration rates and patterns will be highly unpredictable during this period of disequilibrium, and the maps produced in this study would need to be updated.

CMZ maps are designed to aid in community planning, raise awareness of river flood and erosion hazards, and inform decisions about environmental and emergency management and land use. The maps may be used to identify which buildings, critical facilities, transportation infrastructure, and utility lines are potentially at risk from channel migration and to prioritize areas for pre-disaster risk reduction. The maps in this study do not replace a site analysis by a land surveyor, geologist, or engineer. These hazard maps will provide a timely and valuable resource for the county and community planning efforts, including during the development of emergency plans and natural hazard mitigation plan updates.

1.0 INTRODUCTION

1.1 Purpose

The purpose of this project is to help communities better understand channel migration hazards and to provide data that will aid in the identification of areas at greatest risk so that communities may plan, prepare, and mitigate riverine hazards. This is accomplished by providing the best-available information about potential channel migration. This study documents channel migration patterns for the lower 7.8 mi (12.5 km) of the Zigzag River in Clackamas County. The river was selected based on proximity to population centers, transportation corridors, and the need for new or updated mapping of channel migration as requested by communities and counties. In addition, we used the statewide channel migration screening established by Roberts and Anthony (2017) to identify priority areas for CMZ mapping.

The accompanying maps and GIS datasets can be used to perform detailed risk assessments that demonstrate how many people and which buildings and infrastructure are at risk from channel migration hazards. CMZ maps are designed to be shared with local and state emergency managers, planners, elected officials, community leaders, watershed councils, residents, and other stakeholders to inform land use and environmental planning; develop building codes and ordinances; and identify, prioritize, and implement hazard mitigation actions. These hazard maps will provide a timely and valuable resource for county and community planning efforts, including the natural hazard mitigation plan (NHMP) updates.

1.2 Hazard Overview

1.2.1 Channel migration

Channel migration is a geomorphic process by which a stream moves laterally across its floodplain over time. This process includes bed and bank erosion, sediment deposition, and channel avulsion—a process in which the stream abruptly moves to an entirely new location on the floodplain (Slingerland and Smith, 2004). Channel migration can undermine buildings, roads, levees, and other infrastructure; it can rapidly redirect flooding to new areas, erode land, cut off evacuation routes during a flood, and, in rare cases, endanger lives (Olson and others, 2014).

Channels migrate and change as a function of sediment supply, discharge, channel bed and bank geology, climate, riparian vegetation, basin physiography, and human modifications (Knighton, 1998). While bedrock-controlled channels migrate very gradually across centuries, alluvial channels with braided, meandering, and anastomosing channel forms commonly migrate across the landscape over years or decades (Rapp and Abbe, 2003). Channel morphology may change in both horizontal and vertical directions. Horizontal movement is often observed as lateral migration, avulsions, widening, or narrowing. Vertical movement includes channel bed incision and sediment aggradation, both of which can trigger lateral migration.

CMZ mapping seeks to identify the area in which a given stream is likely to move laterally and occupy in the future based on historical channel behavior and current geomorphic conditions. CMZ maps include the areas on the floodplain previously occupied by the channel, as these areas create a high potential for channel reoccupation. They also include those areas susceptible to future erosion that can be identified by establishing a historical rate of bank erosion using aerial photographs and geologic maps (Rapp and Abbe, 2003). Potential avulsion areas are shown in CMZ maps and are mapped based on interpretations of lidar topography, with a focus on low-lying areas near the active channel.

Channel migration is a very poorly understood natural hazard in Oregon for several reasons:

- CMZs have not been mapped along the majority of Oregon's rivers. Although a statewide screening was produced by Roberts and Anthony (2017) to help prioritize mapping, this study did not directly answer primary questions concerning CMZs, such as, which rivers regularly experience channel migration.
- Conventional flood hazard maps like the Federal Emergency Management Agency's (FEMA) Flood Insurance Rate Maps (FIRMs) only examine hazards posed by standing floodwaters modeled on a static floodplain. However, channels commonly migrate during real flood events, creating the potential for new areas to be impacted by erosion and flooding.
- Past damage from channel migration has not been well documented and tends to be included within general flood damages. We do not know what the true impact of channel migration has been on people, buildings, roads, and other infrastructure in Oregon.

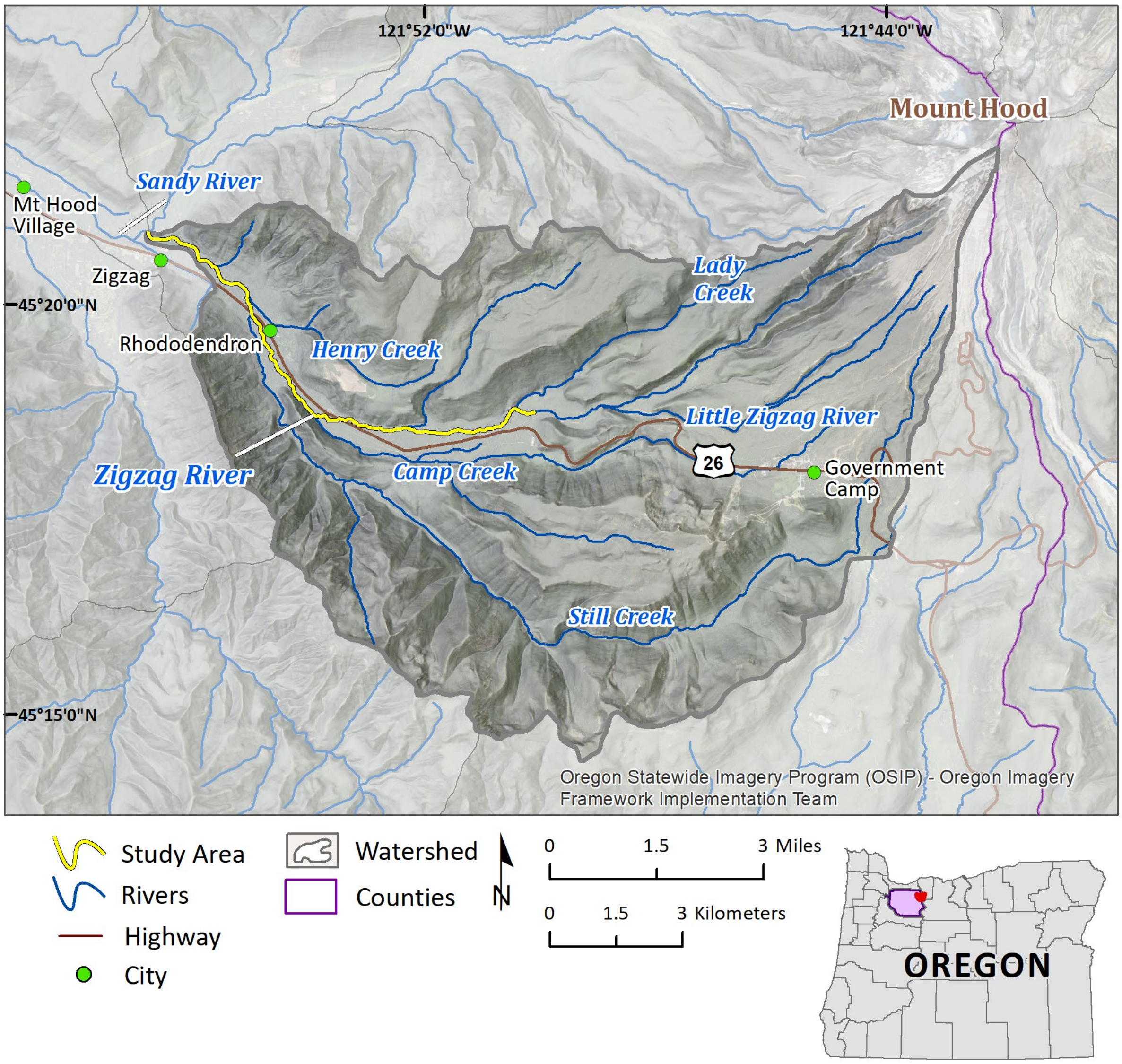
1.3 Study Area

1.3.1 Clackamas County

The Zigzag River flows across the western flank of Mount Hood and is located in northeastern Clackamas County (**Figure 1-1**). It is bordered by Multnomah County to the north, Hood River and Wasco counties to the east, Marion County to the south, and Yamhill and Washington counties to the west. The Clackamas County's urban centers are located in the northwestern corner of the county and include Milwaukie, Oregon City, Lake Oswego, Wilsonville, and a part of Portland. The central part of the county is relatively rural and includes smaller towns such as Scotts Mills, Molalla, Estacada, and Sandy while the southwestern half of the county is largely comprised of the Cascade Mountain Range, which includes Mount Hood and the Mount Hood National Forest. According to the Oregon Blue Book (Oregon Secretary of State, 2024), Clackamas County's economic activity is driven by agriculture, timber production, metals manufacturing, and trucking and warehousing; the area is also widely recognized for its outdoor recreation opportunities.

The Zigzag River and the surrounding Sandy River watershed have a history of devastating floods, (e.g., floods in 1964, 1996, and 2011). The damage from both channel migration and flooding of homes, other buildings, bridges, and roads has been extensive. As described in the following sections, the persistent concerns of communities and landowners in the area are justified in this highly dynamic environment and may be further exacerbated by climate change impacts.

Figure 1-1. Study area (highlighted in yellow) with nearby communities and major tributaries in northeastern Clackamas County, Oregon. The context map shows the location of full Clackamas County (purple) with the Zigzag River watershed highlighted in red.



1.3.2 Zigzag River geology, hydrology, geomorphology, and modifications

The Zigzag River is ~14 mi (~23 km) long and its watershed is ~59 mi^2 (~153 km^2) in area. It originates along the southwestern slopes of Mount Hood (~11,225 ft (3,421 m) above sea level (asl)) and flows predominantly westward until it reaches the confluence with the Sandy River, near the community of Mount Hood Village (~1,375 ft (419 m) asl). The largest named tributaries to the Zigzag River, from upstream to downstream, include the Little Zigzag River and Lady, Camp, Still, and Henry creeks.

The Zigzag River is a major headwater tributary to the Sandy River. However, there are far fewer studies of the geology, hydrology, and geomorphology of the Zigzag River when compared to the Sandy River or Mount Hood. As a result, we have included citations to studies that focused on regional conditions to provide the necessary context.

1.3.2.1 Geology

Mount Hood is one of the many large, active volcanoes in the Cascade Mountain Range (United States Geological Survey (USGS), 2023). It is a relatively young, predominantly andesitic volcano that has erupted repeatedly for hundreds of thousands of years (Scott and others, 1997) with the most recent eruptions in 1859 and 1865 (USGS, 2023). Across the Zigzag River watershed, the underlying geology of the volcano is composed of a variety of older, Miocene Western Cascade Volcanics and High Cascade Volcanics (e.g., andesite, mudflow breccia, sandstones, and intermediate composition intrusive rocks); Pliocene High Cascade Volcanics (e.g., basalt); and younger, Quaternary High Cascade Volcanics (e.g., andesite, basalt, basaltic andesite, dacite, and pyroclastic flow and debris flow deposits) (Burns and others, 2011; Franczyk and others, 2020). These rocks have been reworked into a variety of alluvial and colluvial deposits, including glacial, landslide, and fluvial deposits. Glacial deposits were mapped by Sherrod and Scott (1995) at higher elevations adjacent to the modern Zigzag Glacier, but more recent work has mapped moraine till deposits "at or near the last glacial maximum" at lower elevations, along the valley walls just upstream of the study area (Figure 7 from Scott and Gardner, 2017).

Within the study area, the valley walls have been mapped by Sherrod and Scott (1995) as Miocene mudflow breccias overlain by Miocene, Pliocene, and Quaternary andesite, basaltic andesite, and basalt. The valley bottom is composed of Holocene alluvium, Quaternary colluvium, Quaternary landslide deposits, and two units of pyroclastic flow and debris flow (lahar) deposits (Sherrod and Scott, 1995). These pyroclastic and debris flows were deposited during the Timberline eruptive period (~195-595 A.D.) and the Old Maid eruptive period (Sherrod and Scott, 1995) (deposited ~1781 A.D. (USGS, 2023)). By comparing the spatial extent of the deposits mapped by Sherrod and Scott (1995) to the 2009 lidar-derived topography, we estimate that the older, Timberline deposits make up a terrace surface that is ~10-50 ft (~3-15 m) above the modern river. The younger, Old Maid deposits were mapped along the modern river channel and floodplain. Both were described as "poorly sorted pebbles, cobbles, and boulders in chiefly reddish-gray sandy matrix" (Sherrod and Scott, 1995). In addition, numerous landslide deposits have been mapped along the bottom of the valley and valley walls, including fans and debris flows, as shown in the Statewide Landslide Database for Oregon (Burns and others, 2011; Franczyk and others, 2024). Burns and others (2011) mapped a debris flow deposit along the upper half of the study area produced during the December 1964 storm, although field work in 2023 indicates that some of the debris flow deposits have been remobilized by the river or removed by humans.

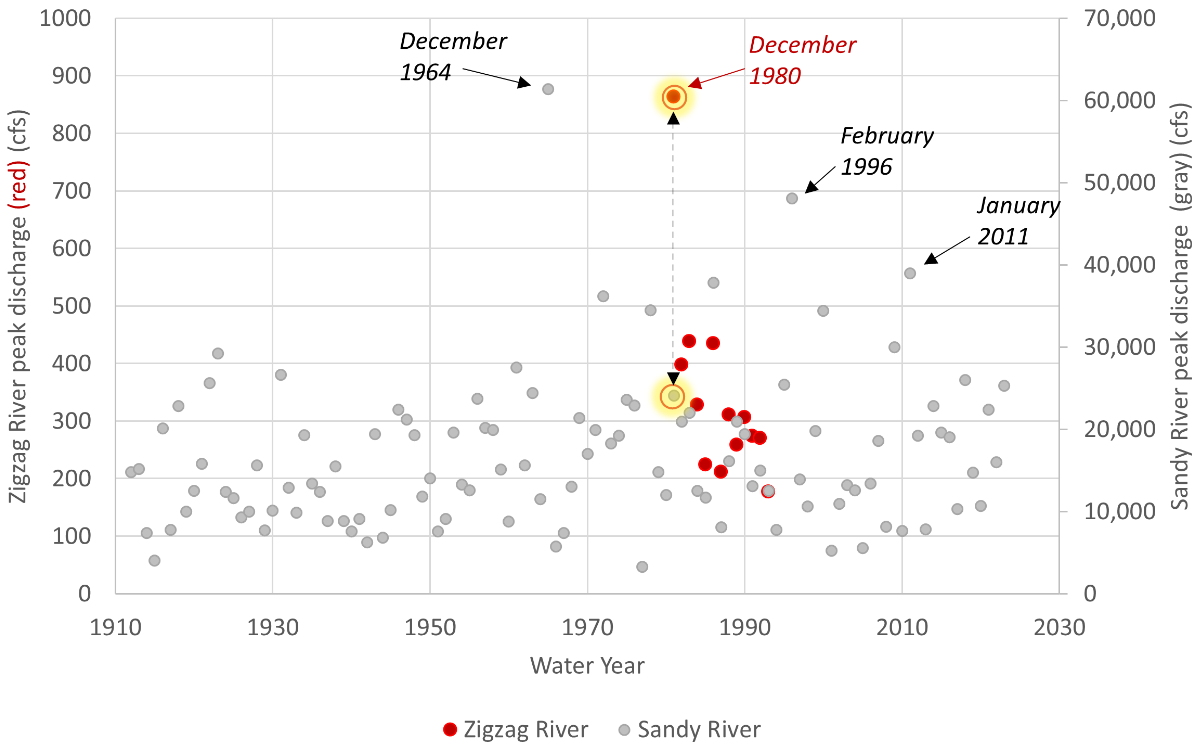
1.3.2.2 Hydrology and flood history

Like much of western Oregon, the Zigzag River watershed experiences cool, wet winters, and warm, dry summers. Streamflow is driven by a combination of rainfall and snow melt. There are transient snow zones in the lower Zigzag watershed (656–3,281 ft (200–1,000 m) altitude), including our study area, which are prone to rain-on-snow triggered flooding (Major and others, 2012). Snowpack accumulates seasonally above 3,281 ft (1,000 m) altitude (Major and others, 2012). Evidence of this transient snow zone is seen in the difference in snowfall records for two Western Regional Climate Center (WRCC) monitoring stations near the study area. Above the study area, at the Government Camp station (elevation of 3,980 ft asl (1,213 m)), the mean annual precipitation was 88 in (224 cm) with an average of 271 in (688 cm) of snowfall between 1951 and 2016 (WRCC, 2024a). By contrast, ~14 mi (~22.5 km) downstream at the Brightwood station (elevation 1,070 ft (326 m) asl), located below the study area), the mean annual precipitation was 86 in (218 cm) with only 25 in (64 cm) of snowfall between 1958 and 1981 (WRCC, 2024b). At both WRCC stations, the greatest amount of precipitation occurred from October through March. As a result, peak streamflow takes place throughout the winter driven by new precipitation and persists through the spring due to snowmelt.

Streamflow is also influenced by groundwater recharge, however no studies have quantified or modeled these contributions for the Zigzag River. It is likely that the permeability is highly variable among the basaltic lava flows and unconsolidated volcanic deposits of various ages that make up the underlying geology of the Zigzag River basin, but the potential for groundwater flow is greater along cooling joints, fractures, interflow zones, and other open spaces (Whitehead, 1994). Regional studies, such as the Oregon Water Resources Department (1991) Sandy Basin Report, focus on the municipal use of the Bull Run watershed and areas of concerning groundwater decline near Sandy, while recognizing an abundance of groundwater at a basin scale.

The largest recorded flood events in the Sandy River watershed took place in 1964, 1996, and 2011, as shown in **Figure 1-2**. Abbe and others (2015) suggest that nearly all the large floods in this area have been produced by atmospheric rivers occurring between November and January. In the case of the most damaging and largest storm in the last century, the 1964 event, several days of cold temperatures and snowfall was followed by an increase in temperature and heavy rainfall. The combined snowmelt and rainfall produced 13 inches (33 cm) of runoff over frozen ground, which limited infiltration, producing widespread flooding (Abbe and others, 2015). Abbe and others (2015) estimated the 1964 event was a ~250-year flood (~0.4 % annual exceedance probability (AEP), the 1996 event was just under a ~100-year flood (~2% AEP), and the 2011 event was a ~30-year flood (~3% AEP) for the Sandy River. Prior to the recorded flood events, the flood in December 1861 was described by the United State Forest Service (USFS, 1995) as “significant” for the region, but no quantitative description was provided for this event that would allow us to compare the flood magnitude to more recent events.

Figure 1-2. Peak streamflow for the Zigzag River at Rhododendron (red dots) (USGS streamgage 14131400) in water years 1981-1993 (USGS, 2024A). Peak streamflow for the Sandy River near Marmot (gray dots) (USGS streamgage 14137000) in water years 1912-2023 (USGS, 2024B). According to the USGS, the Zigzag River gage has an upstream drainage area of ~15 mi² (~39 km²) and the Sandy River gage has an upstream drainage area of ~264 mi² (684 km²). For comparison, the peak discharge in December 1980 was 863 cfs (24 cms) on the Zigzag River and 24,100 cfs (682 cms) on the Sandy River (yellow highlight).



The 1964, 1995, and 2011 floods caused extensive damage to the roads, bridges, homes, and other structures along the floodplain due to the combination of riverine flooding, channel migration, and landslides. Across Oregon, more than 7,000 homes were damaged or destroyed during the 1964 flood (United States Army Corps of Engineers (USACE), 2024) and 20 people lost their lives (Department of Land Conservation and Development (DLCD), 2020). The estimated cost of damages in Oregon ranges from DLCD's (2020) estimate of more than $157 million in 1965 dollars (~$1.6 billion in 2024 dollars) to the USACE (2024) estimate for home damage of $245 million in 1965 (~$2.4 billion in 2024 dollars). According to the Clackamas County Board of Commissioners (Bernard, 2018), 155 dwellings were destroyed in the Upper Sandy River Basin, primarily due to channel migration. The USGS (Waananen and Williams, 1971) reported that there were also two bridges upstream of Rhododendron that suffered damage, and the road and bridge closures isolated approximately 80 people locally. **Figure 1-3** shows an example of one of these homes undermined by channel migration. In response to the flood, the USACE channelized the mainstem of the Zigzag River by deepening and straightening the channel and cutting off meanders, oxbows, and side channels (USFS, 1995). The USACE and USFS also removed large logs and boulders from Still Creek, Camp Creek, and the mainstem of the Zigzag River (USFS, 1995). Unfortunately, the location and extent of these modifications is not well documented. Additionally, the Oregonian newspaper (Tomlison, 2011) reported that the recent 2011 flood destroyed three homes (two along the Sandy River and one along the Zigzag River) by undercutting the banks and foundations; East Lolo Pass Road was heavily eroded and the bridge over the Zigzag River had to be closed due to structural concerns.

Figure 1-3. Photograph of houses on the Zigzag River after the December 1964 and January 1965 floods. Credit: Clackamas County Historical Society, P-2100, January 12, 1965.

Figure 1-2 shows the annual peak discharges of the Zigzag River for the limited time when the gage was maintained between 1981 and 1993 and discharges recorded on the Sandy River (~19.3 mi (~31 km) downstream of the Zigzag River gage) between 1912 and 2023. We display both sets of gage data because the period of record for the Zigzag River spans a fairly short time span, while the Sandy River data is a better representation of long-term trends in peak flood flows. Although the annual peak discharges on the Zigzag River are a small fraction (1-4%) of the flows recorded on the Sandy River, a comparison of the daily and annual flows at the gages show both streams display a similar pattern in the timing and response to precipitation and snowmelt. It may visually appear in **Figure 1-2** that there is a slight increase in peak flow over time, but analysis by Abbe and others (2015) found the change was not statistically significant at a 90% confidence level.

According to the effective FEMA (2019) flood insurance maps for unincorporated Clackamas County, the areas upstream of the confluence with Still Creek in Rhododendron have very narrow 100- and 500-year mapped floodplains and the areas downstream of the confluence have much wider floodplains. In the Flood Insurance Study report, FEMA notes that the main areas of flooding are those where development has caused the river to be constrained, creating risk to properties.

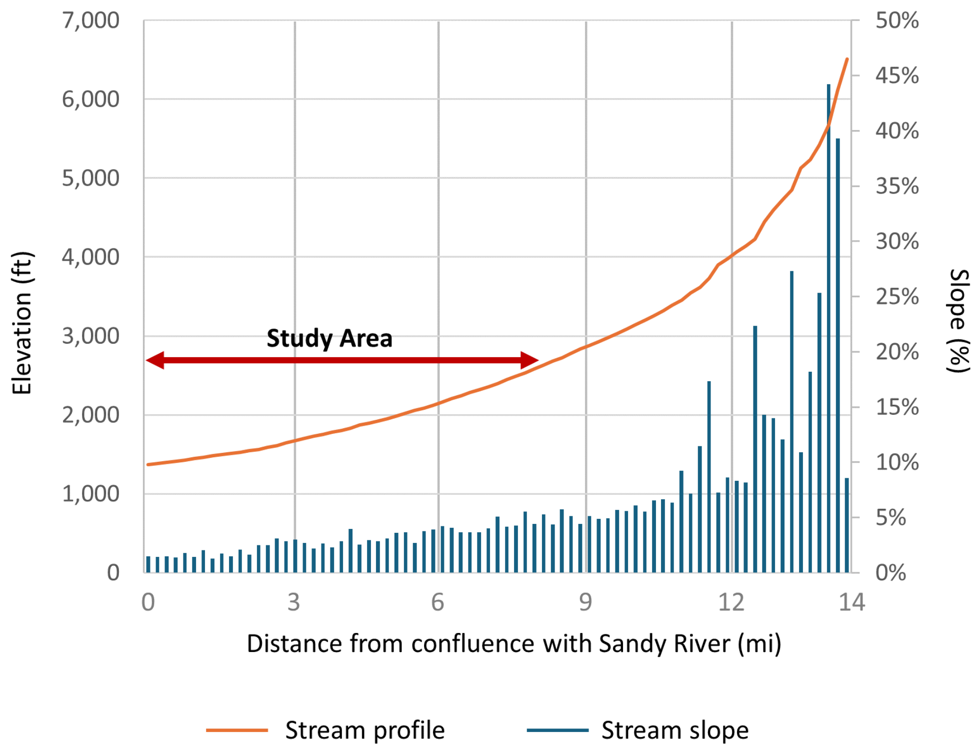
1.3.2.3 Geomorphology

The Zigzag River watershed is a very dynamic area that brings together multiple geologic hazards and surficial processes. Post-glaciation, the Sandy River watershed has experienced cycles of valley infilling with pyroclastic flow and lahar deposits from Mount Hood, producing abundant sediment, followed by downcutting into the new deposits (Abbe and others, 2015). Across several millennia, the Zigzag and Sandy rivers produced new floodplain geometry, and forests eventually reestablished across the valley bottom. Finally, another eruption produced new pyroclastic flow or lahar deposits that filled the valley, and the cycle started again. Within this cycle, debris flows, landslides, and floods provide additional sediment to the river, floodplain, and valley floor. These combined catastrophic disturbances and gradual processes have created the modern surficial geology along the Zigzag River valley. Due to the unpredictable nature of Mount Hood eruptions, it is difficult to suggest when the next depositional event will occur that will again reset the channel elevation and valley form.

The Zigzag River has ample sources of sediment, including the previously noted pyroclastic flow and lahar deposits from previous eruptions; the numerous landslides and debris flows, some deposited as recently as the 1960s; the outwash deposits from the Zigzag Glacier; and Zigzag River floodplain deposits. As described in the previous section, the area also receives immense amounts of precipitation, which, in combination with potential snow melt and a steeply sloping channel (see **Figure 1-4**), provides the energy for the Zigzag River to transport large volumes of sediment downstream into the Sandy River watershed.

In addition, a study by English (2013) showed that in the lower 2 mi (3.2 km) of the Zigzag River, there was a net loss of ~67,000 yd^3 (~51,230 m^3) of primarily bed material between 2007 and 2011, which the authors attributed to erosion during flooding in January of 2009 and 2011.

Figure 1-4. The Zigzag River water surface elevation and slope. To provide perspective, a 5% slope would be the same as ~264 ft (~80 m) change in elevation across 1 mi (1.6 km) and a 20% slope would be the same as a ~1,056 ft (~322 m) change in elevation across 1 mi (1.6 km).



Within the study area, the Zigzag River channel is composed of a wide range of sediment sizes, including boulders, cobbles, and gravels. They form temporary gravel bars, islands, most commonly in a single thread form, but also split into multiple threads in limited areas. The floodplain is relatively narrow in the upstream reaches and becomes modestly wider near the confluence with the Sandy River; FEMA's (2019) flood models show the 0.2% annual chance (500-year) floodplain to range between 0 ft and ~245 ft (0 m and ~75 m) wide, as measured from the floodway edge, upstream of the confluence with the Camp Creek, and ~665 ft (~200 m) wide below the confluence with Still Creek. When left undisturbed, these floodplains are commonly forested by evergreens (i.e., Western Hemlock, Pacific Silver Fir, and Mountain Hemlock (USFS, 1995)) and deciduous shrubs. Although the USFS completed a watershed assessment in 1995, further study is needed to quantify the sediment input, transport, storage, and export capacity of the Zigzag River over time. For more information about the sediment budget for the Sandy River, please refer to the study of the Marmot Dam removal by Major and others (2012).

Due to recent damage from flooding, channel migration, and landslides, several studies have been undertaken to identify areas at risk from future erosion and migration along the Sandy River. These studies include the 2011 study by Burns and others that mapped multiple geologic hazards and risk for Mount Hood, the 2013 study by English and others mapping channel migration hazards along the lower and upper Sandy River, and the 2015 study by Natural Systems Design (Abbe and others) evaluating flood erosion hazard mitigation for the upper Sandy River. Our study compliments these studies and expands mapping efforts to include the Zigzag River and to classify mapped units as low, medium, and high hazard.

1.3.2.4 Human modifications

Although the Zigzag River watershed includes several small communities and is bisected by Highway 26, there has been less human development in this subbasin than in the overall Sandy River watershed. The Zigzag River basin includes several thousand homes and dozens of businesses within the unincorporated communities of Zigzag, Faubion, Rhododendron, and Government Camp. These communities were established in the late 19th and early 20th centuries, which coincided with the construction of a series of post offices, the first Civilian Conservation Corps camp in Oregon, and the construction of the Zigzag Ranger Station (Munro, 2024). The majority of the watershed is heavily forested and located within the Mount Hood National Forest.

There have been many large restoration efforts undertaken across the Sandy River watershed, most notably the removal of the Marmot Dam in 2007; many of these projects have focused on improving salmonid habitat and fish passage. Along the mainstem of the Zigzag River, approximately 1.5 mi (2.4 km) upstream of the confluence with the Sandy River, a large restoration project led by the USFS was completed in 2023 that sought to improve habitat in the channel and floodplain for Chinook and coho salmon, steelhead, and cutthroat trout (M. DeAngelo, USFS, written communication, 2024). This work widened the mainstem, removed levee-like features, added constructed riffles, opened new and increased flow in several side channels, and placed large wood and several log jams along the channel and floodplain. The project is located in an area that was likely modified after the 1964 flood when the Zigzag River was deepened and straightened, and large woody debris was removed (USFS, 1995). If successful, it is anticipated that this work will produce greater flood storage and side channels. Unfortunately, this restoration project concluded after the imagery that was used in this study was collected. As a result, these CMZ maps may not fully account for these recent modifications. Additionally, a series of instream restoration activities took place between 2012 and 2017 along Still Creek, a major tributary to the Zigzag River; this work also aimed to increase the density of spawning and rearing habitat for salmonids (Sandy River Basin Watershed Council, 2017).

Climate change represents the most widespread and complex human modification to the watershed. In Oregon, climate change has, and will, continue to alter the patterns in temperature, precipitation, snowpack, and glacial extent. In Clackamas County, the Oregon Climate Change Research Institute (OCCRI) predicts that, if greenhouse gas emissions remain high, the amount of precipitation on the wettest day and the wettest consecutive five days per year are projected to be greater by the 2020s and 2050s when compared to the 1971-2000 historical baseline (Dalton and others, 2023). They also note that increasing temperatures will lead to an increase in the proportion of precipitation that falls as rain rather than snow, causing a transition of snowfall-dominated areas to become transient snow zones and current transient snow zones to become rainfall dominated. This prediction is further supported by a study of the potential impacts of climate change on streamflow in Oregon by Leibowitz and others (2014) who noted the potential for considerably less streamflow in late spring due to reduced snowpack. In addition, the Zigzag Glacier, like many of the glaciers on Mount Hood, has been rapidly retreating throughout the last century and was reported to have lost approximately one-third of its area between 2015-2023 (Bakken-French and others, 2024).

It is difficult to accurately predict how these collective changes will impact future flooding, sediment supply, and channel migration due to many complex dynamics. While it is generally accepted that greater precipitation can result in higher stream discharge, which would increase the Zigzag River's erosive power, the actual impact on channel migration may be altered by other conditions. For example, past flooding events have been exacerbated by frozen ground, which was impervious to rainfall and runoff; however, if the ground is not frozen during future winters, higher infiltration rates may reduce runoff and peak streamflow. In another example, a study by Leibowitz and others (2014) also suggested that more precipitation falling as rain instead of snow in the winter may change groundwater recharge in areas of the Upper Sandy River watershed with high permeability; they suggested this change may buffer the effects of climate change by providing a source of sustained spring and summer streamflow. We recognize that climate change may also alter landslide, debris flow, and lahar activity, as well as wildfires, but the cumulative effect of these changes on sedimentation in the watershed is yet unknown. Additional studies and monitoring are required to better understand the dynamics at play and interconnected feedback loops and to measure the impact of climate change on channel migration.

2.0 METHODS

2.1 Overview

The goal of this CMZ evaluation is to define the area in which a given stream is most likely to move laterally within the next 30 and 100 years. This boundary is designed to aid in planning, raise awareness of hazards, and to inform decisions about environmental and emergency management. These maps and GIS datasets may be used to identify which buildings, critical facilities, infrastructure, and transportation lines are potentially at risk from channel migration and to prioritize areas for pre-disaster risk reduction.

We created CMZ maps for the Zigzag River located in eastern Clackamas County by following the method outlined in this section. Our approach integrated techniques and mapping units from various prior studies conducted in Oregon, Washington, and Colorado, including Appleby (2024), Appleby and others (2021), English and others (2013), Lagasse and others (2004), Olson and others (2014), Rapp and Abbe (2003), and multiple studies by the King County Department of Natural Resources and Parks from 1991-2020, for example King County (2019). We acknowledge that terminology and definitions of mapping units differ among these previous studies. In our study, we define the following terms as explained below. It is important to note that we use "river," "stream," and "creek" interchangeably.

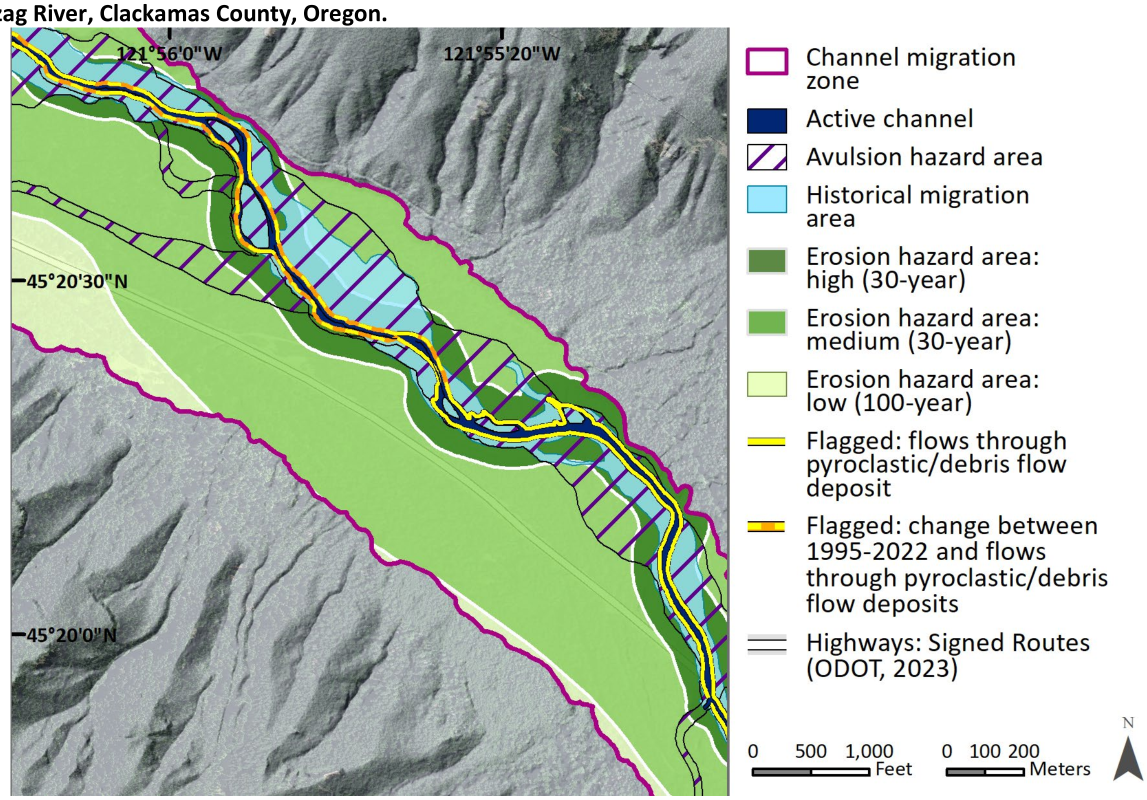
Terminology:

- *Active channel (AC)*: the area within the floodplain that regularly conveys water, including the exposed, unvegetated sediment deposits both within and adjacent to the river; it is inundated at times of high discharge (Montgomery and MacDonald, 2002);
- *Historical migration area (HMA)*: the combined areas that the channel has occupied in the historical record, including the AC (labeled historical migration zone by Rapp and Abbe, 2003);

- *Erosion hazard area (EHA)*: the area most likely to be impacted by lateral migration and channel widening over a specified period of time, based on historical erosion rates (similar to the erosion hazard zone by Rapp and Abbe, 2003);
- *Avulsion hazard area (AHA)*: the area most likely to be impacted by rapid channel diversion and occupation (similar to the avulsion hazard zone by Rapp and Abbe, 2003);
- *Flagged*: channel banks that have been identified for further geotechnical inspection due to signs of recent migration, proximity to landslides, or other sources of uncertainty;
- *Modern valley bottom (MVB)*: the relatively flat area adjacent to the stream, including the current, and potentially historical, floodplains, bounded by steeper valley walls that resist erosion (Rapp and Abbe, 2003; Kline and others, 2007);
- *Lidar-derived digital elevation model (DEM)*: highly accurate and detailed, ~3 ft (~1 m) topographic datasets collected using a laser scanner that can display the ground surface elevations relative to NAVD88 without structures or vegetation;
- *Relative elevation model (REM)*: a visualization used to identify floodplain features with raster values that represent height above water surface; created from a DEM that has been normalized to the elevation of the water surface (Olson and others, 2014);
- *River segment (RS)*: a continuous portion of river that displays relatively similar hydrologic and geomorphic characteristics (similar to channel reach in Rapp and Abbe, 2003); in this study, typically ~4,000-12,000 ft (~1,200-3,700 m) in length;
- *Stream stations (SS)*: evenly spaced points along the river centerline;
- *Confinement*: a characteristic of rivers that indicates if their ability to laterally migrate is limited due to bed and bank materials that resist erosion. Channels that flow within narrow valleys are said to be confined and those that migrate freely through erodible sediment in open valleys are described as unconfined (Montgomery and Buffington, 1997).
- *Incision*: the process of streambed degradation that occurs when the erosive force of a river is greater than the strength of the streambed. In some conceptual models (such as Simon and Hupp's 1987), incision may trigger bank failure, leading to channel widening, the formation of an inset floodplain, and sediment deposition (i.e., aggradation).
- *Single-thread and multi-thread:* a description of river form, which is composed of either a single or multiple channels (the latter includes anabranching and braided streams);
- *Anabranching streams*: a stable, multi-thread channel form with relatively large, often vegetated islands between channels (Knighton, 1998);
- *Braided streams:* an unstable, multi-thread channel form with temporary sediment bars and islands separating the channels (Knighton, 1998);
- *Sinuosity*: a description of river curvature relative to a straight path. Channel sinuosity is measured by dividing the channel length by the valley length; the lower the index value the straighter the channel. For the purposes of this study, very low sinuosity (straight) channels have an index of <1.05; low to moderate sinuosity channels are 1.06-1.3; highly sinuous channels are 1.31-1.8; and very highly sinuous channels are >1.8 (Figure 10.8, Fryirs and Brierley, 2013).

The units that compose the CMZ are the AC, HMA, EHA high hazard (30-year median rate), EHA medium hazard (30-year maximum rate), EHA low hazard (100-year maximum rate), AHA, and flagged. These units are produced using the approaches described in the following section. **Figure 2-1** is an example of an image that can be used to visualize how the channel units are combined. We mapped the high, medium, and low hazard EHA to show potential movement within 30 and 100 years at different levels of confidence. The high hazard area represents the locations directly adjacent to the AC that are most likely to be imminently impacted by channel migration, and the medium and low hazard areas represent the locations beyond the HMA that represent the furthest extent of channel migration within the next 30 and 100 years. A more detailed explanation of each of the components is provided in **Section 2.3**.

Figure 2-1. Example of the components of a CMZ map, including the active channel, historical migration area, avulsion hazard area, erosion hazard areas, flagged streambanks, and channel migration zone mapped along the Zigzag River, Clackamas County, Oregon.



2.2 Data sources

The method we used to define the CMZ components was primarily based on the interpretation of remotely sensed datasets to accommodate the project budget and the size of the study area. Limited fieldwork along the river was also undertaken to help in the interpretation of the remotely sensed data and to identify processes only visible in-person. To guide the mapping of the CMZ, we utilized or created the datasets listed below.

2.2.1 Topographic data

We used ~3 ft (~1 m) lidar DEMs to delineate modern channel and valley features, to estimate water surface elevations, and to create longitudinal profiles. We used the following lidar datasets in this study: OLC Hood to Coast 2009 and OLC Upper Sandy River 2011.

A REM for the Zigzag River was generated to aid in the identification of floodplain features. A REM shows topography relative to the channel's water surface elevation, such as the floodplain or drainage ditch height above or below the channel. We produced these visualizations by normalizing (i.e., detrending) the lidar DEMs to the river's water surface elevation using GIS tools and following the method detailed in Olson and others (2014, Appendix E). Using this method, we extracted water surface elevations from the DEM along the channel as points, created an interpolated raster surface that represented the water surface over a large area (spanning the valley bottom if possible) and subtracted the original DEM from the water surface raster to produce the final REM. In areas with high channel sinuosity, this process was iterative and required that we digitize additional water surface elevation points beyond the channel.

The lidar DEMs were often visualized as slopeshades in combination with other semitransparent datasets such as the REMs, imagery, or geologic maps.

2.2.2 Aerial imagery

We used the most recently collected (2022) high-resolution 1 ft (0.3 m) Oregon Statewide Imagery Program (OSIP) aerial imagery available at the time of mapping. This dataset was used to digitize the AC, characterize channel form and features, and document current land use, land cover, infrastructure, and presence of large woody debris.

We used historical orthoimagery to delineate the HMA and digitize the historical streambank lines that were used to determine erosion rates. We orthorectified historical images collected during the 1950s-1980s era using ArcGIS. National Agriculture Imagery Program (NAIP) statewide imagery was also available for the 1990s-2020s. In our analysis, we used the following imagery:

- Orthorectified USGS single-frame images: 1956, 1967, 1975, 1984, 1986
- Orthorectified NAIP: 1995, 2000, 2005, 2009, 2011, 2012, 2014, 2016, 2020
- OSIP: 2018, 2022

2.2.3 Geology

We used the best-available surficial geologic data for each of the counties to understand the underlying geology of the streambed, streambanks, valley bottom, and valley walls. This included the USGS's preliminary geologic map of Mount Hood (Sherrod and Scott, 1995), DOGAMI's multi-hazard mapping for the Mount Hood region (Burns and others, 2011), Oregon Geologic Data Compilation (OGDC-7) (Franczyk and others, 2020), and the statewide landslide inventory (SLIDO 4.5) (Franczyk and others, 2024). We also evaluated other published literature, including journal articles, reports, and white papers from state and federal agencies, academia, researchers, and watershed councils, for relevant geologic and geomorphic information.

2.2.4 Infrastructure and anthropogenic modifications

We used infrastructure GIS datasets, accessed through the Oregon Geospatial Enterprise Office and Google Maps in 2023 and 2024, to help identify the location of levees, roads, railroads, dams, and bridges that may impact the channel's migration. We reviewed publications and datasets from the USGS, USACE, Clackamas County, and the USFS and communicated with staff at Clackamas County and the USFS to learn more about changes in the watershed. Publications, like news articles and historical photographs, were also useful for understanding past flood impacts and damages.

2.2.5 Local geomorphic and channel migration history

There have been several geomorphic studies of the area surrounding the Zigzag River watershed. Studies by Abbe and others (2015), English and others (2013), Sherrod and Scott (1995), and Burns and others (2011) provide important insights about the Sandy River watershed and the Mount Hood region's geology and history. English (2013) and a USFS watershed analysis (1995) give information respectively about the Zigzag River's response to the 2011 floods in the lower reaches and a preliminary description of geomorphic conditions; however, none of these studies provide a detailed accounting of sediment supply, bed and bank materials, or rates of channel movement.

2.2.6 Flood history

Our understanding of flood history was informed by several major studies, summaries on websites, and news articles. This included the FEMA Flood Insurance Studies (2019), Natural Hazard Mitigation Plans for Clackamas County (University of Oregon, 2024), USGS streamgage data (2024A, 2024B), a watershed analysis from the USFS (1995), and documentation from USACE websites (2024). Additionally, a series of articles and photographs from the Oregonian newspaper provided useful context (e.g., Tomlison, 2011).

We also used the National Hydrography Dataset to initially locate features such as stream centerlines, lakes, and ponds. Because this dataset had a low resolution, it was only used to create broad visualizations, and we instead relied on lidar to delineate more precise feature boundaries.

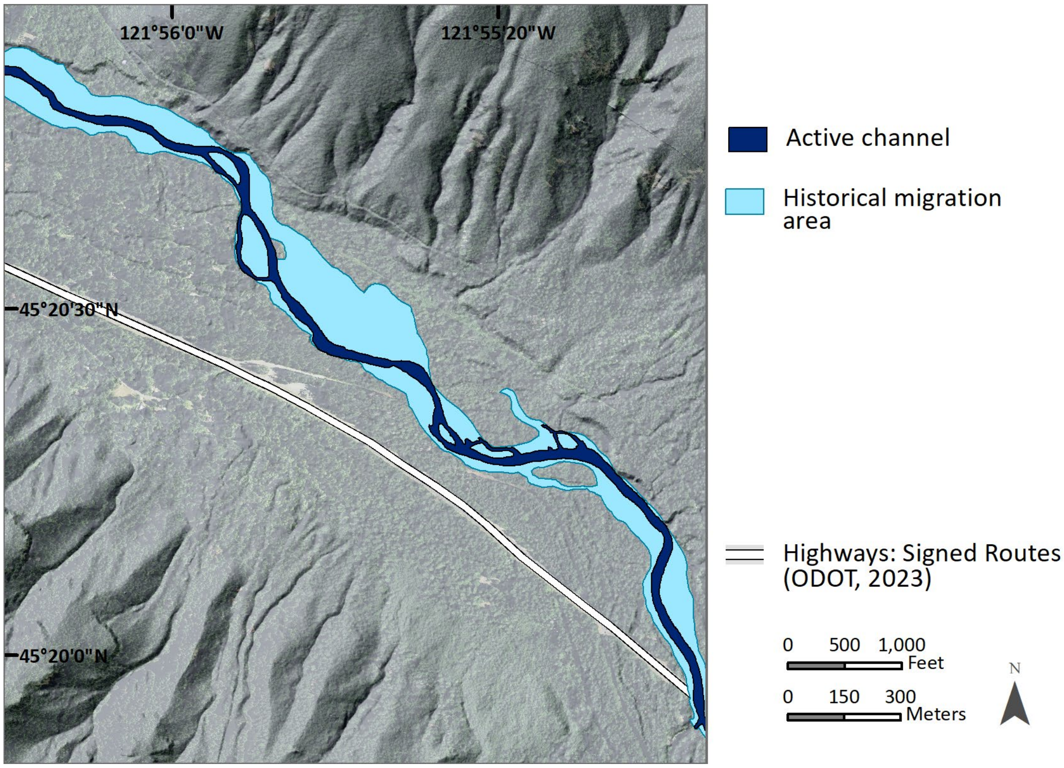
2.3 Channel Migration Zone (CMZ) Mapping

Using the previously described datasets, contextual information, and basemaps, we delineated the AC, HMA, and MVB, and divided the study area into RSs. We mapped the EHAs, AHAs, and flagged banks and created the final CMZ boundary. The process we used to produce these, and several intermediary datasets, is documented in the following eight subsections. We produced the CMZ map components using Esri® ArcGIS software version 10.7. Unless otherwise stated, all new map components were digitized at a scale of 1:4,000, or finer resolution.

2.3.1 Active channel (AC)

The AC is composed of the river's wetted perimeter and the exposed, unvegetated sediment deposits that are adjacent to the river. As shown in **Figure 2-2**, it is limited to the areas that are likely to have conveyed flows in the previous one to two years and where woody vegetation is unable to be maintained (Montgomery and MacDonald, 2002).

Figure 2-2. Example of the 2022 AC and 1952-2020 HMA mapped along the Zigzag River, Clackamas County, Oregon.



We delineated the AC polygon boundary based on the most recent available aerial photography at the time of mapping (i.e., the 2022 OSIP imagery). We also used the lidar slope map and REM as a reference to identify banks and boundaries obscured in the imagery by vegetation. In areas where the channel has migrated in the time since the lidar collection, our digitization aligns to match the most recent aerial imagery.

After mapping the AC boundary, we digitized a stream centerline and stream station points every 100 ft (30.5 m) along the middle line of the AC, parallel to the AC bank edges. These intermediary datasets were used to characterize RS length and sinuosity and produce longitudinal profiles. We also measured average AC width by generating cross-sectional transects that were clipped to the AC boundary.

2.3.2 Historical migration area (HMA)

The HMA is composed of the combined areas occupied by current and past channels visible in historical aerial imagery. These areas are most commonly adjacent to the AC, formed by fluvial processes, and could experience future migration. **Figure 2-2** provides an example of the HMA surrounding the AC.

We mapped the HMA for the Zigzag River using historical aerial photographs at a scale of 1:4,000, or finer resolution. As discussed in **Section 2.2**, these included orthorectified aerial photographs from 1956 to the present day. The lidar DEMs and REMs were also used to verify the location of the historic channel in areas where imagery was difficult to accurately interpret due to dense vegetation obscuring the banks or because of errors produced during orthorectification.

2.3.3 Modern valley bottom (MVB)

The MVB is composed of the relatively flat area adjacent to the stream, including the current, and potentially historical, floodplain. It is bounded by steeper valley walls and is typically composed of erodible, Quaternary alluvial sediments.

We mapped the MVB polygon boundaries for the river using the lidar DEM, REM, and surficial geologic maps. The valley margin was identified by an abrupt change in slope; this margin is often readily apparent in small-scale maps as the valley bottom commonly has <2% slope when measured across wide areas and the valley wall commonly has >5% slope. Bedrock and older pre-Holocene terraces that did not show signs of recent fluvial erosion were considered to be outside of the MVB. The MVB is used to constrain the EHA. Additionally, we mapped the MVB centerline as an intermediary dataset by digitizing a line that runs along the valley, parallel to the valley walls, following the method of Kline and others (2007).

2.3.4 River segments (RS)

Each stream is divided into RSs that display relatively similar hydrologic and geomorphic characteristics. These valley-scale segments are typically ~4,000-12,000 ft (~1,200-3,700 m) in length, which is longer than 'geomorphic reaches' that are commonly used in site-specific studies with much smaller scopes.

We divided the streams in this study into different segments characterized by changes in channel slope, valley width, channel confinement, channel pattern, discharge (i.e., at confluences with large tributaries), infrastructure, geology, land use, and HMA width. This list of characteristics is similar to the method used in Olson and others (2014). These segments are used to organize the CMZ components and as a part of the EHA mapping process.

Once the RSs were established, we produced several intermediary datasets that characterized the river geomorphology, including the segment length, average channel width within each segment, and the segment sinuosity (channel length/valley length). These characteristics are summarized in the spreadsheets that accompany this report.

2.3.5 Erosion hazard area (EHA)

The EHA identifies the area most likely to be impacted by lateral erosion, where the channel is most likely to move to over a specified period of time. For this study, the high, medium, and low hazard EHAs were mapped to show potential movement across 30 and 100 years. **Figure 2-3** provides an example of the EHA zones. As explained below, this study follows the same method that was used by Appleby (2024); it expands on the units mapped in Appleby and others (2021) by categorizing the EHA components by hazard level and adding the high hazard component.

Figure 2-3. Example of the high hazard (median erosion rate projected 30 years into the future), medium hazard (maximum erosion rate projected 30 years into future), and low hazard (maximum erosion rate projected 100 years into future) mapped along the Zigzag River, Clackamas County, Oregon.

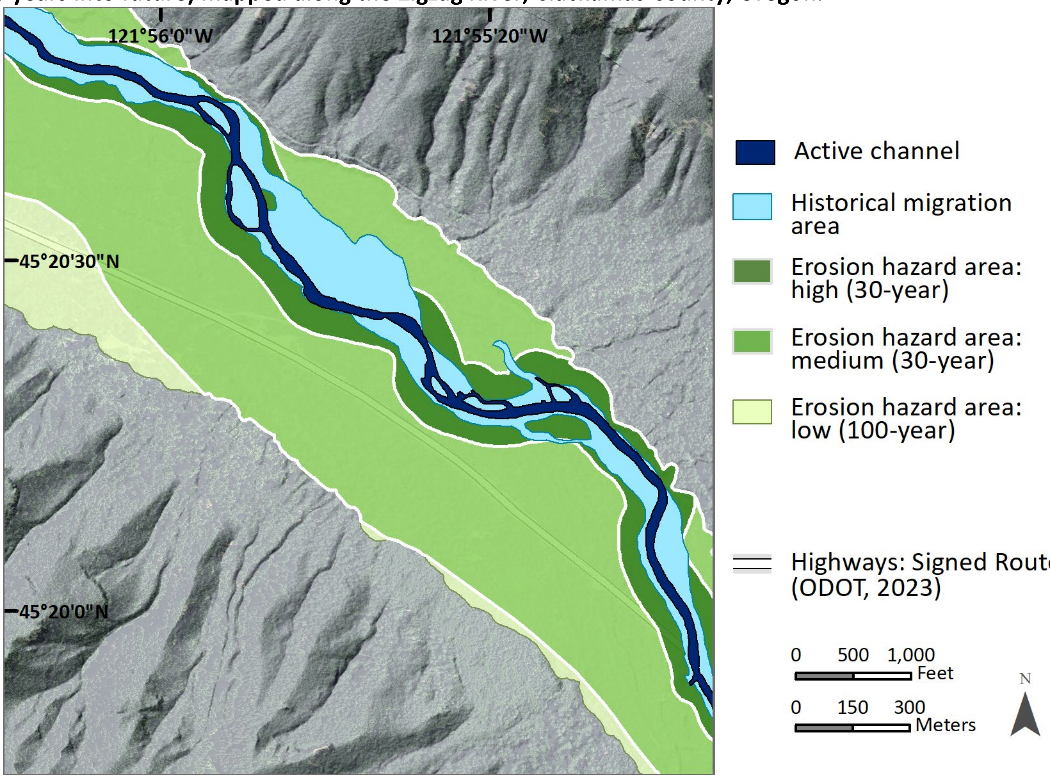
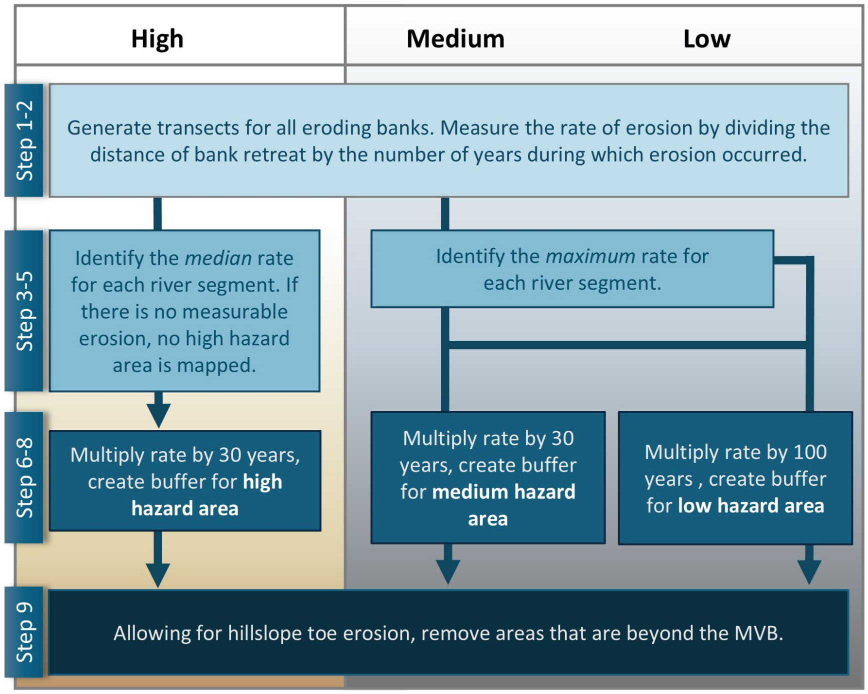


Figure 2-4 presents a summary of the overall process used to map the EHA, including measuring and selecting historical erosion rates, projecting the erosion rates 30 and 100 years into the future, and removing areas from the EHA that extend beyond the MVB or are constrained by other geologic controls (e.g., bedrock). The EHA methodology was designed to include the median and maximum-possible extent of lateral erosion for an RS based on the observed historical erosion patterns.

Figure 2-4. Conceptual model for EHA mapping method, divided into high, medium, and low hazard components.



We mapped the high, medium, and low hazard EHA to show potential movement within 30 and 100 years at different levels of confidence. The high hazard area represents the locations directly adjacent to the AC that are most likely to be imminently impacted by channel migration; the erosion rates for these areas reflect the median rate of erosion within each RS and thus may underestimate the full extent of channel migration within the next 30 years. The medium and low hazard areas are the locations beyond the HMA that represent the farthest extent of potential channel migration within the next 30 and 100 years. These areas are based on the maximum-observed erosion rate for the RS or the adjacent RSs and thus may overestimate channel migration along most banks. In terms of risk to people and infrastructure, the medium and low hazard areas could be considered the worst-case scenario. The timeframes of 30 and 100 years were selected to aid individuals and communities that need to make short- and long-term decisions and plans. In addition, the 30-year timeframe is familiar to most people, as it is a standard length of a mortgage and is often used by FEMA to describe the chance of flooding for a given property.

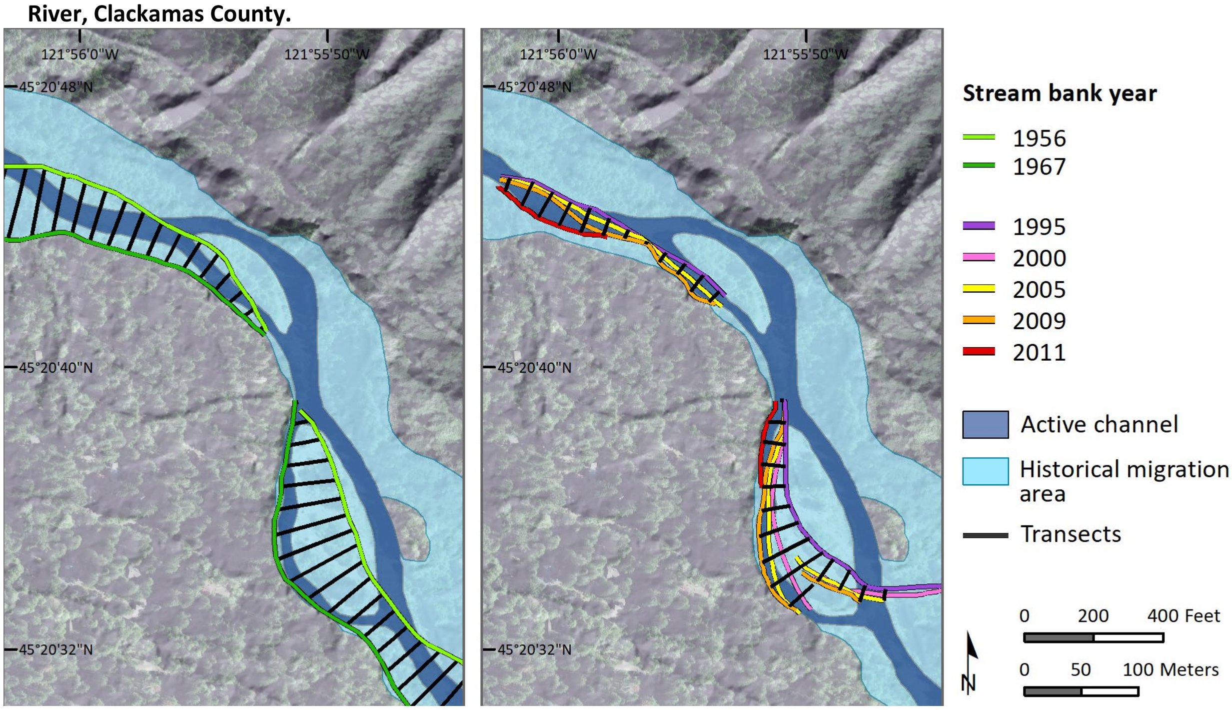
Measuring and selecting the historical erosion rate

1) We converted the HMA polygons into right and left bank lines. As shown in **Figure 2-5**, transects were generated that crossed these successively eroding bank lines every 100 ft (30 m). At minimum, the transects had to include at least 10 years (for this study the timespan was typically 11-16 years) and >10 ft (>3 m) of movement. Transects showing <10 ft (<3 m) of movement were not used because this minor bank movement cannot be differentiated from errors in bank line digitization due to dense vegetation covering some of the banks, shadows, variable water surface elevations, and image orthorectification errors. In a limited number of areas, where the sequential eroding banks had very different curvatures, the transects were divided into several segments to allow for better delineation of bank retreat.

Along the Zigzag River, the stream underwent widespread channel widening after the 1964 flood; this event has been followed by a period of channel narrowing, floodplain reforestation, and more gradual erosion. We measured erosion rates both between 1956 and 1967 and again after 1967 in areas where the floodplain stabilized and was reforested. As a result, as shown in **Figure 2-5**, there are many areas in the lower RS where the same bank has two sets of transects. We expedited the production of these transects by using the USGS's ArcGIS tool Digital Shoreline Analysis System v.5, but the same effect can also be achieved solely using Esri's ArcGIS.

2) We measured the bank erosion rates along these transects and identified the median and maximum erosion rate (ft/yr (m/yr)) within each RS.

Figure 2-5. Example of left streambank lines from 1956-1967 and 1995-2011 and transects along the Zigzag River, Clackamas County.



Selecting erosion rates

3) The median erosion rates were selected to represent the high hazard for each RS. The median value was selected to represent the central tendency of the rates, because there are often outlier maximum values that skew the mean value.
4) The maximum erosion rates were selected to represent the medium and low hazard areas. The erosion rates are provided in the accompanying Excel spreadsheets.

Projecting erosion rate

5) To create the high hazard EHA, we multiplied the median erosion rate (ft/yr (m/yr)) for each RS by 30 years. The AC was buffered by this value to identify the areas most likely to be impacted by erosion in the near future.
6) To create the medium and low hazard EHAs, we multiplied the selected maximum erosion rate (ft/yr (m/yr)) for each RS by 30 and 100 years. The HMA was buffered by this value to identify the widest area potentially at risk from erosion.

7) We examined the EHAs and removed erroneous buffer artifacts, such as small gaps and sharp cusps. We also smoothed the transition between RSs in areas where there were differences in buffer widths.

Removing areas beyond the MVB

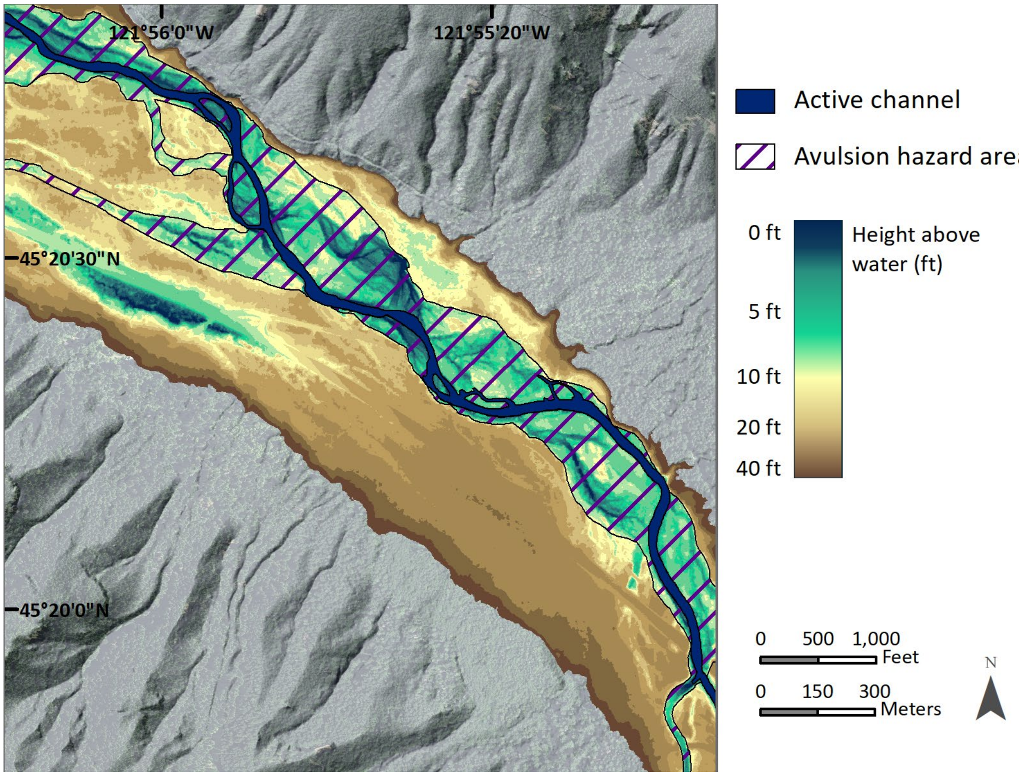
8) Based on the assumption that the stream will erode into the areas outside of the MVB that are constrained by the local geology very gradually, we removed much of the area outside of the MVB from the high, medium, and low hazard EHA. We included a small geotechnical setback area that extended one-half of the AC width outside of the MVB as a part of the EHAs to account for a small amount of valley wall erosion. This was used as a simpler alternative to the "geotechnical setback" used by Olson and others (2014).

2.3.6 Avulsion hazard area (AHA)

The AHA includes the land adjacent to the AC and HMA that the channel has the potential to occupy or reoccupy. Avulsions occur when the channel is abruptly diverted from its main course and flow is redirected along a different path. Avulsions may take place at a very local, reach scale, or at a large, valley scale, depending on the conditions of the channel and valley, and are typically caused by aggradation of the sediment, which triggers the stream to find a more efficient, steeper gradient path within the floodplain (Slingerland and Smith, 2004).

To map the AHA, we used the DEMs, REMs, geology, and imagery to digitize the areas within each RS where avulsions may occur. Areas in the AHA have a width equal to or greater than the average channel width for the segment. We focused on low-lying areas on the floodplain that had unconfined channels and potential avulsion paths that had steeper gradients than the existing channel. Secondary and relic channels, swales, meander-neck cut offs, and channels with an absence of dense and woody riparian vegetation along the banks, were all included in the AHA. Areas with manmade ponds or drainage ditches, and streams with channel-spanning logs and large woody debris jams were also examined for potential avulsions. **Figure 2-6** provides an example of the AHA where low-lying areas adjacent to the channel, shown in the REM, are included in this component. We noted the number of avulsions observed from the historical imagery or described in prior studies and included these data in the tables that accompany this publication. Highly localized conditions, such as a migrating head cut or new or growing accumulation of large woody debris, may trigger an avulsion, but these conditions are very difficult to predict. As a result, we were intentionally overinclusive in the areas we mapped within the AHA.

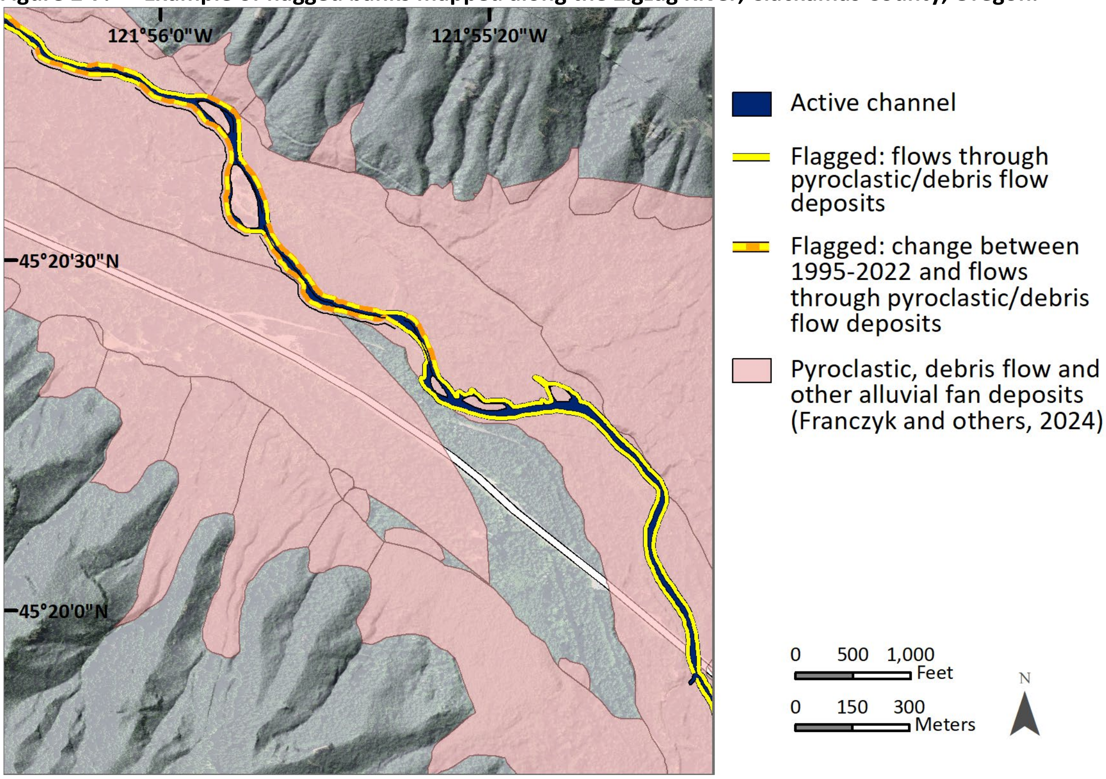
Figure 2-6. Example of the AHA with the REM basemap mapped along the Zigzag River, Clackamas County, Oregon.



2.3.7 Flagged

Flagged streambanks highlight areas with a higher likelihood for bank instability or areas where current conditions create greater uncertainty about future channel migration. **Figure 2-7** provides an example of flagged banks. In this study, we flagged streambanks based on two characteristics: recent lateral migration or banks composed of pyroclastic and debris flow deposits. These conditions may indicate potentially unstable channel conditions, increased sources of sediment supply, or the possibility of future landslides or debris flows to confine or block channel flow, all of which could result in channel migration or avulsion.

Figure 2-7. Example of flagged banks mapped along the Zigzag River, Clackamas County, Oregon.



We flagged streambanks where channel migration and streambank erosion were observed between 1995 and 2022. We used images available from the last 20-30 years to define our "recent" erosion flagged banks because this period of time has relatively similar hydrologic and land use conditions to the present day and includes the impacts of several large flood events in Oregon.

We also flagged AC streambanks that were flowing through pyroclastic and debris flow deposits. In this study area, all of the Zigzag River's AC flows through, or is adjacent to, mapped pyroclastic, debris flow, and other alluvial deposits. As a result, we flagged all banks in this study area. Erosion into these deposits may trigger landslides and hillslope failures, which creates greater uncertainty in future channel migration.

The flagged streambanks were annotated where one or both conditions were met. As the streams will continue to change with time, we recognize the need to monitor, and potentially update, the flagged areas every five years and/or after major disturbances, such as large floods or anthropogenic channel relocation.

2.3.8 Channel migration zone (CMZ)

The CMZ is composed of all areas within the AC, HMA, EHA (high, medium, and low hazard), and AHA. Because the low hazard EHA encompasses all areas within the AC, HMA, and high and medium EHAs, the CMZ was created by merging the low hazard EHA and the AHA.

Potential future changes, such as alterations in hydrology due to climate change, sediment supply, land use, riparian vegetation, and human modifications to the river and watershed, could lead to migration beyond the mapped CMZ. As a result, we recognize the need to monitor and update the CMZ every 30 years and/or after major disturbances like flood events, landslides and debris flows, and channel-changing restoration projects.

3.0 RESULTS

This study mapped CMZs along the lower 7.8 mi (12.5 km) of the Zigzag River (as shown in **Figure 3-1-Figure 3-4**). The Zigzag River is predominantly a single-thread channel with moderate to steep slopes and low to moderate sinuosity. Overall, our results show that the channel experienced widespread change triggered by the 1964 flood and modest changes in the period following the late 1960s. Between 1995 and 2022, the majority of the channel migration occurred in the lower 1.4 mi (2.3 km) of the river.

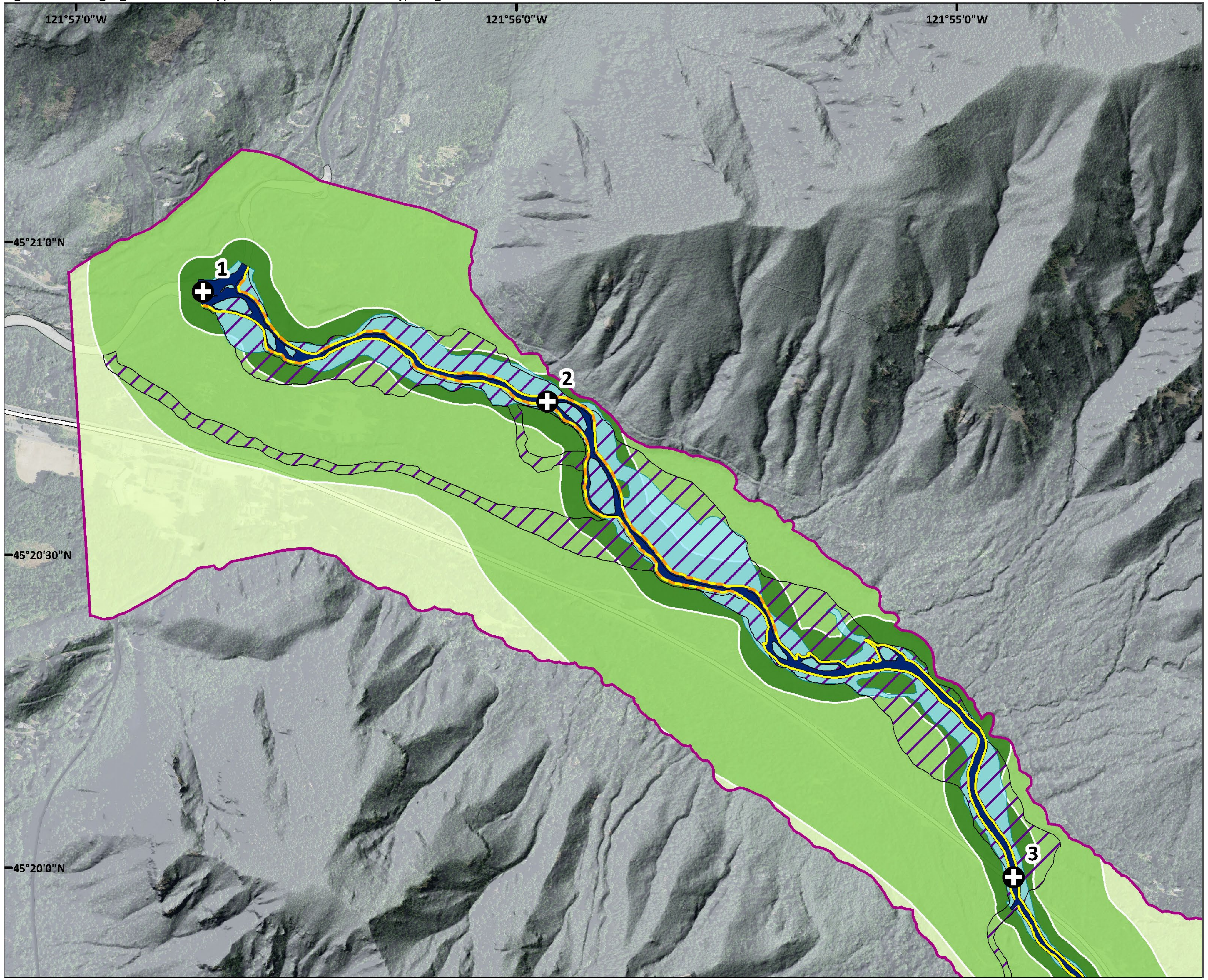
In the accompanying Excel spreadsheets, we provide the stream characteristics, including channel length, average width, water surface slope, and sinuosity for each RS, along with brief descriptions of the channel pattern. We also noted recent migration, the presence of large woody debris, and the channel bank and valley geology. The spreadsheets also include information about the EHA, AHA, and flagged banks for each RS. Here, we briefly present the main study findings. For unfamiliar terminology, please review the definitions provided in **Section 2.1.**

- All five of the RS in this study area display measurable lateral migration between 1956 and 2022. The maximum RS erosion rates recorded were 8.9 to 40.4 ft/yr (2.7 to 12.3 m/yr) with the highest rate recorded in RS 2; all of the maximum rates were recorded in the period between 1956 and 1967, associated with flooding during December 1964 and January 1965.
- Between 1995 and 2022, ~2.1 mi (~3.4 km) of the streambanks eroded laterally. This represents ~13% of the total streambank length in the study area (which has a combined right and left bank length of 15.7 mi (25.3 km)). There has been widespread migration in RS 1 and 2, specifically within the lower 1.4 mi (2.3 km) of the river, and very limited migration observed in RS 3-5 during this period.
- Aerial imagery indicates there have been many avulsions across the study area with at least one taking place in each RS between 1956 and 1967. RS 2 has experienced the greatest number of avulsions over time with two occurring between 1956 and 1967 and three between 1995 and 2011. Compared to other recently studied rivers in Oregon (i.e., McKenzie and Middle Fork Willamette rivers (Appleby, 2024) and Johnson Creek (Appleby and Anthony, 2024)), these data indicate a relatively high frequency and concentration of avulsions.
- When compared to the effective FEMA FIRMs (2019), the 2022 AC extends beyond the floodway boundary in each RS. In many areas, the difference ranges from minor (<10 ft (<3 m)) to moderate (10-30 ft (3-9 m)), but there is at least one, if not more, active streambanks in each RS that are currently >30 ft (>9 m) beyond the mapped floodway. In many of these cases, the AC flows at the very edge of the mapped 100-year floodplain.

  Although FEMA recently revised their floodplain maps for unincorporated areas of Clackamas County, the floodway is a highly regulated zone and FEMA may not have modified the floodway boundary since the original studies in 1983 and 1998 (FEMA, 2019). As a result, the mapped floodway may not reflect current conditions. In some areas where the difference is minor or moderate, this discrepancy is likely due to different interpretations of imagery and the use of pre-lidar data in FEMA models. In other areas, where the difference is moderate or major, the misalignment may be due to a change in the channel location between the original floodway modeling and/or due to errors associated with modeling multi-threaded channel flow using HEC-RAS's older 1-dimensional models.
- In this study area, all of the Zigzag River's AC flows through, or is adjacent to, mapped pyroclastic, debris flow, and other landslide deposits. As a result, we flagged all banks in this study area as

areas with greater uncertainty. As described in **Section 4.0**, the new pyroclastic flows and/or lahar deposits can trigger the channel into a state of disequilibrium and make future channel movement highly unpredictable.

Figure 3-1. Zigzag River CMZ map, RS 1-2, in Clackamas County, Oregon.



Zigzag River, River Segment 1-2

River segment divide, downstream end labeled

Channel migration zone

Active channel

Avulsion hazard area

Historical migration area

Other rivers

Erosion hazard area: high risk (30-year)

Erosion hazard area: medium risk (30-year)

Erosion hazard area: low risk (100-year)

Flagged: flows through pyrocalstic/debris flow deposits

Flagged: change bewteen 1995-2022 and flows through pyroclastic/debris flow deposits

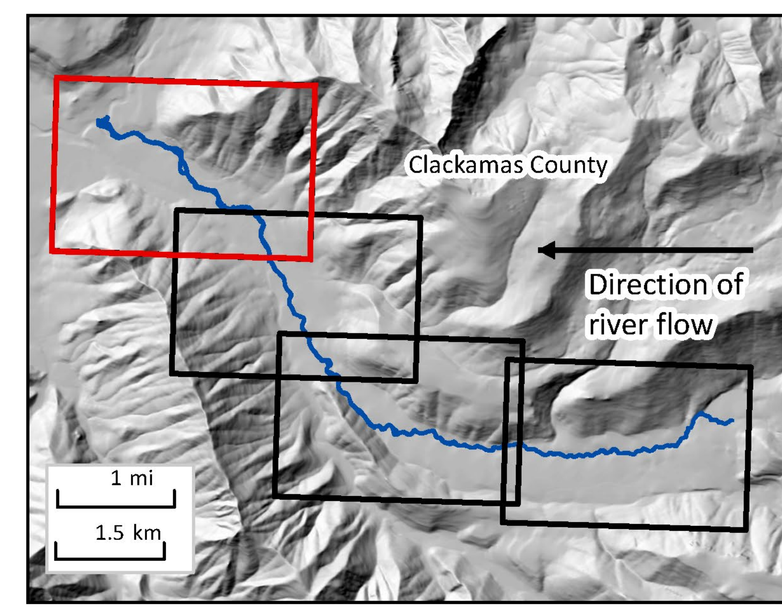
Highways: Signed Routes (ODOT, 2023)

Feet: 0 1,000 2,000

Meters: 0 100 200

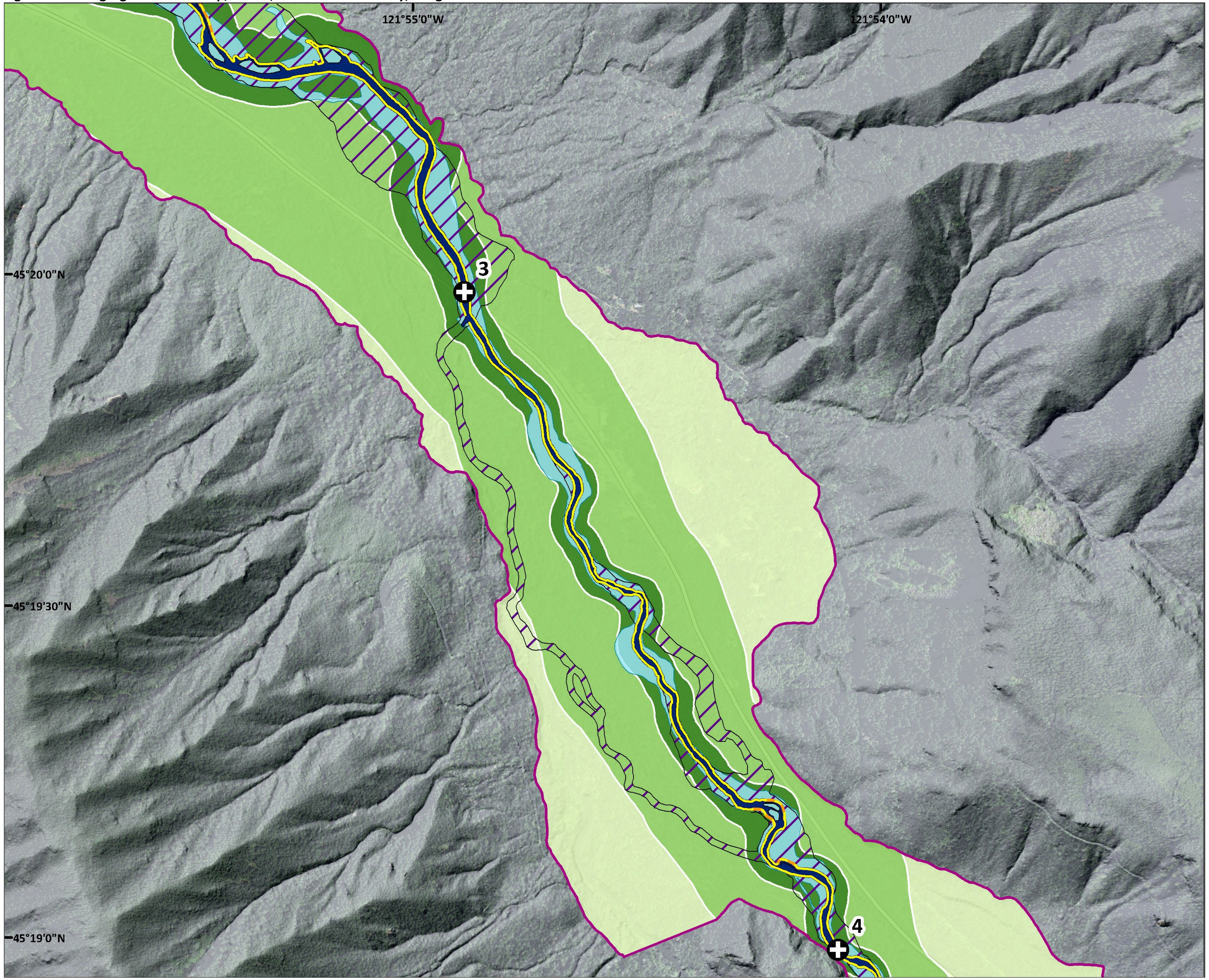
N

Basemap: Lidar hillshade and National Agricultural Imagery Program 2020



Location map of Zigzag River in Clackams County with current extent of map highlighted in red.

Figure 3-2. **Zigzag River CMZ map, RS 2-3, in Clackamas County, Oregon.**

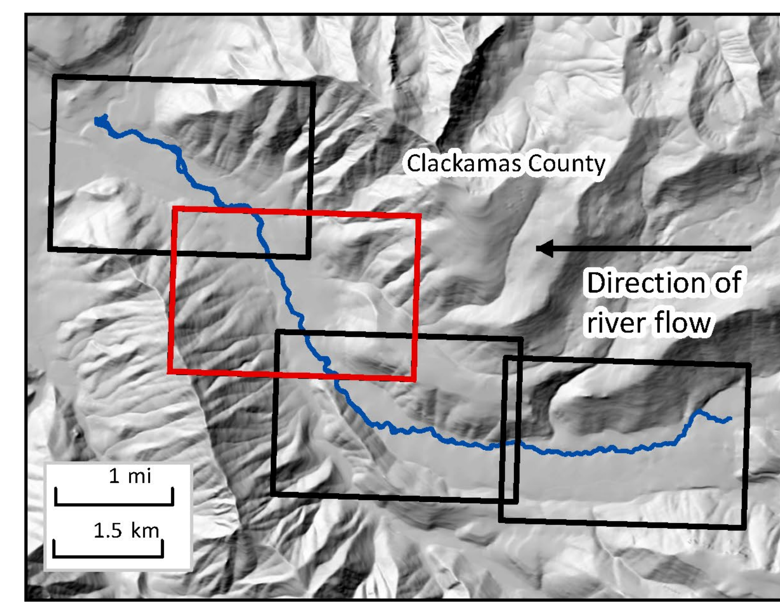


Zigzag River, River Segment 2-3

- River segment divide, downstream end labeled
- Channel migration zone
- Active channel
- Avulsion hazard area
- Historical migration area
- Other rivers
- Erosion hazard area: high risk (30-year)
- Erosion hazard area: medium risk (30-year)
- Erosion hazard area: low risk (100-year)
- Flagged: flows through pyrocalstic/debris flow deposits
- Flagged: change bewteen 1995-2022 and flows through pyroclastic/debris flow deposits
- Highways: Signed Routes (ODOT, 2023)

0 1,000 2,000 Feet
0 100 200 Meters
N

Basemap: Lidar hillshade and National Agricultural Imagery Program 2020



Location map of Zigzag River in Clackams County with current extent of map highlighted in red.

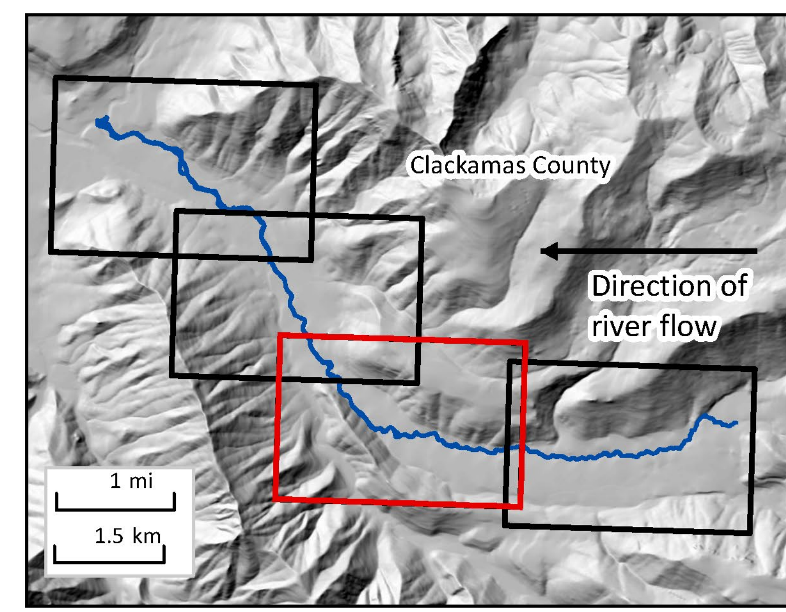
Figure 3-3. **Zigzag River CMZ map, RS 3-4, in Clackamas County, Oregon.**

Zigzag River, River Segment 3-4

- River segment divide, downstream end labeled
- Channel migration zone
- Active channel
- Avulsion hazard area
- Historical migration area
- Other rivers
- Erosion hazard area: high risk (30-year)
- Erosion hazard area: medium risk (30-year)
- Erosion hazard area: low risk (100-year)
- Flagged: flows through pyrocalstic/debris flow deposits
- Flagged: change bewteen 1995-2022 and flows through pyroclastic/debris flow deposits
- Highways: Signed Routes (ODOT, 2023)

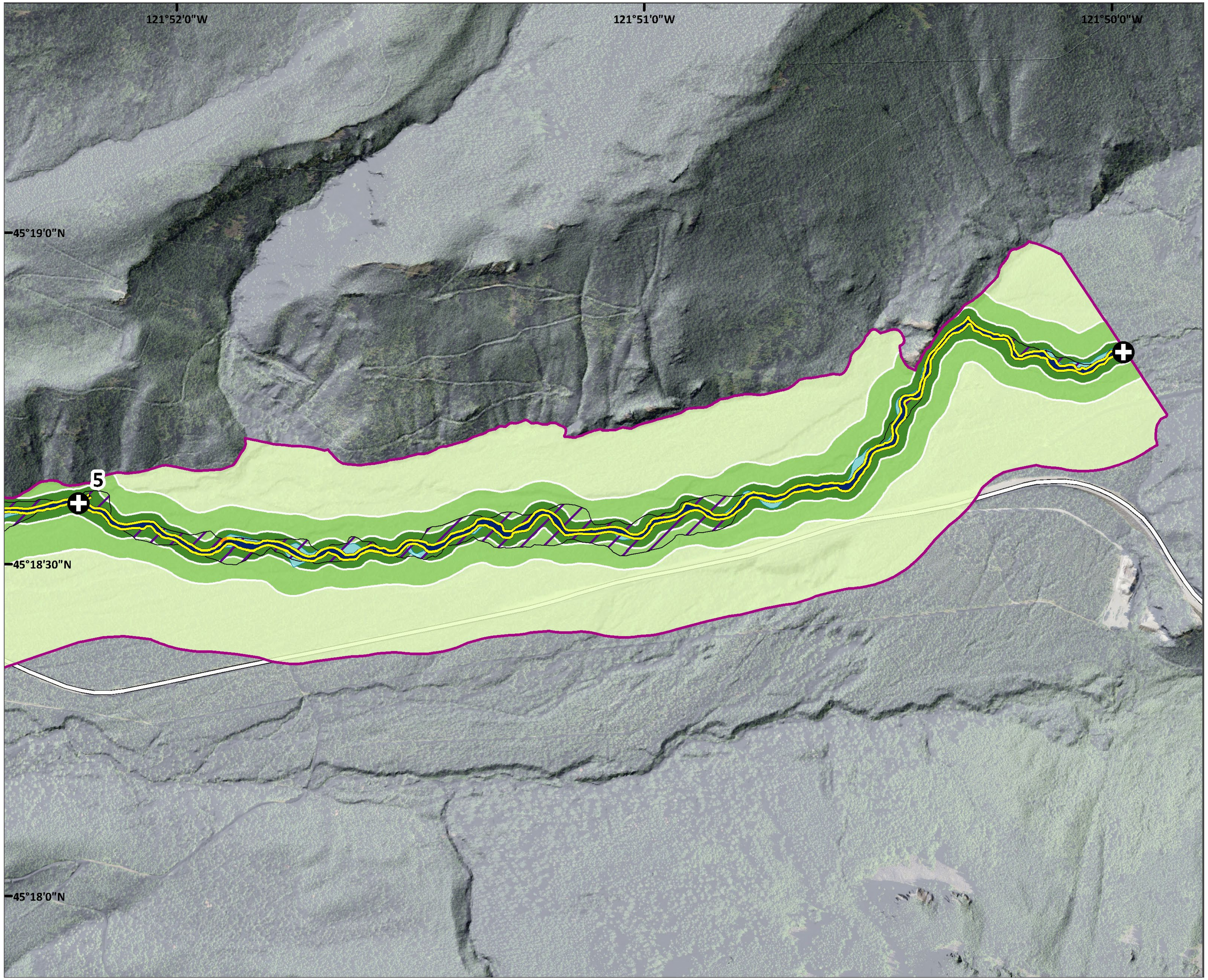
Feet: 0, 1,000, 2,000
Meters: 0, 100, 200
N

Basemap: Lidar hillshade and National Agricultural Imagery Program 2020



Location map of Zigzag River in Clackams County with current extent of map highlighted in red.

Figure 3-4. Zigzag River CMZ map, RS 5, in Clackamas County, Oregon.

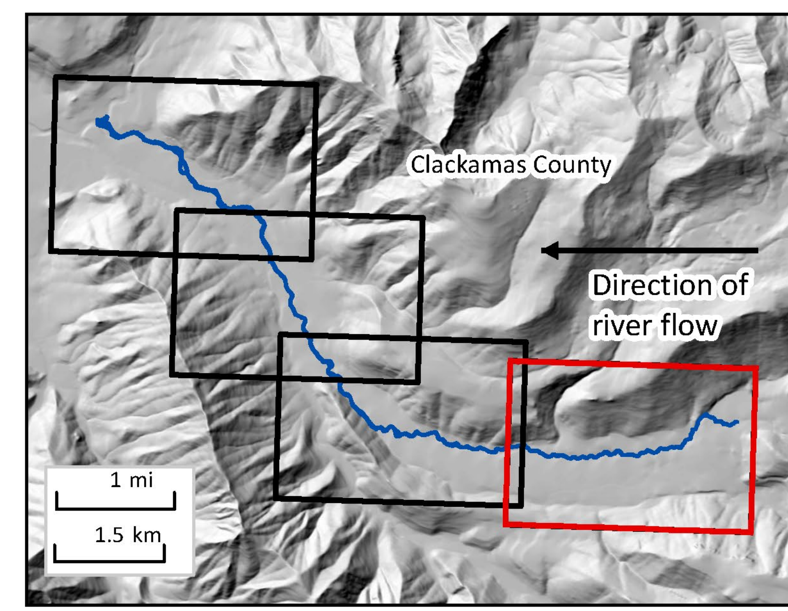


Zigzag River, River Segment 5

- River segment divide, downstream end labeled
- Channel migration zone
- Active channel
- Avulsion hazard area
- Historical migration area
- Other rivers
- Erosion hazard area: high risk (30-year)
- Erosion hazard area: medium risk (30-year)
- Erosion hazard area: low risk (100-year)
- Flagged: flows through pyrocalstic/debris flow deposits
- Flagged: change bewteen 1995-2022 and flows through pyroclastic/debris flow deposits
- Highways: Signed Routes (ODOT, 2023)

Feet: 0, 1,000, 2,000
Meters: 0, 100, 200
N

Basemap: Lidar hillshade and National Agricultural Imagery Program 2020



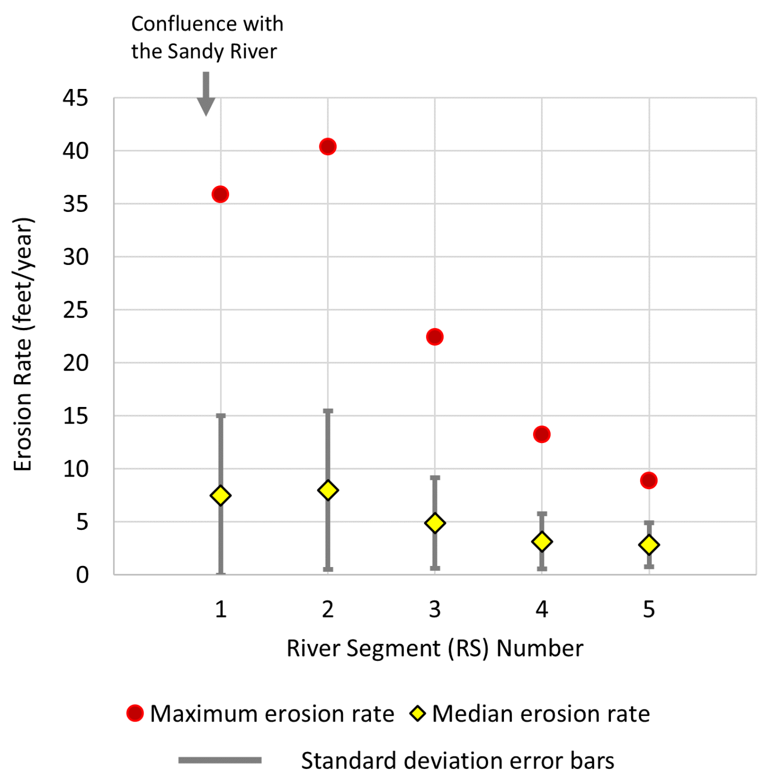
Location map of Zigzag River in Clackams County with current extent of map highlighted in red.

4.0 DISCUSSION AND RECOMMENDATIONS

The CMZ maps produced for this study identify the areas within which the Zigzag River is most likely to move laterally and change its course within the next 30 and 100 years. The maps demonstrate that all of the segments in the study area experienced some degree of lateral migration during the last 66 years and remain vulnerable to future channel migration.

Although channel migration can occur gradually, the largest recent channel change along the Zigzag River was rapid and the result of major flooding. The catastrophic flood in December of 1964 caused the Zigzag River to undergo widespread, accelerated change including heavy erosion to the banks and floodplain which widened the channel by hundreds of feet. This change represents the fastest channel migration between 1956 and 2022; the resulting erosion rates are shown as the outlier, maximum erosion rates in **Figure 4-1**. In addition, at least seven avulsions were documented in the study area during this period, a relatively high frequency in a small study area, when compared to other rivers with CMZ maps in Oregon. This event was followed by a period of channel narrowing, floodplain reforestation and stabilization, and more gradual erosion. The rates shown in **Figure 4-1** within gray standard deviation bars are more typical of the post-1960s erosion responses.

Figure 4-1. The maximum (red circles) and median (yellow diamonds) erosion rates for each RS along the Zigzag River, Clackamas County. The gray bars show one standard deviation above and below the median rate.



Spatially, the lower RSs have higher erosion rates than the upper RSs, as shown in **Figure 4-1**. RS 1 and RS 2 also have a greater density of active gravel bars, mid-channel islands, and greater floodplain connection than the other three segments, which is described in the Excel table that accompanies this report. RS 2 has experienced more frequent avulsions than the other segments. RS 4 and 5 have much steeper slopes and narrow channels and floodplains and have undergone much less lateral migration; they likely convey flow and sediment more efficiently and do not appear to store sediment as bars or islands.

From a broader geologic perspective, the Mount Hood region brings together multiple hazards and the interactions between these hazards can be complex. While the purpose of this study is to examine the channel migration hazard, the history of volcanism, landslides, and debris flows must also be recognized. During two recent eruptions on Mount Hood (~241 and ~1400-1800 years ago), the Zigzag River valley filled with sediment from pyroclastic flows and lahar debris flows. Since that time, the valley bottom has evolved as the river has reestablished a new channel and floodplain. The valley and river have been altered by repeated debris flows and landslide events. Burns and others (2011) mapped RS 4 and RS 5 in the 10% annual chance (10-year), RSs 3-5 in the 1% annual chance (100-year), and all RSs in the 0.1%–0.2% annual chance (500- to 1,000-year) lahar hazard zones. The next time a volcanic eruption or very large debris flow fills the river or valley with sediment, the Zigzag River may take decades, if not centuries, to reestablish a channel and floodplain. Even a series of smaller events, such as multiple years with large debris flows, can cause significant damage and alter channel migration rates. Channel movement will be highly unpredictable during the ensuing period of disequilibrium, and the maps produced in this study, particularly the high and medium EHA, may no longer be applicable.

As described in **Section 1.3.2**, there have been two studies that mapped channel migration zones directly adjacent to this study area, along the Sandy River. English and others (2013) created the original CMZ maps, and these extended into RS 1 of the lower Zigzag River on Plate 12 of their report. Their method was different from this study, but the resulting CMZ width is fairly similar (slightly wider) than the High EHA zone and narrower than the medium- EHA mapped here. The maps produced by English and others (2013) removed "the portion of the CMZ where human-made structures physically eliminate channel migration," described as the disconnected migration area. Our study did not remove the areas beyond levees, berms, and revetments, because we have observed that channel migration frequently causes damage to roads and bridges despite human-made physical structures. If these structures were not constructed and/or maintained to withstand the erosive force of the river, excluding these areas from the CMZ may create a false sense of safety. The study by Abbe and others (2015) updated English and other's (2013) CMZ maps along the mainstem of the Sandy River to reflect channel migration in 2011 and 2012 but did not update the mapping along the lower Zigzag River.

It is important to understand, monitor, and prepare for potential future channel migration. The following sections outline the application of the CMZ maps, limitations of the methods and datasets used, and opportunities for future work that can deepen our understanding of channel migration hazards.

4.1 Applications of Data and Maps

- **Risk Assessments and Risk Reduction**: The CMZ maps and GIS datasets produced in this study are designed to be used to perform risk assessments, including the identification of buildings, critical facilities, transportation infrastructure, and utility systems that are potentially in harm's way. This information can then be used to estimate the potential financial impact of future channel migration and the number of people who may be at risk from this hazard. Furthermore, these maps can be used to perform exposure analyses to estimate economic losses due to building damage. The results of these risk assessments can then be used to identify specific, targeted mitigation actions that may be implemented to reduce risk and increase community resilience (e.g., establishing CMZ setbacks, restoring riparian vegetation, buyouts for properties at risk, stabilizing banks, etc.).

- **Planning and Decision-Making**: The CMZ maps may be used to inform land use planning, develop building ordinances and codes, and identify, prioritize, and implement needed hazard mitigation actions. They can be used in planning documents such as NHMPs and Comprehensive Plans and can also help stakeholders decide which locations have the greatest need for mitigation actions. By including CMZ maps in the land use and development planning process, communities will also increase their resilience to climate change.
- **Education and Awareness**: CMZ maps are tools for sharing information with local and state emergency managers, planners, elected officials, community leaders, residents, and other stakeholders. They can be used for public awareness campaigns, educational presentations, and other outreach products to demonstrate the extent and severity of these natural hazards. To that end, such products may be used to show the need for insurance.
- **FEMA Flood Insurance Study Updates**: CMZ maps can quickly highlight areas where the modern AC has moved beyond the original area used in the effective FEMA FIRMs. In this study, we have noted RSs in which the 2022 Zigzag River AC flows beyond the FEMA floodway boundary and further comparison can be done as part of a risk assessment with the data produced in this study. The difference in boundaries may be due to channel migration, the use of low spatial accuracy and pre-lidar topographic maps in FEMA flood studies, the challenges of using HEC-RAS 1-dimensional models to capture split-channel flow, or some combination thereof. The differences indicate the FEMA FIRM floodway does not reflect current conditions and may need to be updated.
- **Other**: This work can also be applied for uses beyond immediate hazard mitigation. CMZ maps are especially useful for identifying areas best suited for riparian habitat conservation and potential ecological restoration. Clackamas County may find these data useful for planning new partnerships, prioritizing future restoration opportunities, and performing outreach with landowners.

4.2 Limitations of Data and Maps

- **Changing conditions:** Although it is common practice, using historical patterns to predict future channel migration may be inaccurate if key conditions change. As previously discussed, changes driven by other natural hazards, including volcanic eruptions and landslides, may result in dramatically different topography, sediment supply, and bank erosion rates that differ from those identified from historical images. Climate change, wildfires, human-caused channel modifications, and changes in riparian vegetation, land use, and infrastructure can lead to unprecedented patterns in channel migration. The maps we produced represent predictions based on the last nearly 70 years of history. If key conditions change, these maps will need to be updated.

  Changes as a result of restoration projects represent another source of uncertainty in these CMZ maps. Depending on the site-specific conditions and the goals of the restoration designs, these projects have the potential to reestablish more geomorphically dynamic and unstable bank and bed conditions. It is important to consider what impact these projects may have on nearby people and infrastructure. Our maps may need to be updated to recognize large channel changes. However, these projects also provide a unique opportunity to learn about the modern river dynamics and responses to these interventions. For example, a large restoration project led by the USFS was completed in 2023 that modified the channel approximately 1.5 mi (2.4 km) upstream of the confluence with the Sandy River. At the time this study was completed, the most recent available imagery, used to map the AC, was collected in 2022. As a result, the maps in this study may only partially capture the changes made during this restoration work.

- **Period of historical observation:** To predict future channel changes more accurately, we limited our window of observation to 1950s-2020s conditions that reflect current patterns in precipitation, snowpack, and land use. One of the disadvantages of using a limited, approximately 70-year window of observation is that we may miss long-term trends, the impacts of very infrequent storm events, such as those larger than the 1964 event, and other natural variability of a river's behavior.
- **Image quality:** The orthoimages collected prior to 1995 had varying resolution. For some datasets, this created challenges in identifying key geomorphic features due to shadows and channel-spanning vegetation. As a result, this approach may result in errors in the measured rates of erosion.
- **Method validation:** Our mapping method has not been rigorously validated based on multiple decades of channel migration data. Our aim was to produce maps that are both reasonable, based on current channel conditions and past migration patterns, and that give a range of future conditions, including the maximum extent of possible bank retreat. In this study, we have not quantified our uncertainty in CMZ mapping, but our method requires that we use orthorectified historical images that were georeferenced with a root mean square error of <2 pixels and digitize features at a scale of 1:4,000 or a higher resolution. While the results of the mapping provide reasonable results, further studies are needed to validate this method.
- **Local conditions and site-specific analysis**: This study does not replace the need for site-specific analyses. For any point along a mapped RS, there may be local conditions that change the migration pattern at that location, such as unmapped bedrock outcrops, revetment, or bridge abutments. Without site-specific analysis, detailed hydraulic modeling, and geotechnical knowledge of the existing infrastructure, we cannot assume the infrastructure has been designed and constructed in a way that resists erosion and channel migration stresses. In areas where the CMZ extends beyond bank stabilizing structures, landowners or managers may need to monitor and/or maintain these structures if they wish to continue limiting bank erosion.

4.3 Recommendations and Future Studies

- **Risk assessments**: As discussed in **Section 4.1**, CMZ maps are designed to be used in risk assessments. Risk assessments that utilize the CMZ maps can be used to identify which structures may be at risk from channel migration during the next 30 and 100 years and the potential cost of damages. Recent examples of this type of analysis have been completed for Washington (Williams and Burns, 2022), Marion (Williams and Madin, 2022), Benton (Williams and Calhoun, 2023), and Morrow (Williams and others, 2024) counties.
- **Update CMZ maps**: CMZ maps will become out of date over time and will require periodic updates. We recommend that all elements of the CMZ maps are remapped every 20 to 30 years (when sufficient time has passed to develop new erosion rates) and/or after a significant flood

event. In addition, we recommend that the flagged map components be reviewed every 5 years, or more frequently, to determine if new areas need to be included.

- **Study areas**: We recommend performing additional CMZ mapping across Oregon. In particular, we recommend a multicounty-scale Willamette River mapping effort that leverages ongoing work by the USGS. Such a study would be particularly useful since there are numerous communities in the Willamette Valley that are potentially at risk from channel migration.
- **Advancing the CMZ method**: As discussed in **Section 4.2**, multidecadal validation of our CMZ mapping methods is needed, particularly as it relates to quantifying the uncertainty inherent in the mapping approach. We also would like to compare the CMZ method here to alternative mapping techniques that are being developed elsewhere, such as those utilized in Colorado, which may be more applicable to their steeply sloping rivers, mountainous terrain, and potential for deadly flash flooding.
- **Advancing our understanding of channel migration processes**: There are many unanswered questions about channel migration patterns for rivers in Oregon. Using the data presented here and from future studies, we plan to answer questions such as:
    - Which RSs and what overall proportion of rivers in Oregon experience channel migration over interannual to interdecadal time periods across the state?
    - What are the key characteristics that drive, and can be used to identify, those segments that are highly susceptible to channel migration in the rivers of Oregon? Are these characteristics consistent statewide, regionally, or locally? Characteristics may include, but are not limited to, sediment supply, discharge, slope, riparian vegetation, large woody debris, bed and bank geology, and human modifications to the stream and adjacent land.
    - What impact is climate change having on channel migration and erosion rates in Oregon and how will this impact change in the future?

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