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Sarah Lewis, Interim State Geologist

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FLOOD DEPTH AND CHANNEL MIGRATION ZONE MAPS, BENTON, MARION, MORROW, AND WASHINGTON COUNTIES, OREGON

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WHAT'S IN THIS REPORT?

This report describes the methods and results of flood depth and channel migration zone mapping for Benton, Marion, Morrow, and Washington Counties, Oregon. This information can help communities plan and prepare for natural disasters.

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Depth_10yr; Depth_50yr; Depth_100yr; Depth_500yr

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Washington County CMZ.pdf

EXECUTIVE SUMMARY

This study provides Oregon communities with new information about the natural hazards from floods and channel migration. During 2018 to 2021, the Oregon Department of Geology and Mineral Industries (DOGAMI) produced flood depth maps for rivers in Benton, Marion, and Morrow Counties and based on Federal Emergency Management Agency (FEMA) flood insurance studies. Also developed are channel migration zone maps for major rivers within Benton, Marion, Morrow, and Washington Counties. These maps are the first of their kind published for these study areas.

We produced flood depth maps for the 10-, 50-, 100- and 500-year flood zones using the adopted FIS maps for each individual stream within the study area most current data (as of December 2020). The maps were created by interpolating each flood model's cross section elevation data into a continuous water surface elevation (WSEL) surface, and then subtracting the corresponding lidar-based ground surface digital elevation model (DEM). Although this approach is simple, great care was needed to prepare the data for this process in order to create accurate and detailed representations of the modeled flood depths.

Channel migration zone (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 a total of 464 river miles, across 20 rivers in four counties. The components that comprise these CMZ maps are the active channel, historical migration area, 30-year and 100-year erosion hazard area, avulsion hazard area, and flagged stream banks. The method we used was primarily based on the interpretation of historical aerial photographs, high-resolution lidar topography, geologic and flood inundation maps.

These maps were designed to be used in risk assessments to identify people, places, buildings, and infrastructure most vulnerable to floods and channel migration at a neighborhood-scale. The maps in this study do not replace a site analysis by a land surveyor, geologist, or engineer. The hazard maps and risk assessment results can be used by local and state emergency managers, planners, community leaders, residents, and other stakeholders to make informed decisions about flood hazards including their mitigation, land use, and environmental management. These hazard maps will provide a timely and valuable resource for the county and community planning efforts including when developing Natural Hazard Mitigation Plan (NHMP) updates.

1.0 INTRODUCTION

1.1 Purpose

The purpose of this project is to help communities better understand their risk from riverine floods and channel migration and in order to increase resilience to such hazards across Oregon. This is accomplished by providing accurate, detailed, and best available information about the flood hazard characteristics, including maps depicting the flow depths simulated for different return period floods, as well as the potential for channel migration.

The main objectives of this study are to:

- Produce flood depth maps in Benton, Marion, and Morrow Counties based on existing FEMA Flood Insurance Study (FIS) data.
- Map channel migration zones for major rivers in Benton, Marion, Morrow, and Washington Counties.

These maps can be used to perform detailed risk assessments that demonstrate how many people and which buildings and infrastructure are at risk from flood and channel migration hazards. They are designed to be shared with local and state emergency managers, planners, elected officials, community leaders, residents, and other stakeholders to inform land use planning, develop building ordinances and codes, and identify, prioritize, and implement hazard mitigation actions. The flood depth maps may also be used to help prioritize future flood map updates by highlighting areas where there have been changes in land use and new, high-resolution topographic map are available.

1.2 Hazard Overview

1.2.1 Floods

Floods occur when river or stream flows exceed their normal bank range and the excess water flows over and inundates areas that are typically dry. Most floods result from naturally occurring, intense or prolonged rainfall or rain on snow events and less commonly from naturally occurring dams like ice jams and landslides. River floods can also result from the failure of man-made levees or dams. Regardless of cause, several factors can increase both the severity and frequency of flooding, including frozen or saturated ground, recent wildfires, impervious surfaces due to development, and impedance of stream flow by development on the floodplain (Wright, 2007). The terms stream, river, and creek are used interchangeably in this report and within the flood mitigation and scientific communities.

Common flood events in Oregon include flooding of major rivers in the Cascades, Coast Range, and Willamette Valley due to prolonged intense rainfall, often made worse by saturated ground or rain falling on low elevation snow (Oregon State Interagency Hazard Mitigation Team, 2020). Coastal areas are also subject to ocean flooding from the combined effects of storm-driven wave runup coupled with high tides and storm surge (Allan and Komar 2002). In eastern Oregon, flash floods are common and ice jams can occur.

Floods are considered a hazard when they negatively impact humans and are one of the most common natural hazards. Globally, floods are often deadly and cause damages amounting to billions of dollars annualy (Kousky and Golnaraghi, 2020). Approximately 94 million acres (4%) of the land in the United States is susceptible to flooding (U.S. Army Corps of Engineers, 2009). A recent study suggests that, as of 2018, there are approximately 13 million people living in the 100-year floodplain in the United States as defined by FEMA Flood Insurance Studies (FISs) but potentially up to 41 million Americans living in 100-year floodplains when estimated using new, 2D models (Wing and others, 2018). In the United States, flood losses increase annually due to population growth and increased development in floodplains, as well as from changes in land use, climate, and aging infrastructure (Kousky and Golnaraghi, 2020).

Modern, large scale approaches to flood risk management in the United States began nearly a century ago with the Flood Control Act of 1928, which emphasized building dams to catch floodwaters and levees to protect floodplain development. In recent decades the focus has shifted from flood control to increased public awareness, changes in land use, economic development, mitigation, and insurance (Kousky and Golnaraghi, 2020).

The National Flood Insurance Program (NFIP) managed by the Federal Emergency Management Agency (FEMA) was initiated in 1968 with the passage of the National Flood Insurance Act. The NFIP enables communities to regulate their floodplains and to provide access to flood insurance to homeowners and businesses. FEMA produces Flood Insurance Rate Maps (FIRMs), which are official maps used by communities to adhere to the standards set by the NFIP, and FISs, which are reports that compile the data and models used to create FIRMs for a community. FIRMs are used to guide insurance and regulation in flood-prone areas and must be adopted by a community before they can be used to enforce floodplain standards (FEMA, 2011). The flood zones shown on a FIRM define areas that are expected to flooded in either a 100-year flood (1% chance of occurring in any year) or a 500-year flood (0.2% chance of occurring in any year) for regulatory purposes. Since 2004, FEMA has produced digital FIRMs and provides data used in the mapping in a geographic information system (GIS) format.

In addition to knowing the extent of a flood, it is valuable to know the depth of flood waters within the flood zone. Flood depth is an important tool for assessing flood impacts and for planning mitigation. In this study, we have used the FEMA flood data to produce 10% (10-year), 2% (50-year), 1% (100-year), and 0.2% (500-year) flood depth maps for areas of Benton, Marion, and Morrow Counties where flood modeling data is available.

1.2.2 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.

Channel migration zone (CMZ) mapping seeks to identify the area the channel is most likely to 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. Areas susceptible to future erosion are mapped based on the past rate of erosion observed in historical aerial photographs (Rapp and Abbe, 2003). Potential avulsion areas are also included in CMZ maps and are 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.

- First, CMZs have not been mapped along most Oregon's rivers. Although a statewide screening was produced to help prioritize mapping Roberts and Anthony in 2017, this study did not directly answer primary questions about CMZ such as which rivers regularly experience channel migration.
- Second, conventional flood hazard maps like FEMA's FIRMs only examine hazards posed by standing floodwaters on a static floodplain. During a real-life flood, however, channels commonly migrate, creating the potential for new areas to be impacted by erosion and flooding.
- Third, past damage from channel migration has not been well documented, often being incorporated into general flood damages. We do not know what the true impact of channel migration has been on the people, buildings, roads, and other infrastructure in Oregon.

1.3 Study Areas

The study areas described in this report were determined by the need for new or updated mapping of channel migration and flood hazards. Rivers were selected based on proximity to population centers, transportation corridors, and requests from counties and communities. In addition, we used the statewide channel migration screening established Roberts and Anthony (2017) to identify priority areas for channel migration zone mapping. Only portions of streams that have been studied and modeled for use in FEMA FIRMs were included in this study. These hazard maps will provide a timely and valuable resource for county and community planning efforts, including the Natural Hazard Mitigation Plan (NHMP) updates that are scheduled to occur in each of the counties studied here.

Historic floods

Written historic flood data, gathered from stream gages and highwater marks, have been collected in Oregon for approximately 160 years. These numeric records are the primary basis for the statistical analyses used to forecast future riverine flooding. The more extensive the available flood record , the more accurately future flood risks for that river can be predicted. As previously noted, both large-scale (e.g. climatic) and local changes (e.g. property land use) can create a challenge in making accurate predictions despite an extensive flood record.

Oregon's historic record includes many significant floods that have caused significant loss of life and property damage. Unusually high floods originating from rapid snowmelt, intense rainfall, and overly saturated soils from persistent rainfall have occurred throughout the past 160 years in Benton, Marion, Morrow, and Washington Counties. Locally these floods have been made worse by logs and other debris obstructing bridge openings, including the 1903 flash flood in Morrow County which remains Oregon's most deadly natural disaster with nearly 250 fatalities (DenOuden, 2004). Ice jams have also caused large local floods in eastern Oregon. Notable floods are described for each study area in the following sections.

Flood protection

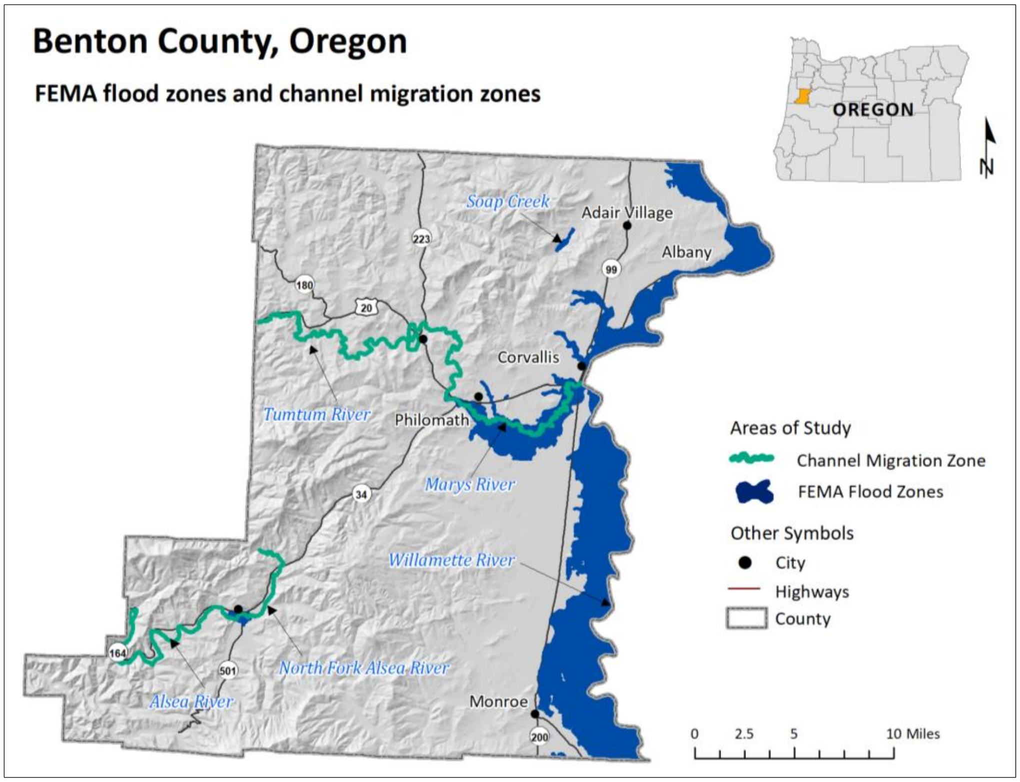
Engineered structures, such as dams, revetments, gabions, walls, culverts, diversion ditches, levees, and retention ponds are typically used to reduce the risk to lives and property by containing or diverting water during a flood. While these measures can be very expensive, they can also be effective ways to control floodwaters.

In Benton, Marion, Morrow, and Washington Counties, common flood protection structures have been used for flood mitigation. Several larger construction projects for flood protection in the study areas were built following major flood events. Notable flood protection construction projects are further described for each study area in the following sections.

1.3.1 Benton County

Benton County, Oregon is located in the northwestern portion of the state in the Willamette Valley, also colloquially known as the I-5 corridor (**Figure 1-1**). It is bordered by Polk County to the north, Lincoln County to the west, Lane County to the south, and Linn County to east. The entire boundary with Linn County is defined by the Willamette River. The total area of Benton County is 676 square miles (1,751 square kilometers).

Figure 1-1. **Benton County study area map.**



The western half of the county is dominated by the rugged, heavily forested Oregon Coast Range and contains the range's highest mountain, Marys Peak, elevation 4,097 feet (1,249 meters). The eastern portion of the county transitions from mountains to gently rolling farmlands and then into the floodplain of the Willamette River.

Areas in the eastern portion of the county are well populated and include most of the county's agricultural lands. The total population of Benton County is approximately 94,700 according to population estimates for July 2020 (Portland State University, 2021). The county's largest city and county seat is Corvallis, with a population of approximately 59,700 (Portland State University, 2021). The majority of residents in Benton County live in moderately developed urban areas surrounded by less dense suburbs and farmlands. The Benton County NHMP Steering Committee stated that the county has a moderate vulnerability to flood hazard, suggested that between 1-10% of the population and assets in the county would be impacted by a major flood event (University of Oregon and others, 2016a). DOGAMI will produce Hazus-based flood loss estimates for Benton County in an upcoming study using the data generated by this report.

Flood depth map study area

We produced flood depth maps for all streams with digital flood insurance rate maps (DFIRMs), which includes a total of 85 stream miles (136.8 kilometers) (**Figure 1-1**). The largest streams in the study area are the Marys River and the Willamette River. We have listed all streams in the study and the communities they affect in **Table 1-1**.

Table 1-1. Studied streams in Benton County for flood depth mapping.

Stream name	Studied stream miles	Affected communities
Dixon Creek	2.8	Corvallis
Dunawi Creek	0.5	Corvallis
East Fork Newton Creek	0.2	Philomath
Frazer Creek	2.3	Corvallis
Jackson Creek	1.6	Corvallis
Marys River	11.6	Corvallis, Philomath
Millrace	1.1	Corvallis
Newton Creek	2.2	Philomath
North Fork Alsea River	1.3	rural
Oak Creek	1.0	Corvallis
Quarry Road East Overflow	0.3	Corvallis
Quarry Road West Overflow	0.5	Corvallis
Soap Creek	1.4	rural
South Fork Dixon Creek	0.4	Corvallis
Stewart Slough	5.8	Corvallis
Thornton Lakes Overflow	4.7	Albany
Willamette River	47.3	Albany, Monroe

Channel migration zone study area

We produced channel migration zone maps for 66 river miles covering the Alsea, North Fork Alsea, Marys, and Tumtum Rivers (**Figure 1-1, Table 1-2**). The Alsea River and the North Fork Alsea River originate in the Coastal Range Mountains in western Benton County. They flow westward into the Alsea Bay and Pacific Ocean near Waldport in Lincoln County. Much of the land surrounding the Alsea River is heavily forested timberlands, with Oregon Route 3 (also known as the Alsea Highway) adjacent to the river for many miles. The unincorporated community of Alsea is also located adjacent to the Alsea River.

The Marys River and its major tributary the Tumtum River originate in the Coast Range Mountains in Lincoln County, flow east into the Willamette Valley, and join the Willamette River in easter Corvallis, Benton County. Within the county, the Tumtum River flows through forested timberlands adjacent to U.S. Route 20. The Marys River flows through forested timberlands, agricultural lands, the cities of Philomath and Corvallis, and several unincorporated communities.

Although the Willamette River has historically experienced channel migration within the county, we excluded this area from our study. The Willamette River extends across many county and city boundaries and studying limited sections based on political boundaries will not be as effective as several larger studies that span multiple counties. The river also has had numerous flood control projects, such as dams and bank protection constructed along the mainstem and major tributaries, further complicating the river's migration history. In addition, we recognize the work the US Geological Survey has been doing to understand the geomorphic dynamics of the mainstem of the Willamette River (e.g., Wallick and others, 2007; Wallick and others, 2013) and will need to leverage these longer-term studies in a future study to most accurately map CMZs in the valley.

Table 1-2. Studied streams in Benton County for channel migration zone mapping.

River name	Drainage area (sq. miles)	Average slope (%)	Average active channel width (feet)	Studied stream length (miles)	Total stream length (miles) from National Hydrography Dataset, U.S. Geological Survey, 2020	50-year annual exceedance probability (2-year flood), StreamStats (Cooper, 2005) (cubic feet per second)
Alsea River	160	0.14	84	15.2	70.0	10,900
Marys River	301	0.21	52	34.9	60.4	10,300
North Fork Alsea River	64	0.48	52	6.4	23.2	4,540
Tumtum River	35	0.13	27	9.7	12.5	1,950

Benton County historic floods

Table 1-3 provides a summary of the historical flood events identified in the 2016 Benton County and additional events listed in 2020 Oregon State NHMP that occurred after the county plan was written. We have also included the ten highest recorded peak annual stream flows recorded on the Willamette River at the Albany gage (U.S. Geological Survey, 2021a).

Table 1-3. Recorded historical flood events in Benton County.

Month and Year	Source
Dec. 1861	Benton County NHMP (University of Oregon and others, 2016a); U.S. Geological Survey (2021a)
Jan. 1881	U.S. Geological Survey (2021a)
Feb. 1890	Benton County NHMP (University of Oregon and others, 2016a); U.S. Geological Survey (2021a)
Jan. 1901	U.S. Geological Survey (2021a)
Jan. 1903	U.S. Geological Survey (2021a)
Feb. 1907	U.S. Geological Survey (2021a)
Nov. 1909	U.S. Geological Survey (2021a)
Jan. 1923	U.S. Geological Survey (2021a)
Dec. 1937	Benton County NHMP (University of Oregon and others, 2016a)
Jan. 1943	U.S. Geological Survey (2021a)
Dec. 1945	U.S. Geological Survey (2021a)
Jan. 1953	Benton County NHMP (University of Oregon and others, 2016a)
Dec. 1964-Jan. 1965	Benton County NHMP (University of Oregon and others, 2016a)
Jan. 1974	Benton County NHMP (University of Oregon and others, 2016a)
Dec. 1978	Benton County NHMP (University of Oregon and others, 2016a)
Feb. 1986	Benton County NHMP (University of Oregon and others, 2016a)
Feb. 1987	Benton County NHMP (University of Oregon and others, 2016a)
Feb. 1996	Benton County NHMP (University of Oregon and others, 2016a)
Nov.–Dec. 1996	Benton County NHMP (University of Oregon and others, 2016a)
Dec. 2005-Jan. 2006	Benton County NHMP (University of Oregon and others, 2016a)
Dec. 2006	Benton County NHMP (University of Oregon and others, 2016a)
Dec. 2007	Benton County NHMP (University of Oregon and others, 2016a)
Jan. 2009	Benton County NHMP (University of Oregon and others, 2016a)
Jan. 2012	Benton County NHMP (University of Oregon and others, 2016a)
Dec. 2014	Oregon NHMP (Oregon State Interagency Hazard Mitigation Team, 2020)
Dec. 2015	Benton County NHMP (University of Oregon and others, 2016a)
Nov. 2016	Oregon NHMP (Oregon State Interagency Hazard Mitigation Team, 2020)
Feb. 2017	Oregon NHMP (Oregon State Interagency Hazard Mitigation Team, 2020)
Oct. 2017	Oregon NHMP (Oregon State Interagency Hazard Mitigation Team, 2020)
Apr. 2019	Oregon NHMP (Oregon State Interagency Hazard Mitigation Team, 2020)

The Willamette River flood of 1861 is considered the largest known historical flood of the Willamette River although no stream gages were established at the time. The U.S. Geological Survey (2021a) estimates that the peak flood discharge on the Willamette River in Albany was approximately 340,000 cubic feet per second (cfs). This flood was the product of intense rainfall over a two-week period and impacted every town along the Willamette River (FEMA, 2016).

The 1964 floods on the Willamette River, Marys River, and Alsea River are considered the most damaging in Benton County history. They are collectively known as the Christmas flood of 1964 because they occurred in late December 1964 through early January 1965. The cause of the flooding was attributed to a combination of frozen ground and a heavy snowfall that was followed by two large storms bringing record breaking rainfall (FEMA, 2016). At its peak flood flow, the Willamette River experienced an 80-year (1.25% probability) flood (FEMA, 2016) with peak flood discharge of 186,000 cfs (U.S. Geological Survey, 2021a) at Albany despite flood control structures regulating the flow. During the same event, the North Fork Alsea River experienced a 90-year (1.1% probability) flood, while Marys River experienced a 35-year flood (2.9% probability) near Philomath (FEMA, 2016).

January of 1974 brought heavy precipitation and rapid snowmelt that flooded several streams in Benton County. The Willamette River's peak flow at the Albany gage was 118,000 cfs (U.S. Geological Survey, 2021a) and was described by FEMA as a 15-year flood (6.7% probability) (2016). The Marys River near Philomath was also described as a 15-year flood (FEMA, 2016).

In February of 1996, intense persistent rain and rapid snowmelt caused flooding all along the Willamette River and Marys River. Many streams within the valley flooded to record levels. The flooding that occurred is considered the biggest flood event in the past 50 years. The Willamette River gage near Albany recorded a 20-year flood (5% probability) at its peak (FEMA, 2016) with a discharge of 125,000 cfs (U.S. Geological Survey, 2021a).

Benton County flood protection

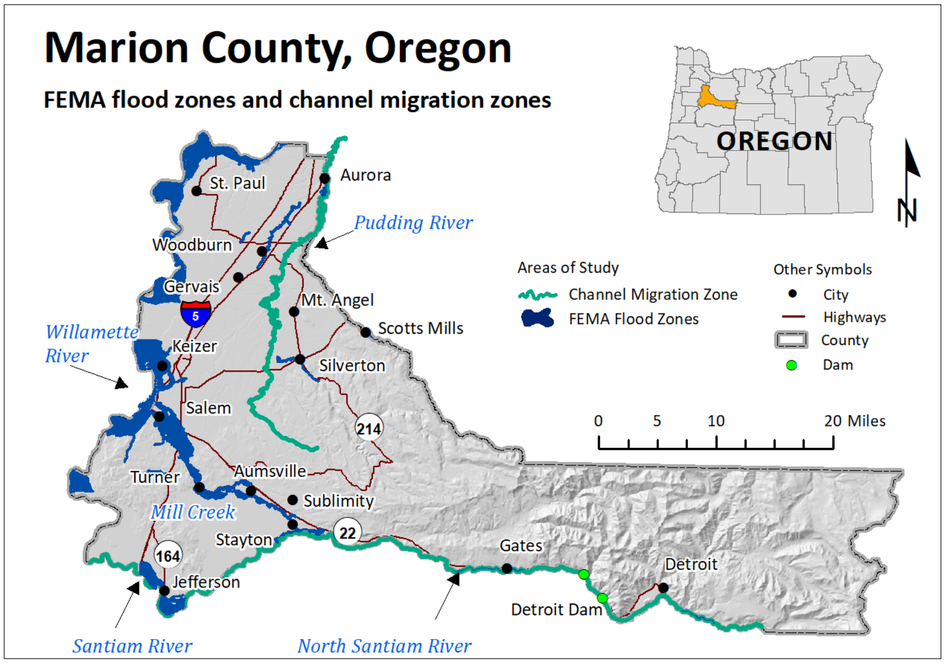
Although large-scale modifications to the Willamette River began in the mid-1800s for transportation and agricultural purposes, most of the major flood control measures and rapid land development took place in the Willamette Valley between 1932-1972 (Wallick and others, 2007). These activities included the construction of dams, revetment and bank stabilization structures, levees, drainage ditches, and urbanization. Every major tributary of the Willamette River had at least one flood control project by 1970, resulting in a total of 13 reservoirs (Wallick and others, 2007). According to the work of Wallick and others (2013), historically large floods (such as those larger than the 1964 flood) have been largely eliminated on the Willamette River since 1970, and the magnitude and frequency of small floods have also been significantly diminished. Work by US Army Corps of Engineers shows that there were seven operational flood management dams regulating flow during the 1964 flood; without the flood control of these dams, it is believed the flood magnitude on the Willamette River would have been similar to the 1861 event (U.S. Army Corps of Engineers, 1969).

In Benton County, these structures primarily impact potential flooding on the Willamette River itself. According to the FEMA (2016) FIS, no flood-control structures have been built for Marys River, Alsea River, or any of the other smaller streams within Benton County.

1.3.2 Marion County

Marion County, Oregon is located in the northwestern portion of the state in the Willamette Valley (**Figure 1-2**). It is bordered by Clackamas County to the north, Wasco County and Jefferson County to the east, Linn County to the south, and Polk County and Yamhill County to the west. The entire boundary with Polk County and Yamhill County is defined by the Willamette River. The total area of Marion County is 1,184 square miles (3,070 square kilometers).

Figure 1-2. **Marion County study area map.**



The geography of the county's eastern panhandle half consists of the heavily forested Cascade Range. Mount Jefferson, a stratovolcano in the Cascade Range, is located at the southeastern tip of Marion County's boundary. The Willamette National Forest makes up a significant portion of the county's eastern half. The western half of the county transitions from the heavily forested mountains to gently rolling farmland and then onto the broad flat bottom of the Willamette Valley.

The western and central portions of the county are well populated and include most of the county's agricultural lands. The total population of Marion County is approximately 349,000 according to population estimates for July 2020 (Portland State University, 2021). The county's largest city is Salem, Oregon's state capital. The city spans both Marion and Polk Counties; the population of Salem within Marion County is approximately 141,400 (Portland State University, 2021). The majority of residents in Marion County live in moderately dense urban areas surrounded by less dense suburbs and farmlands.

The Marion County NHMP Steering Committee stated that the county has a high vulnerability to flood hazard, suggested that > 10% of the population and assets in the county would be impacted by a major flood event (Oregon Partnership for Disaster Resilience, 2011). DOGAMI will produce Hazus-based flood loss estimates for the county in an upcoming study using the data published with this report.

Flood depth map study area

A total of 136 stream miles (218.9 kilometers) were mapped in Marion County (**Figure 1-2**); we included all streams in the county with DFIRM maps. The primary streams mapped are Mill Creek (near Salem), Mill Creek (near Woodburn), and the North Santiam, Pudding, Santiam, and Willamette Rivers. We have listed all the streams in this study and the communities they affect in **Table 1-4**.

Table 1-4. Studied streams in Marion County for flood depth mapping.

Stream name	Studied stream miles	Affected communities
Battle Creek	2.8	Salem
Beaver Creek	3.6	Aumsville
Butte Creek	1.4	Scotts Mills
Claggett Creek	1.3	Salem
Croisan Creek	3.6	Salem
East Fork Pringle Creek	2.8	Salem
Middle Fork Pringle Creek	2.8	Salem
Lake Labish Ditch	1.4	Keizer
Mill Creek (near Salem)	20.5	Aumsville, Salem, Stayton, Sublimity, Turner
Mill Creek (near Woodburn)	7.4	Hubbard, Woodburn
North Santiam River	14.9	Idanha, Detroit, Gates, Mill City, Stayton
Powell Crek	0.4	Salem
Pringle Creek	1.4	Salem
Pudding River	5.9	Aurora
Santiam River	8.4	Jefferson
Senecal Creek	1.3	Woodburn
Shelton Ditch	2.2	Salem
Silver Creek	4.9	Silverton
Turner Bypass	0.8	Turner
West Fork Pringle Creek	1.6	Salem
Willamette River	46.6	Keizer, Salem

Channel migration zone study area

In Marion County, we mapped CMZs along 136 river miles of the Santiam River, North Santiam River, and Pudding River (**Figure 1-2, Table 1-5).** The Santiam and North Santiam Rivers originate in the heavily forested Cascade Range and flow west into the agricultural and urbanized lands of the Willamette Valley, ending in a confluence with the Willamette River. Detroit Dam, Detroit Lake, and the community of Detroit are located on the North Santiam River, approximately 50 miles east of Salem. The North Santiam flows adjacent to Oregon Route 22 and through the communities of Idanha, Niagara, Gates, Mill City, Mehama, and Stayton. The Santiam River flows through the town of Jefferson and passes under Interstate-5.

The Pudding River originates in the Cascade Range and flows west and north until it joins the Mollala River near Canby. It meanders through the community of Aurora and other unincorporated rural lands that are predominantly privately owned forest and agricultural lands. Although the Willamette River has been a historical area of channel migration within Marion County, we excluded this area from our study for the reasons described in **Section 1.3.1**.

Table 1-5. Studied streams in Marion County for channel migration zone mapping.

River name	Drainage area (sq. miles)	Average slope (%)	Average active channel width (feet)	Studied stream length (miles)	Total stream length (miles) from National Hydrography Dataset, U.S. Geological Survey, 2020	50-year annual exceedance probability (2-year flood), StreamStats (Cooper, 2005) (cubic feet per second)
Santiam River	1,800	0.09	384	12.3	17.2	69,200
North Santiam River *(below Detroit Lake)*	734	0.37	273	46.7	65.2	38,500
North Santiam River *(above Detroit Lake)*	221	1.17	136	9.4	49.0	8,630
Pudding River	527	0.21	60	68	90.7	11,300

Marion County historic floods

Table 1-6 provides a summary of the historical flood events identified in the 2011 Marion County and additional events listed in 2020 Oregon State NHMP that occurred after the county plan was written (Oregon State Interagency Hazard Mitigation Team). We have also included the ten highest recorded peak annual stream flows recorded on the Willamette River at the Salem gage (U.S. Geological Survey, 2021b). Marion County lies a short distance downstream from Benton County on the Willamette River and consequently has a similar flood history.

Table 1-6. Recorded historical flood events in Marion County.

Month and year	Source
1861	U.S. Geological Survey (2021b)
1881	U.S. Geological Survey (2021b)
1890	U.S. Geological Survey (2021b)
1901	U.S. Geological Survey (2021b)
1903	U.S. Geological Survey (2021b)
1907	U.S. Geological Survey (2021b)
1909	U.S. Geological Survey (2021b)
1923	U.S. Geological Survey (2021b)
1943	U.S. Geological Survey (2021b)
Dec. 1964-Jan. 1965	Marion County NHMP (Oregon Partnership for Disaster Resilience, 2011); U.S. Geological Survey (2021b)
Jan. 1974	Marion County NHMP (Oregon Partnership for Disaster Resilience, 2011)
Feb. 1986	Marion County NHMP (Oregon Partnership for Disaster Resilience, 2011)
Feb. 1996	Marion County NHMP (Oregon Partnership for Disaster Resilience, 2011)
Nov. 1996	Marion County NHMP (Oregon Partnership for Disaster Resilience, 2011)
Jan. 1997	Marion County NHMP (Oregon Partnership for Disaster Resilience, 2011)
Dec. 2005	Marion County NHMP (Oregon Partnership for Disaster Resilience, 2011)
Jan. 2006	Marion County NHMP (Oregon Partnership for Disaster Resilience, 2011)
Jan. 2012	Oregon NHMP (Oregon State Interagency Hazard Mitigation Team, 2020)
Feb. 2014	Oregon NHMP (Oregon State Interagency Hazard Mitigation Team, 2020)
Feb. 2017	Oregon NHMP (Oregon State Interagency Hazard Mitigation Team, 2020)
Apr. 2017	Oregon NHMP (Oregon State Interagency Hazard Mitigation Team, 2020)

The flood of 1861 had a significant impact on lives and property in Marion County. The Willamette River and many of its tributary streams also experienced major backwater flooding. The persistent and heavy rainfall continued for more than two weeks. Notably, the flood completely destroyed the former town of Champoeg (Oregon Partnership for Disaster Resilience, 2011). The stream peak discharge during this event was estimated to be 500,0000 cfs, approximately twice the discharge of the 1996 peak flood on the Willamette near Salem (U.S. Geological Survey, 2021b). Modern flood control structures in the Willamette River watershed have changed the frequency and magnitudes of floods so greatly that it is unrealistic to describe the probability of the 1861 flood using modern flood frequency statistics.

During the Christmas floods of 1964, flooding occurred along the Willamette River, Mill Creek (near Salem), Santiam River, North Santiam River, Pringle Creek, and other streams. Despite the newly built flood control structures, this flood caused ten deaths, 5 million dollars of damage to state bridges, and 10 million dollars of damage in Marion County (Oregon Partnership for Disaster Resilience, 2011). According to FEMA's (2019) revised FIS, this flood was approximately a 100-year flood on the Willamette River in Salem. However, when we evaluated the flood magnitude only within the context of the recent, regulated flows from 1960-2020, peak flows on the Willamette River at Salem and the Santiam River at Jefferson are considered to be > 200-year floods (U.S. Geological Survey, 2021b; U.S. Geological Survey, 2021c). This flood was also the largest flood recorded on the Pudding River (FEMA, 2019). Salem Memorial Hospital and homes in Salem and Turner were evacuated as a result of the flooding (City of Salem, 2021).

January of 1974 brought heavy precipitation and rapid snowmelt that caused flooding on the Willamette River and Mill Creek (near Salem) and again caused many to evacuate their homes in the City of Turner and the City of Salem. Damages in Marion County were approximately 1.75 million dollars (Oregon Partnership for Disaster Resilience, 2011). When compared to the period of regulated flooding from 1960-2020, the Willamette River peak flood flow at the Salem gage was approximately a 20-year flood (U.S. Geological Survey, 2021b).

The February 1996 flood, caused by persistent rain and rapid snowmelt, affected the Willamette River, Mill Creek (near Salem), and Pudding River. The flood was widespread in the region with record level flooding occurring along many streams (Oregon Partnership for Disaster Resilience, 2011). Most of Salem's residents were indirectly impacted by the flood, which not only damaged businesses and property, but also temporarily cut off transportation routes and access to drinking water (City of Salem, 2021). We calculate that this was approximately a 70-year flood on the Willamette River at Salem using data from 1960-2020 (U.S. Geological Survey, 2021b).

The most recent major Willamette River flooding in Marion County was in 2012 and resulted in a presidential disaster declaration. When compared to the period of regulated flooding from 1960-2020, the Willamette River peak flow at the Salem gage was approximately an 8-year flood and the peak flow on the Santiam River at the Jefferson gage was a 10-year flood. (U.S. Geological Survey, 2021b; U.S. Geological Survey, 2021c). We calculated that this event was approximately a 20-year flood along the Pudding River near Aurora based on the available stream gage data for water years 1929-1965 and 1994-2020 (U.S. Geological Survey, 2021d). In some parts of Marion County, this was the worst flood since the 1996 flood (City of Salem, 2021).

Marion County flood protection

As previously discussed, Willamette Valley flood control projects, including the construction of dams, revetment and bank stabilization structures, levees, and drainage ditches, have significantly changed flooding in the area. By 1970, there was at least one flood control structure protecting every major tributary to the Willamette River, resulting in 13 large reservoirs (Wallick and others, 2007). According to the work of Wallick and others (2013), historically large floods (such as those larger than the 1964 flood) have been largely eliminated on the Willamette River after 1970, and the magnitude and frequency of small floods have also been significantly reduced.

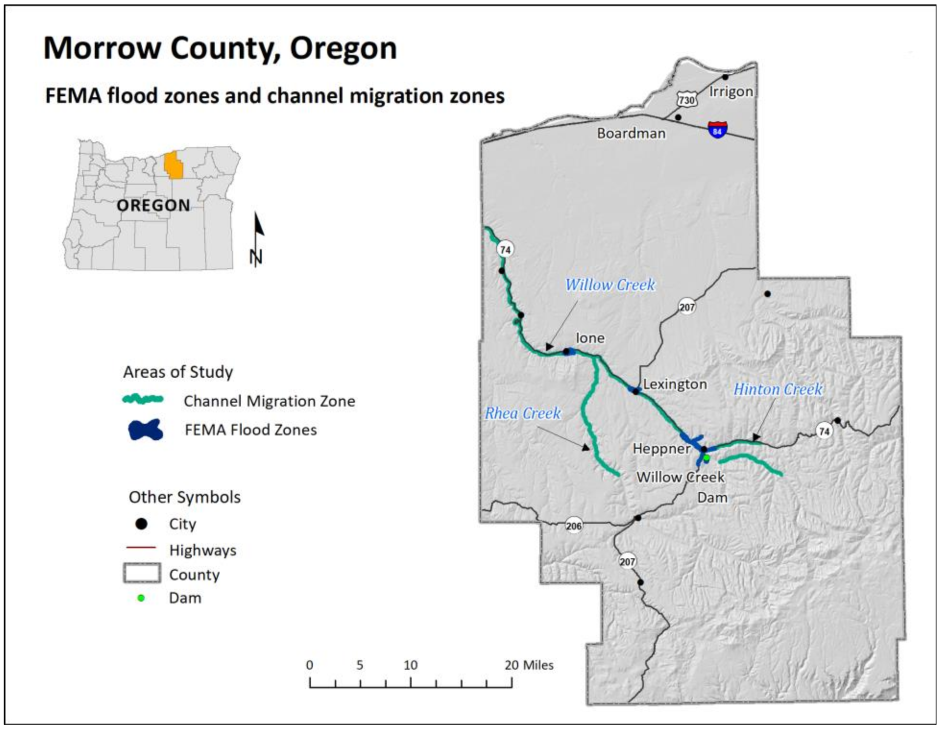
In Marion County, these structures primarily impact flooding on the Willamette River, North Santiam River, and Santiam River. Detroit Dam and Big Cliff Dam were constructed in 1953 to provide flood risk management. These flood control structures, together with the Green Peter Dam and Foster Dam on the South Santiam River, have reduced flooding for many communities in Marion County located along the North Santiam River and the Santiam River. Channel migration patterns are directly impacted by the changes in flood patterns and the reduction in sediment transported downstream due to these structures.

The Sheldon Ditch diversion channel was constructed in 1936, diverting some of the streamflow of Mill Creek into the Willamette River and reducing some flooding in the City of Salem (FEMA, 2019). A diversion ditch was also built for West Fork Pringle Creek and the Middle Fork Pringle Creek in 1988 for portions of Salem. Other bypass channels or culverts were built for many of the tributaries that frequently flood inhabited areas in Marion County (FEMA, 2019).

1.3.3 Morrow County

Morrow County, Oregon is located in the northcentral portion of the state along the Columbia River Gorge. It is bordered by Umatilla County to the east, Grant County to the south, Wheeler County to the southwest, Gilliam County to the west, and the State of Washington to the north. The entire boundary to the north is defined by the Columbia River. The total area of Morrow County is 2,032 square miles (5,263 square kilometers).

Figure 1-3. Morrow County study area map.



Most of Morrow County is in the treeless high plains of the Columbia Plateau. The Plateau rises gently to the south into the forested Blue Mountains and is cut by many steep-walled, flat-bottomed canyons carrying streams. The northern portion of the Plateau has large areas of irrigated agriculture, while the higher southern parts are largely farmed for dryland wheat.

The majority of residents of the county live along the Columbia River and Willow Creek. The total population of Morrow County is estimated to be 12,800 as of July 2020 (Portland State University, 2021). The largest city in the county is Boardman with a population of approximately 4,600 (Portland State University, 2021) and is located near the Columbia River. The county seat is Heppner with a population of approximately 1,300 (Portland State University, 2021) and is in the middle of the county along Willow Creek below Willow Creek Dam. The Morrow County emergency managers have assessed that the county has a high vulnerability to flood hazard, suggested that >10% of the population and assets in the county would be impacted by a major flood event (Morrow County and others, 2016). DOGAMI will produce Hazus-based flood loss estimates for the county in an upcoming study using the data generated by this report.

Flood depth map study area

We produced flood depth maps for all streams with FEMA DFIRMs in Morrow County, resulting in a total of 12 mapped stream miles (19.3 kilometers) (**Figure 1-3**). The primary streams mapped are Willow Creek, Hinton Creek, and Rhea Creek. Prior to the construction of Willow Creek Dam, flooding along Willow Creek had a major impact on the residents of Heppner, Lexington, and Ione. We have listed all the streams in this study and the communities they affect in **Table 1-7**.

Table 1-7. Studied streams in Morrow County for flood depth mapping.

Stream name	Studied stream miles	Affected communities
Balm Fork	0.5	Heppner
Black Horse Canyon	0.6	Lexington
Hinton Creek	1.5	Heppner
Little Blackhorse Canyon	1.2	Heppner
Lorraine Canyon	0.7	Ione
Rietmann Canyon	0.3	Ione
Shobe Creek	1.3	Heppner
Willow Creek	5.9	Heppner, Ione, Lexington

Channel migration zone study area

We mapped CMZs along 78 river miles along Hinton Creek, Rhea Creek, and Willow Creek in Morrow County (**Figure 1-3, Table 1-8**). Hinton Creek and Rhea Creek are tributaries to Willow Creek. All three rivers originate near the north edge of the Blue Mountains and flow north and west across the Columbia Plateau. Downstream of the confluences with Hinton and Rhea Creek, Willow Creek flows into Gilliam County before reaching the confluence with the Columbia River. The streams pass through several communities including Heppner, Lexington, and Ione and commonly flow adjacent to Oregon Route 74. Willow Creek is divided into upper and lower sections by Willow Creek Dam.

Table 1-8. Studied streams in Morrow County for channel migration zone mapping.

River name*	Drainage area (sq. miles)	Average slope (%)	Average active channel width (feet)	Studied stream length (miles)	Total stream length (miles) from National Hydrography Dataset, U.S. Geological Survey, 2020
Willow Creek (below Willow Creek Reservoir)	582	0.63	17	45.6	79.3
Willow Creek (above Willow Creek Reservoir)	68	1.30	28	7.6	29.6
Hinton Creek	43	1.39	12	6.6	25.6
Rhea Creek	228	0.70	16	18.5	62.2

*StreamStats 50-year Annual Exceedance Probability discharge not available

Morrow County historic floods

Table 1-9 provides a summary of the historical flood events identified in the 2007 FEMA FIS and additional events listed in 2020 Oregon State NHMP that occurred during or after FEMA study was completed (Oregon State Interagency Hazard Mitigation Team). We have also included the ten highest recorded peak annual stream flows recorded along Willow Creek at the Heppner gage (U.S. Geological Survey, 2021e).

Table 1-9. Recorded historical flood events in Morrow County.

Month and Year	Source
1885	FEMA FIS (2007)
1888	FEMA FIS (2007)
1891	FEMA FIS (2007)
Jun. 1903	FEMA FIS (2007); U.S. Geological Survey (2021e)
1904	FEMA FIS (2007)
1917	FEMA FIS (2007)
1918	FEMA FIS (2007)
Feb. 1949	U.S. Geological Survey (2021e)
May 1957	U.S. Geological Survey (2021e)
Mar. 1961	FEMA FIS (2007)
Jan. 1965	FEMA FIS (2007); U.S. Geological Survey (2021e)
Jun. 1969	U.S. Geological Survey (2021e)
Jan. 1970	U.S. Geological Survey (2021e)
Jan. 1971	FEMA FIS (2007)
Jan. 1974	U.S. Geological Survey (2021e)
Jan. 1976	U.S. Geological Survey (2021e)
Feb. 1979	FEMA FIS (2007); U.S. Geological Survey (2021e)
May 1983	FEMA FIS (2007)
Feb. 1997	FEMA FIS (2007)
Apr. 2005	Oregon NHMP (Oregon State Interagency Hazard Mitigation Team, 2020)
Mar. 2006	Oregon NHMP (Oregon State Interagency Hazard Mitigation Team, 2020)
May-June 2011	Oregon NHMP (Oregon State Interagency Hazard Mitigation Team, 2020)
Oct. 2018	Oregon NHMP (Oregon State Interagency Hazard Mitigation Team, 2020)
Apr. 2019	U.S. Geological Survey (2021e)

A major flash flood occurred in 1903 on Willow Creek and Balm Creek which nearly destroyed the community of Heppner. The flooding was exacerbated by a debris dam that broke loose and released a surge of water into the community. It is considered one of the deadliest natural disasters in Oregon's history with ~240 fatalities. Damages also occurred in the communities of Ione and Lexington further downstream (FEMA, 2007). The peak stream flow in this event was 36,000 cfs, more than 20 times greater discharge than any other recorded peak stream flow on Willow Creek at Heppner between 1949-2020 (U.S. Geological Survey, 2021e).

A flashflood occurred in Shobe Canyon within the community of Heppner in 1971. Shobe Creek is an intermittent stream that flows through the canyon and connects with Willow Creek in a residential portion of Heppner. The flood caused significant damage including eroded stream banks, deposits of debris (FEMA, 2007), and two washed-out city bridges, and resulted in over $200,000 damage (U.S. Army Corps of Engineers, 1971).

Morrow County flood protection

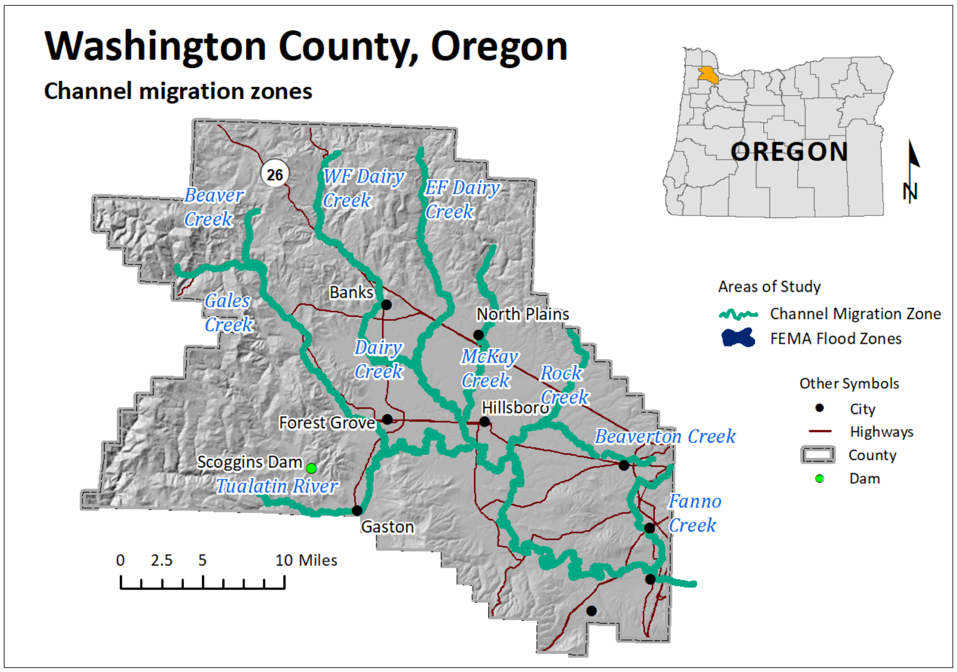
Following the repeated floods from Willow Creek, including the devastating 1903 flood, the Willow Creek Dam was constructed in 1982 by the U.S. Army Corps of Engineers just upstream of the city of Heppner. The dam forms the Willow Creek Reservoir and is the primary flood control structure for many of the residents of Morrow County.

After the 1971 Shobe Canyon flood, the Shobe Creek diversion channel was constructed. The project was sponsored by the Conservation Reserve Program. Since the construction of Willow Creek Dam and Shobe Creek drainage, no damaging floods have occurred in Heppner. (Morrow County and others, 2016).

1.3.4 Washington County

Washington County, Oregon is in the northwestern portion of the state in the Willamette Valley, also colloquially known as the I-5 corridor, and is included in the Portland Metro area (**Figure 1-4**). It is bordered by Columbia County to the north, Tillamook County to the west, Multnomah and Clackamas Counties to the east, and Yamhill County to the south. The total land area of Washington County is approximately 724 square miles (1,875 square kilometers).

Figure 1-4. **Washington County study area map.**



The county centers around the Tualatin Valley, which is bounded by the Tualatin Mountains (Portland Hills) along the north and east side of the county and the Oregon Coast Range along the west and south sides of the county. Much of the northwestern half of the county is heavily forested, rugged terrain and the central and southeastern sections of the county are urbanized or commonly used for agricultural purposes. The highest peak within the county is South Saddle Mountain at 3,464 feet (1,056 meters) above sea level.

With an estimated population of 620,100 in 2020, Washington County is the second most populous in Oregon (Portland State University, 2021). Most of the population in Washington County is located in the central and southeastern portion of the county, adjacent to and including a small portion of the city of Portland. The largest cities by population completely contained within Washington County are Hillsboro, with an estimated population of 104,700, and Beaverton, with an estimated population of 99,000 (Portland State University, 2021). Over 260,000 people are estimated to live in unincorporated areas of Washington County (Portland State University, 2021). The Washington County NHMP Steering Committee stated that the county has a moderate vulnerability to flood hazard, suggested that between 1-10% of the population and assets in the county would be impacted by a major flood event (University of Oregon and others, 2016b).

We did not create flood depth maps for Washington County within this study. Unpublished maps were produced for Washington County in 2019 as part of a separate project and are available from DOGAMI upon request. In an upcoming study, DOGAMI will produce Hazus-based flood loss estimates for Washington County in an upcoming study using the unpublished flood depth data.

Channel migration zone study area

We produced channel migration zone maps for 225 river miles in Washington County (**Figure 1-4, Table 1-7**). This study area includes the mainstem of the Tualatin River, seven tributaries to the Tualatin River (Beaver Creek, Beaverton Creek, Dairy Creek, Fanno Creek, Gales Creek, McKay Creek, and Rock Creek) and two tributaries to Dairy Creek (East Fork Dairy Creek and West Fork Dairy Creek). These streams originate in the forested Tualatin Mountains and Oregon Coastal Range. They collectively flow towards the center of Washington County, eventually joining the Tualatin River which flows east into the Willamette River. These rivers flow through wetlands and forested, agricultural, and urbanized lands including the communities of Gaston, Forest Grove, Hillsboro, Beaverton, Tigard, and Tualatin.

Table 1-10. Studied streams in Washington County for channel migration zone mapping.

River name	Drainage area (sq. miles)	Average slope (%)	Average active channel width (feet)	Studied stream length (miles)	Total stream length (miles) from National Hydrography Dataset, U.S. Geological Survey, 2020	50-year annual exceedance probability (2-year flood), StreamStats (Cooper, 2005) (cubic feet per second)
Beaver Creek	10	0.57	24	7.5	11.4	541
Beaverton Creek	38	0.20	25	11.0	11.4	735
Dairy Creek	230	0.04	50	11.2	15.0	5,890
East Fork Dairy Creek	64	0.64	35	22.2	35.8	2,110
Fanno Creek	32	0.18	28	14	21.1	669
Gales Creek	75	0.67	66	25.9	42.7	3,400
McKay Creek	67	0.33	33	20.8	36.6	1,740
Rock Creek	76	0.16	35	17.1	28.7	1,490
Tualatin River	694	0.05	88	68.6	121.3	16,400
West Fork Dairy Creek	80	0.89	25	26.5	40.0	2,480

Washington County historic floods

Table 1-11 provides a summary of the historical flood events identified in the Washington County NHMP and additional events listed in 2020 Oregon State NHMP that occurred after county plan was written (Oregon State Interagency Hazard Mitigation Team). We have also included the ten highest recorded peak annual stream flows recorded along the Tualatin River at West Linn gage available from 1928-2020 (U.S. Geological Survey, 2021f).

Table 1-11. **Recorded historical flood events in Washington County.**

Month and Year	Source
Dec. 1861	Washington County NHMP (University of Oregon and others, 2016b)
Feb. 1890	Washington County NHMP (University of Oregon and others, 2016b)
Dec. 1933	Washington County NHMP (University of Oregon and others, 2016b); U.S. Geological Survey (2021f)
Jan. 1936	U.S. Geological Survey (2021f)
Dec. 1937	Washington County NHMP (University of Oregon and others, 2016b); U.S. Geological Survey (2021f)
Jan. 1953	Washington County NHMP (University of Oregon and others, 2016b)
Dec. 1955	U.S. Geological Survey (2021f)
Dec. 1964-Jan. 1965	Washington County NHMP (University of Oregon and others, 2016b); U.S. Geological Survey (2021f)
Jan. 1972	Washington County NHMP (University of Oregon and others, 2016b)
Jan. 1974	Washington County NHMP (University of Oregon and others, 2016b); U.S. Geological Survey (2021f)
Dec. 1977	U.S. Geological Survey (2021f)
Dec. 1978	Washington County NHMP (University of Oregon and others, 2016b)
Feb. 1986	Washington County NHMP (University of Oregon and others, 2016b)
Feb. 1987	Washington County NHMP (University of Oregon and others, 2016b)
Feb. 1996	Washington County NHMP (University of Oregon and others, 2016b)
Nov. 1996	Washington County NHMP (University of Oregon and others, 2016b); U.S. Geological Survey (2021f)
Jan. 1997	U.S. Geological Survey (2021f)
Mar. 1999	U.S. Geological Survey (2021f)
Dec. 2005-Jan. 2006	Washington County NHMP (University of Oregon and others, 2016b)
Nov.-Dec. 2006	Washington County NHMP (University of Oregon and others, 2016b)
Dec. 2007	Washington County NHMP (University of Oregon and others, 2016b)
Dec. 2008	Washington County NHMP (University of Oregon and others, 2016b)
Dec. 2012	Washington County NHMP (University of Oregon and others, 2016b)
Dec. 2015	Washington County NHMP (University of Oregon and others, 2016b)
Nov. 2016	Oregon NHMP (Oregon State Interagency Hazard Mitigation Team, 2020)
Feb. 2017	Oregon NHMP (Oregon State Interagency Hazard Mitigation Team, 2020)
Feb. 2019	Oregon NHMP (Oregon State Interagency Hazard Mitigation Team, 2020)

Although the floods in 1861 and 1890 are recognized as some of the largest and most damaging in the Willamette Valley's history, the impact of these floods on the Tualatin watershed is not well documented. There were no stream gages in the Tualatin Valley or estimates made of the magnitude of the flooding.

Since the establishment of a stream gage on the Tualatin River at West Linn in 1928, there have been a series of notable documented floods. In 1933, the Tualatin River experienced a 60-year flood (U.S. Geological Survey, 2021f) that heavily damaged the Tualatin central business district when the river overtopped its banks and entered the Nyberg Slough (FEMA, 2018). In 1974, flooding on the Tualatin River again resulted in damage to the Tualatin business district and a declared disaster. Using data from the U.S. Geological Survey Gage at West Linn, we estimate this flood was slightly larger than a 50-year flood.

In 1996, record-breaking rainfall in Oregon triggered major flooding, including the highest recorded flood levels on the Tualatin River. Based on U.S. Geological Survey gage data at West Linn, this was approximately a 100-year flood event (U.S. Geological Survey, 2021f). Total damages from flooding and landslides cost Washington County nearly $10 million (University of Oregon and others, 2016b).

There were also floods and landslides in Dec. 2007 and Dec. 2015 that caused significant building damage, closed dozens of roads, caused millions of dollars in damage, and led to declared disasters across multiple counties (Oregon State Interagency Hazard Mitigation Team, 2020; University of Oregon and others, 2016b). Although the 2007 flood was the largest flow on the Tualatin River near Dilley since the 1996 flood, this same flood only resulted in a 2-year flood in West Linn (U.S. Geological Survey, 2021f).

Washington County flood protection
Scoggins Dam is a multi-purpose flood control structure built in 1975 by the Bureau of Reclamation. It is the only large flood control project in the Tualatin watershed (FEMA 2018). This dam captures water from the southwestern corner of the Tualatin watershed and collects it in Henry Hagg Lake. Flow is discharged into Scoggins Creek, which is a tributary to the Tualatin River. Some levees exist along the streams in Washington County, but it is unknown if these levees offer protection channel migration or floods. The Bureau of Reclamation has plans for additional flood storage areas that could alleviate flooding from the Tualatin River near the City of Gaston (FEMA, 2019).

1.4 List of Past Studies

Below is a list of previous flood and channel migration related studies in Benton, Marion, Morrow, Washington County. Additional geologic and geomorphic studies relevant to channel migration processes in these counties are listed in the methods section.

Statewide

- Roberts, J. T. and Anthony, L. H. 2017. Statewide subbasin-level channel migration screening for Oregon: Oregon Department of Geology and Mineral Industries Interpretive Map 56, 17 p. https://www.oregongeology.org/pubs/ims/p-ims-056.htm.
- Beechie, T., and Imaki, H., 2014, Predicting natural channel patterns based on landscape and geomorphic controls in the Columbia River basin, USA: Water Resources Research, v. 50, no. 1, p. 39–57. https://agupubs.onlinelibrary.wiley.com/doi/full/10.1002/2013WR013629
- Wallick, J.R., Jones, K.L. O'Connor, J.E., Keith, M.K., Hulse, David, and Gregory, S.V., 2013, Geomorphic and vegetation processes of the Willamette River floodplain, Oregon—Current understanding and unanswered questions: U.S. Geological Survey Open-File Report 2013-1246., 70 p., http://dx.doi.org/10.3133/ofr20131246

Benton County

- Federal Emergency Management Agency, 2016, Flood insurance study: Benton County, Oregon and incorporated areas: Washington D.C., Flood Insurance Study Number: 41003CV000B v. 1, 78 p. https://map1.msc.fema.gov/data/41/S/PDF/41003CV000B.pdf?LOC=8efdb8c3f9919d0cabd894c4e5b2af5f
- Ellis-Sugai, B., 1998, Lateral Channel Migration and Bank Erosion along the Marys River and Selected Tributaries: Marys River Watershed Council. 43 p. https://www.mrwc.org/media/channel_migration_2010.pdf

Marion County

- Federal Emergency Management Agency, 2019, Flood insurance study: Marion County, Oregon and incorporated areas: Washington D.C., Flood Insurance Study Number: 41047CV001B v. 1, 87 p. https://map1.msc.fema.gov/data/41/S/PDF/41047CV001B.pdf?LOC=4a8f5d0e4f5571d7f62d09a41b2254fa

- Risley, J. C., Wallick, J. R., Mangano, J.F., and Jones, K. L., 2012, An Environmental Streamflow Assessment for the Santiam River Basin, Oregon.: U.S. Geological Survey. 66 p. https://pubs.er.usgs.gov/publication/ofr20121133

Morrow County

- Federal Emergency Management Agency, 2007, Flood insurance study: Morrow County, Oregon and incorporated areas: Washington D.C., Flood Insurance Study Number: 41049CV000A, 48 p. https://map1.msc.fema.gov/data/41/S/PDF/41049CV000A.pdf?LOC=d8a3c8b092498427b1baba8cfcc0126a
- U.S. Army Corps of Engineers, 1971, Environmental Statement, Shobe Canyon Channel Clearing, Walla Walla, WA, 41 p. https://usace.contentdm.oclc.org/digital/api/collection/p16021coll7/id/10957/download

Washington County

- Federal Emergency Management Agency, 2018, Flood insurance study: Washington County, Oregon and incorporated areas: Washington D.C., Flood Insurance Study Number: 41067CV001B v. 1, 105 p. https://map1.msc.fema.gov/data/41/S/PDF/41067CV001B.pdf?LOC=0ede29cc5581fc2f569cdccbf56242bf

2.0 METHODS

2.1 Flood Depth Maps

2.1.1 Overview

The NFIP works to reduce the risk of flooding in the United States by mapping flood hazards, providing mitigation assistance, and providing an avenue for homeowners to purchase flood insurance. The flood mapping comes in the form of FIRMs and their supporting FISs, which show the extent of expected flooding for the 100- and 500-year floods, but not depth. FIRMs and FISs also include stream model data showing flood water surface elevations at surveyed cross sections along a given stream reach. If the maps have been modernized, the FIS and FIRM data are stored in spatial and tabular formats in a National Flood Hazard Layer (NFHL) geodatabase. If the maps have not been modernized, the data are typically available in paper format. This information, whether digital or paper, can be used to create a raster map of the water surface elevation (WSEL) for a flood. The WSEL map can be combined with a Digital Elevation Model (DEM) of the land surface to produce a flood depth map, showing the water depth for a specific flood. Each pixel value of the raster indicates a depth of flooding for that specific location. Depth maps provide an improved understanding of the impacts of floods because damage is usually dependent on flood depth.

In Oregon, highly accurate (+/- 15 cm in open terrain) and detailed DEMs made with lidar topographic data are available for much of the inhabited area of the state (https://www.oregongeology.org/lidar/). When WSEL data is combined with the lidar DEMs, the result is a detailed flood depth map, with accuracies constrained by the FIS modeling. These maps can be used for floodplain delineation, supplemental non-regulatory NFIP information, and for flood damage modeling and risk assessments using Hazus-MH, a damage and loss estimation program produced by FEMA.

In this study, we used Esri ArcGIS software version 10.7 to produce depth maps for the 10-, 50-, 100- and 500-year floods using input FIS data and lidar DEMs based on the methods described below.

Terminology:

- *Flood insurance rate map (FIRM)*: A official map used by a community to adhere to the standards set by the National Flood Insurance Program (NFIP).
- *Flood insurance study (FIS)*: reports that compile the data and models used to create FIRMs for a community.
- *Flood zone*: the area expected to be flooded by the 100- or 500-year flood as designated by the FIRM. No delineation on FIRM for 10- or 50-year floods.
- *Depth map*: a raster dataset with cell values that describe the depth of flooding.
- *Difference raster*: intermediary dataset produced by subtracting the WSEL from the lidar DEM.
- *Lidar*: Light detection and ranging elevation data, used to create digital elevation models (DEMs)
- *Water surface elevation (WSEL)*: height above sea level of a river or other body of water. Elevations are relative to a specific vertical datum (e.g. NAVD88).
- *Stream profiles*: a line along the length of a stream's centerline showing the WSEL (typically 10-, 50-, 100-, 500-year elevations) for a modeled flood included in an FIS.
- *Cross sections*: surveyed cross section which provide detailed bathymetric/topographic characteristics of a stream for use in a stream model.
- *Floodway data table*: a table included in an FIS that shows the regulatory elevation of a modeled flood at a series of cross sections.
- *Recurrence interval or return period*: the average frequency of a specified flood event based on statistics derived from past observed floods. The 100-year flood for example has a 1% chance of happening in any given year, so it is statistically possible to have 100-year floods in successive years.
- Triangulated irregular network (TIN): a vector dataset comprised of a network of triangles connecting vertices with location and elevation values that approximate a continuous surface

2.1.2 Data sources

Flood information - We downloaded effective FIS documents and NFHL geodatabases for each of the three counties from FEMA's Map Service Center (https://msc.fema.gov/portal/home). We used the most current (effective) FIS data, described in Table 2-1 for each individual stream within the study areas.

Table 2-1. Effective FIRM data sources

County	Date of effective data	Date(s) of revisions to effective data
Benton County	12/08/2016	01/17/2017; 06/29/2018; 03/29/2018
Marion County	10/18/2019	No revisions post-effective date.
Morrow County	12/18/2007	No revisions post-effective date.

Stream profile data and floodway data tables were included in the FIS PDF documents, and cross sections were included as line feature classes in the NFHL geodatabases.

Lidar information – We extracted a mosaic of the most current lidar DEMs for each study area from the statewide lidar data collection maintained by DOGAMI. The DEMs have a raster cell size of 3 ft. All lidar information used in this report was referenced to the NAVD88 vertical datum.

Table 2-2. Lidar sources

County	Project name	Acquisition date
Benton County	Willamette Valley 2009	08/31/2008 – 07/01/2009
Marion County	Willamette Valley 2009 Santiam 2018 Clackamol 2013	08/31/2008 – 07/01/2009 11/18/2018 – 11/20/2018 05/07/2013 – 09/30/2013
Morrow County	Morrow County 3DEP 2018	10/03/2018 – 11/15/2018

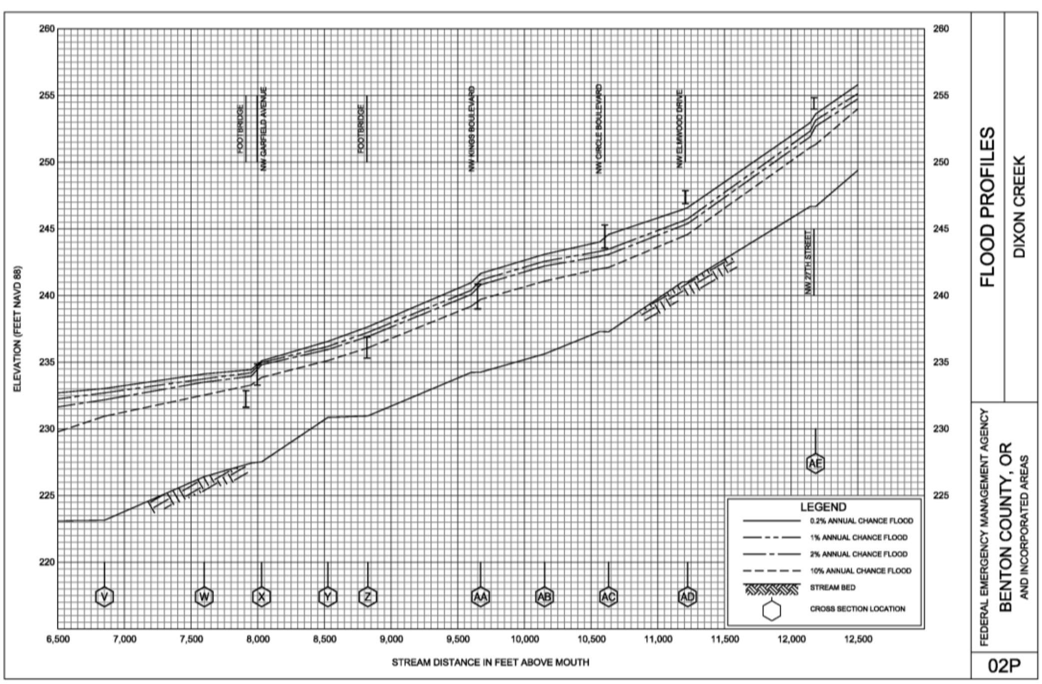
2.1.3 Methods

We created flood depth maps by interpolating each flood model's cross section elevation data into a continuous WSEL surface, and then subtracting the corresponding lidar-based ground surface DEM. Although this is simple procedure, we had to take significant steps to prepare the data for this process.

For all three counties, the FEMA cross sections were only attributed with the 100-year regulatory flood WSEL data. The WSEL values for the 10-, 50-, and 500-year floods were approximated by inspecting the stream profiles and selecting the value for the appropriate flood at each of the cross sections, such as those shown in **Figure 2-1**. Stream profiles are drawn on a grid at 1 or 0.5 ft intervals, and we interpolated flood elevations to the nearest tenth of a foot.

Flood elevations reported in the FIS and in the cross section attributes were based on a reference vertical datum. Benton and Morrow Counties' flood information was referenced to the NAVD88 vertical datum and Marion County's was a mixture of NAVD88 and the older NGVD29 datum. Marion County's elevation data that was referenced to the NGVD29 was converted to NAVD88, which increased flood elevations by 3.4 ft. The conversion factor was calculated using the U.S. Army Corps of Engineers software, CorpsCon.

Figure 2-1. Stream profile example of Dixon Creek in the FIS for Benton County.



The original cross section data was published as a cartographic feature and was not drawn to ensure a complete and accurate WSEL interpolation. If we created WSEL interpolations using the original cross sections, there would have been areas that would have been erroneously excluded and unrealistic interpolation artifacts such as sharp bends. As demonstrated in **Figure 2-2**, there were flood zones longitudinally between cross section end points that required us to extend the cross sections across the floodplain for the purposes of interpolation. While we prioritized extending cross sections to be perpendicular to stream flow at the cross section, the shape of backwater areas between cross sections also influenced the way they were extended. As shown in **Figure 2-3**, there were also complex areas where multiple streams or channels running parallel to one another had overlapping floodplains that we did not wish to exclude from the WSEL interpolation. As a result, we extended existing cross sections so that they spanned the entire stream channel and floodplains and drew new cross sections to provide a continuous data for the WSEL interpolation. We frequently needed to extend cross sections in areas that showed backwater flooding, but only rarely needed to address multi-channel cross section modifications.

Figure 2-2. Example of cross section extension in the City of Woodburn, OR. Red lines define the original cross sections and black lines are the extensions which are drawn to span the entire flood zone. The flood zone is shown in blue. The purple hatched lines highlight the area between the original cross sections and the yellow hatched lines highlight the area between the extended cross sections that would have been excluded from the flood zone if the cross sections had not been extended.

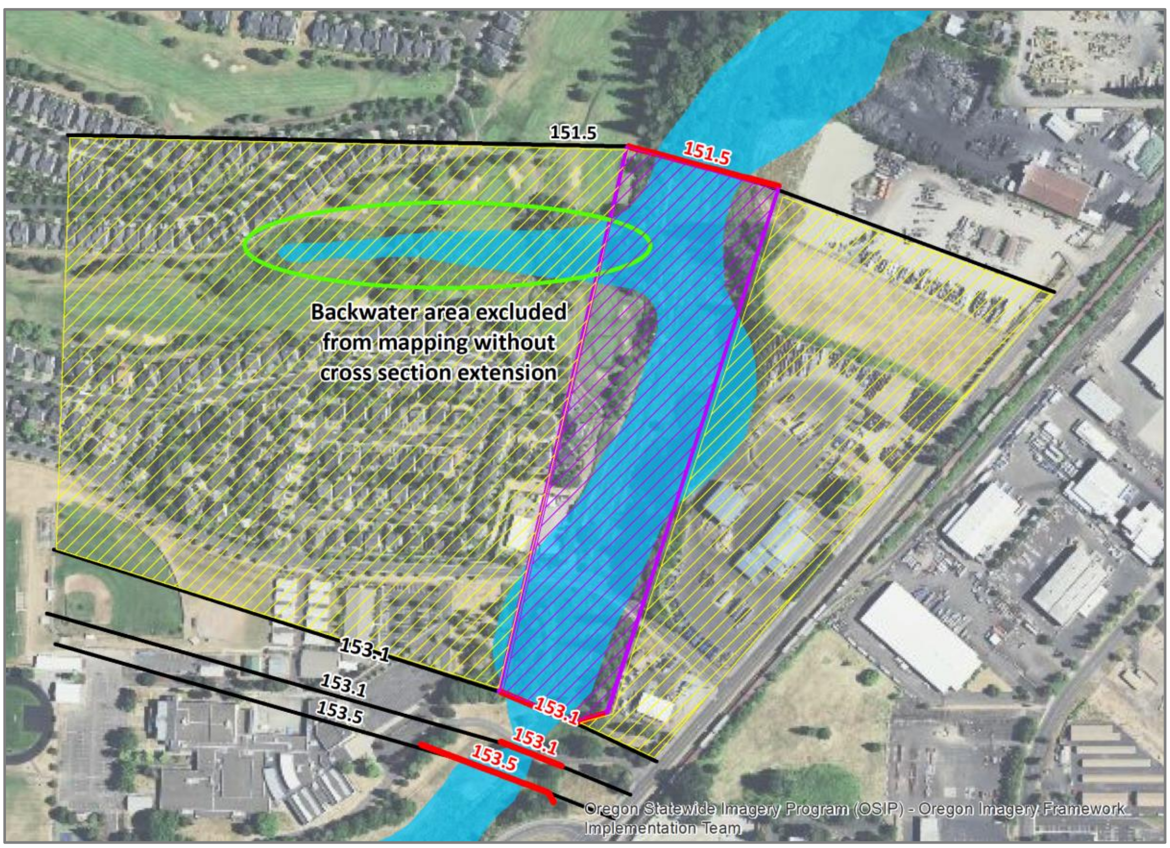
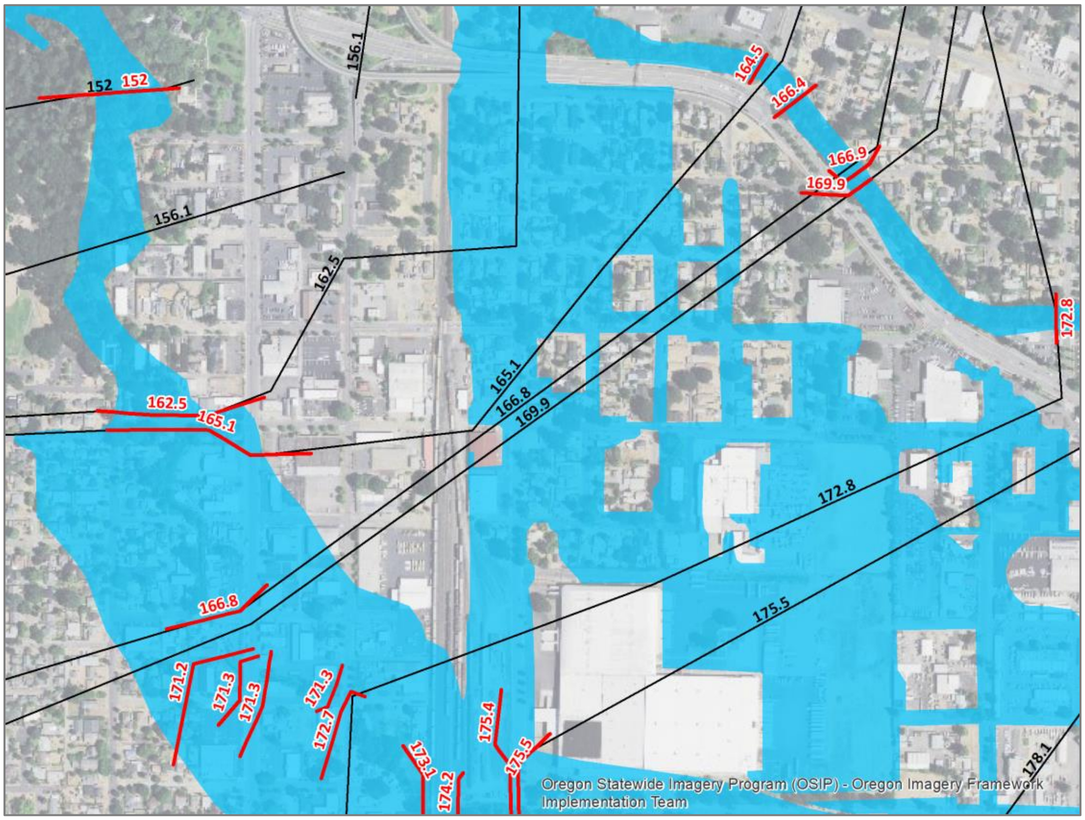


Figure 2-3. Example of cross section extension near the Salem Municipal Airport. Red lines are the original cross sections, black lines are the extensions which are drawn to span the entire flood zone, and the flood zone is shown in blue shading.



In some areas, the stream was highly sinuous and bends in the river were so tight that the WSEL interpolation from one bend would overlap with the WSEL interpolation from another bend. In those cases, we created separate WSELs upstream and downstream of the overlapping bends to avoid overlap. Later, we merged the WSELs together at a common cross section (i.e. a common elevation) to result in a seamless WSEL.

For each stream and each of the modeled floods, we used the FIS cross section data to create an interpolated WSEL raster using a triangulated irregular network (TIN) method in Esri ArcGIS software version 10.7. We clipped the TIN to the extent of the stream segment and then converted it to a WSEL raster at the same 3 ft horizontal resolution as the lidar DEM. If there was more than one segment for a stream, the individual WSEL rasters were combined.

We made difference rasters by subtracting the DEM raster from each of the WSEL rasters and setting any negative values to "Null" or "No Data." Negative values were present because the higher resolution lidar DEM can be substantially different from the more generalized ground elevation model used in the original flood modeling. The modified difference rasters were then clipped to the flood zone extents to produce the final flood depth maps. Because there are no flood zone boundaries for the 10-year and 50-year floods, their difference rasters were clipped to the flood zone of the 100-year flood.

2.2 Channel migration zones

2.2.1 Overview

The goal of the channel migration zone (CMZ) evaluation is to define the area in which a given stream is likely to move laterally within the next 30- and 100-years. The established boundary is designed to be used to inform planning efforts, increase hazard awareness, and to be integrated into environmental and land management. We can use these maps to identify which buildings, critical facilities, infrastructure, and transportation lines that are potentially at risk of channel migration and prioritize these areas for pre-disaster risk reduction. This method produces maps that are accurate at a neighborhood-scale and does not replace the need for site-specific geotechnical investigations.

CMZ maps were produced for rivers in Benton, Marion, Morrow, and Washington County using the method described in this section. The approach we used incorporated techniques and mapping units developed by several previous studies in Oregon, Washington, and Colorado. We recognize that terminology and mapping unit definitions vary across previous studies. In this study, we define the following terms as presented below. Please note that river, stream, and creek are used interchangeably.

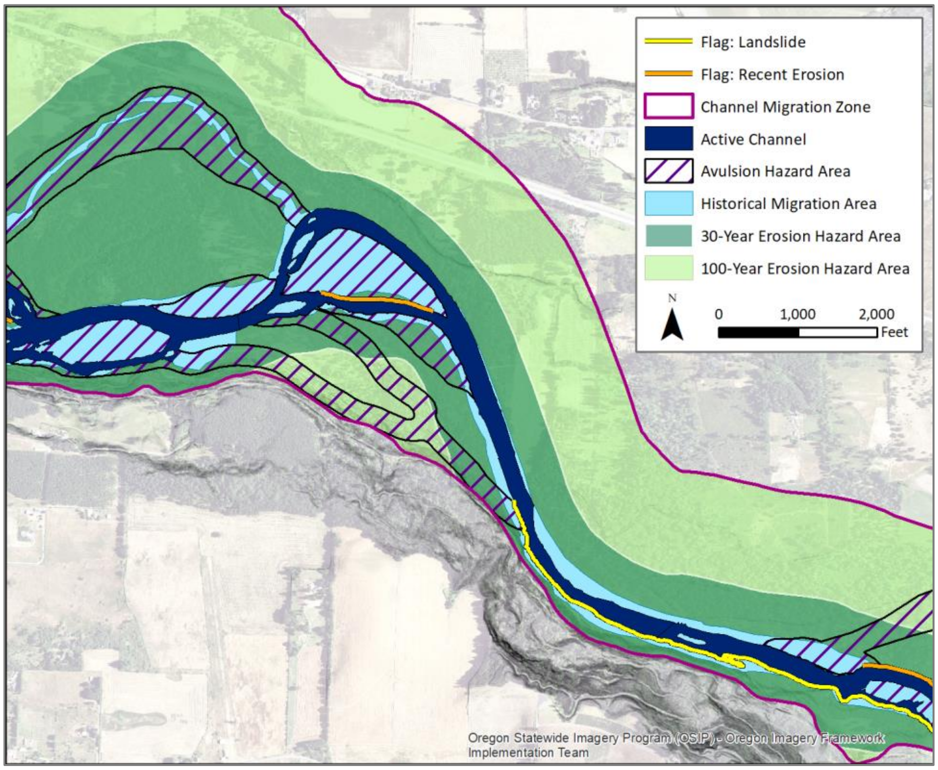
Terminology:

- 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
- Historical migration area (HMA): the active channel combined with areas that the channel has occupied in the documented historical record
- Erosion hazard area (EHA): the areas at risk from lateral migration and channel widening over a specified period based on historical erosion rates
- Avulsion hazard area (AHA): the areas at greatest risk of rapid channel diversion and occupation
- Flagged: channel banks which have been identified for further geotechnical inspection due to signs of recent migration or directly adjacent to landslide deposits
- 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
- Centerline: the line which runs parallel and midway between the active channel boundaries or modern valley bottom walls
- Lidar-derived digital elevation model (DEM): highly accurate and detailed 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; created from a DEM that has been normalized to the elevation of the water surface at the time of the lidar collection
- River segment (RS): A length of river that displays relatively similar hydrologic and geomorphic characteristics, typically ~2,000-14,000 ft in length
- Stream stations (SS): Evenly spaced points along the river centerline
- Channel confinement: Confinement is a characteristic of rivers that are limited in their ability to laterally migrate due to bed and bank materials that resist erosion. Channels that flow within narrow valleys are said to be confined and those that flow freely through erodible sediment in open valleys are described as unconfined.
- Incised: Incision is the process in which a river erodes downward into its bed; during small floods, the channel is less frequently able to flow onto the floodplain.

- Single thread and multi-thread: Channels with a single active channel are described as single thread. Channels with multiple active channels flowing through the floodplain are described as multi-thread.
- Anabranching and braided streams: Stable, multi-thread channels with relatively large, often vegetated islands between channels are described as anabranching. Unstable, multi-thread channels with temporary sediment bars and islands separating the channels are described as braided (Knighton, 1998).
- Low, medium, and high water surface slope: Water surface slope is calculated based on the change in elevation of the water surface (extracted from lidar) divided by the change in distance between two given locations, often the end points of a river segment. Describing the water surface slope as low, medium, and high is a relative term and does not have a set of universal thresholds. For the purposes of this study, very low describes channels with a slope of ~<0.1%, low slope channels are ~0.1-0.25%, moderate slopes are ~0.25-0.75%, and high slopes are ~0.75-3%.
- Sinuosity: Channel sinuosity is a description of channel curved form relative to a straight path. It is quantified as an index by dividing the channel length by the relatively straight valley length; the lower the index value the straighter the channel. For the purposes of this study, very low sinuosity channels have an index of <1.1, low sinuosity channels are 1.1-1.25, moderately sinuous channels are 1.25-1.5, highly sinuous channels are 1.5-2.0, and very highly sinuous channels are >2.

The units that comprise the CMZ are the AC, HMA, EHA 30 year, EHA 100 year, AHA and Flagged. These units are produced using the approaches described in **Sections 2.2.2** and **2.2.3. Figure 2-4** is an example of an image that can be used to visualize how the channel units are combined. We created these datasets using Esri ArcGIS software version 10.7.

Figure 2-4. Example diagram of the components of a CMZ map including the active channel (AC) in dark blue, historical migration area (HMA) in light blue, avulsion hazard area (AHA) with hatched lines, 30-year and 100-year erosion hazard areas (EHA) in dark and light green, flagged stream banks with yellow and orange lines, and channel migration zone (CMZ) boundary outlined in magenta.



The following sections will describe the methodology used to delineate the CMZ within this study. This methodology was developed after review of several other key channel migration studies including:

- English, J. T., and Coe, D. E., 2011, Channel migration hazard maps, Coos County, Oregon: Oregon Department of Geology and Mineral Industries, Open-File Report O-11-09, 27 p., scale 1:6,000. http://www.oregongeol-ogy.org/pubs/ofr/p-O-11-09.htm
- Lagasse, P. F., Zevenbergen, L. W., Spitz, W. J., and Thorne, C. R., 2004, Methodology for predicting channel migration: Washington, DC., The National Academies Press. https://doi.org/10.17226/23352
- Olson, P. L., Legg, N. T., Abbe, T. B., Reinhart, M., and Radloff, J. K., 2014, A methodology for delineating planning-level channel migration zones: Olympia, Wash., Washington Department of Ecology, Publication 14-06-025, 83 p. https://fortress.wa.gov/ecy/publications/documents/1406025.pdf
- Rapp, C. F., and Abbe, T. B., 2003, A framework for delineating channel migration zones: Olympia, Wash., Washington Department of Ecology, Publication 03-06-027, 135 p. https://fortress.wa.gov/ecy/publications/doc-uments/0306027.pdf
- Multiple studies by the King County Department of Natural Resources and Parks between 1991-2020, including King County, prepared by Radloff, J. and Lott, F, 2019, Middle White River channel migration study RM27.4 to 20.3: Seattle, Washington., King County Department of Natural Resources and parks, Water and Land Resources Division. 125 p. https://kingcounty.gov/services/environment/water-and-land/flooding/maps/migration.aspx

2.2.2 Preliminary data sources and development

The method we used was primarily based on the interpretation of remotely sensed datasets to accommodate the very large study areas. Several days of field work were completed to guide interpretations of remotely sensed data. We used or developed the following datasets to inform the CMZ mapping.

Topographic data:

- We used lidar digital elevation models (DEMs) to delineated modern channel and valley features and to estimate water surface elevations and create longitudinal profiles. These DEMs were often visualized as slope map.
- Relative elevation models (REMs) for all of the rivers in this study were generated to identify floodplain features. An REM shows topography relative to the active channel water surface elevation, such as the floodplain's or drainage ditch's height above or below the channel. We produced these visualizations by normalizing or 'detrending' the lidar DEMs to the river's water surface elevation using GIS tools following the method detailed in Appendix E (Olsen and others, 2014). 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.

Aerial Imagery

- We used the most recently collected 3-ft (nominal 1-m or higher resolution) aerial imagery available at the time of mapping, which included 1-ft 2018 Oregon Statewide Imagery Program (OSIP) imagery available for Benton, Marion, and Washington County, and 1-ft 2017 OSIP and ~3 ft 2020 National Agriculture Imagery Program (NAIP) available for Morrow County. These datasets were used to digitize the active channel, characterize channel form and features, recent land use, land cover, infrastructure, and instream large woody debris.
- We used historical orthoimagery to delineate the HMA and digitize the historical stream bank lines that were used to determine erosion rates. We orthorectified historical images collected during the 1950s for all streams and, where channel change was observed; additional imagery from the 1960s-1980s were also orthorectified. NAIP statewide imagery was also available for 1990s-2010s. We used the following imagery in this study:
    - Benton County:
        - Orthorectified U.S. Geological Survey single-frame images for parts of study area: 1955, 1967, 1976
        - Complete for county study area: Orthorectified NAIP 1995, 2000, 2005, 2009, 2011, 2012, 2014, and 2016; OSIP 2018
    - Marion County:
        - Orthorectified U.S. Geological Survey single-frame images for parts of study area: 1950, 1952, 1953, 1954, 1955, 1960, 1962, 1967, 1970, 1973, 1976, 1980
        - Complete for county study area: Orthorectified NAIP 1995, 2000, 2005, 2009, 2011, 2012, 2014, and 2016; OSIP 2018
    - Morrow County:

        - Orthorectified U.S. Geological Survey single-frame images for parts of study area:1952, 1960, 1965, 1977
        - Complete for county study area: Orthorectified NAIP 1995, 2000, 2005, 2009, 2011, 2012, 2014, 2016, and 2020; OSIP 2017 and 2018
    - Washington County:
        - Orthorectified U.S. Geological Survey single-frame images for parts of study area: 1951, 1952, 1953, 1954, 1960, 1970, 1973, 1980, 1982, 1987,
        - Complete for county study area: Orthorectified NAIP 1995, 2000, 2005, 2009, 2011, 2012, 2014, 2016; OSIP 2018

Geology

- We used the best available surficial geologic, GIS data for each of the counties to understand the underlying geology of the stream bed and banks and valley bottom and walls. For all four counties in this study this information came from Franczyk and others (2020) and Hairston-Porter and others (2021).
- Published literature including journal articles, reports, and white papers from state and federal agencies, academia, researchers, and watershed councils were reviewed for relevant geologic background.

Infrastructure

- We used infrastructure GIS datasets available through the Oregon Geospatial Enterprise Office to help identify the location of levees, roads, railroads, dams, and bridges that may impact channel's migration.

Local geomorphic and channel migration history

- Local county and community planners, emergency managers, and GIS staff shared some locations and areas of concerns about past or present channel migration that provided uniquely useful insights.
- We reviewed journal publications, reports, and white papers from a variety of sources including state and federal agencies, researchers, academia, watershed councils, county governments, and communities. These documents provided additional context and information about the historical changes within the watershed including human modifications to the channel, major floods, past observed channel migration, and geologic units susceptible to erosion. These publications included but were not limited to Ellis-Sugai (1998) and Bureau of Land Management (1999) in Benton County, Wallick and others (2007), Wallick and others (2013), and Orr and Eden (date unknown) in Marion County, Madin and Geitgey (2007) in Morrow County, and Labbe and others (2011), Hawksworth (2001), and Sobieszcyk (2012) in Washington County.

Flood history

- We used National Hydrography Dataset (NHD) to initially locate features such as stream centerlines, lakes, and ponds. The low resolution of the dataset meant that these datasets were only used as visualizations and not used for analysis.
- We reviewed the FEMA Flood Insurance Study maps for each of the counties to understand the potential areas impacted by frequent floods. This information was particularly useful for characterizing the stream's potential to avulse within the 10-year floodplain.

- We reviewed the flood history for each county as documented in the most recent Natural Hazard Mitigation Plan. This included the University of Oregon and others (2016a) for Benton County, Oregon Partnership for Disaster Resilience (2011) and Oregon Partnership for Disaster Resilience (2017) for Marion County, Morrow County and others (2016) for Morrow County, and University of Oregon and others (2016b) for Washington County.

2.2.3 Channel Migration Zone Mapping

After gathering the necessary datasets, contextual information, and basemaps, we delineated the active channel, historical migration area, and modern valley bottom and divided the study area into river segments (RSs). We mapped the erosion hazard areas, avulsion hazard areas, and flagged banks and created the final channel migration zone. The process we used to produce these, and several intermediary datasets is documented in the follow eight subsections.

2.2.3.1 Active channel

The active channel (AC) is composed of the river's wetted perimeter and the exposed, unvegetated sediment deposits adjacent to the river; it is limited to the areas that are likely to have conveyed flows in the recent past and where woody vegetation is unable to be maintained (Olsen and others, 2014).

We mapped the AC polygon boundary based on the most recent available aerial photography. The Morrow County AC was mapped using the ~3-ft 2020 NAIP imagery while also using the higher-resolution 1-ft 2017 OSIP imagery for verification. The Benton, Marion, and Washington County AC was mapped based on the 1-ft 2018 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, we digitized solely based on the more recent aerial imagery.

After mapping the AC boundary, we digitized a stream centerline and stream station points every 100 feet along the middle line of the AC, parallel to the AC bank edges. These intermediary datasets were used to characterize river segment length, sinuosity and produce longitudinal profiles. We also measured average active channel width by measuring cross sectional transects clipped to the active channel boundary. Cross sectional transects were automatically generated proportional to the active channel width.

2.2.3.2 Historical migration area

The historical migration area (HMA) consists of the combined areas occupied by current and past active channels visible in historical aerial imagery. These areas are most commonly adjacent to the active channel, formed by fluvial processes and may be prone to future migration.

We mapped the HMA for all rivers in this study primarily based on historical aerial photographs. As discussed in **Section 2.2.2**, these included orthorectified aerial photographs from the 1950s to present day. We did not include the historical photographs before 1950 because they predate the significant hydrological, infrastructure, and land use changes including the construction of large dams and they are not available for all studied streams. Lidar DEMs and REMs were also used to confirm the location of the historic channel in areas where potential errors from the photograph orthorectification appeared to occur.

2.2.3.3 Modern valley bottom

The modern valley bottom (MVB) is comprised of the relatively flat area adjacent to the stream, including the current and potentially historical floodplains. It is bounded by steeper valley walls and is typically comprised of erodible Quaternary alluvium sediments.

We mapped the MVB polygon boundaries for all rivers using the lidar DEM, REM, and surficial geologic maps. The valley margin was identified by a steep change in slope of the valley walls. Bedrock and older pre-Holocene terraces that did not show signs of recent fluvial erosion were considered outside of the MVB. The MVB is used to constrain the erosion hazard area (EHA). In addition, 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).

2.2.3.4 River segments

Each stream is divided into river segments (RSs) that display relatively similar hydrologic and geomorphic characteristics. These valley-scale segments are typically ~2,000-14,000 ft 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 Olsen 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).

2.2.3.5 Erosion Hazard Area (EHA)

The erosion hazard area (EHA) includes the land where the channel is most likely to erode laterally over a specified period. For this study, we used each RS historical erosion rate to map potential movement beyond the historical migration area (HMA) over the next 30 and 100 years.

The process we used to develop the EHA included three steps: 1) measuring the historical erosion rate, 2) projecting the erosion rate 30 and 100 years into the future, and 3) removing areas from the EHA that extend beyond the MVB. For the segments that did not have measurable migration during the period of observation, we used an erosion rate established by was established by Lagasse and others (2004) that conservatively includes the area of erosion for streams that are static for long periods of time (see step 6 below for more detail). Our EHA methodology was designed to include the maximum possible extent of lateral erosion for a RS based on the observed historical erosion patterns.

Measuring the historical erosion rate

1) Using the historical aerial imagery, we identified the area within each RS where the channel had eroded the furthest and most rapidly.
2) We digitized chronologically successive stream bank lines using the historical imagery.
3) We digitized a transect or transects between the bank lines to measure the distance the bank has eroded in the time between historical photograph acquisition.
    a. For those transect bank lines that were >10 years apart, we defined these transect as having a 'long-term' erosion rate.

    b. If there were multiple transects drawn that were each based on bank lines fewer than 5 years apart, we defined these transects as having a 'short-term' erosion rate.
4) For each transect(s), we recorded the erosion rate in two ways: first in units of feet per year and second as channel widths/year (i.e., the feet per year divided by the RS average channel width). If both a long-term rate and short-term rate could be measured, the higher erosion rate value was used to project the 30 and 100 year change. By recording the erosion rate in channel widths/year, we were able to compare proportional rates between different river segments with different widths and build our understanding of the maximum erosion rates observed across Oregon.
5) We calculated the local median erosion rate for segments in areas with similar valley-scale geologic and confinement characteristics. This step produced one local median erosion rate across approximately 5-10 adjacent RSs.
6) Selecting the final erosion rate:
    a. For single thread channels that did not appear to experience bank erosion during the period of observation, did not have sediment bars, and showed low variability in channel width, or that had an erosion rate of less than 0.023 channel widths per year, we used an erosion rate of 0.023 channel widths per year. This erosion rate was established by Lagasse and others (2004), who observed that 90% of single thread channels tend to exhibit a migration rate less ≤0.023 channel widths per year.
    b. For all other streams with measurable erosion rates, we selected highest value from the long-term, short-term, or local median erosion rate for each RS.

Projecting erosion rate

7) For each RS, we multiplied the selected erosion rate (ft/year) by 30 and 100 to calculate two buffer widths.
8) We created a buffer covering the area beyond the HMA using the designated buffer widths. This produced the initial 30- and 100-Year EHAs for each RS.
9) We examined the 30- and 100-Year 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

10) Based on the assumption that the stream will not erode the areas outside of the MVB, we removed much of the area outside of the MVB from the 30- and 100-Year EHAs. 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 is similar to the 'geotechnical setback' used by Olsen and others (2014).

2.2.3.6 Avulsion Hazard Area (AHA)

The avulsion hazard area (AHA) includes the land adjacent to the AC and hazard migration area (HMA) that the channel has the potential to occupy or reoccupy. Avulsions occur when the active 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 a large, valley-scale depending on the conditions of the channel and valley and is 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, 10-year floodplain extracted from the FIRMs, 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 areas within the 10-year 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, channels with an absence of dense and woody riparian vegetation along the banks, were all included in the AHA. Areas with manmade ponds, drainage ditches, and streams with channel-spanning logs and large woody debris jams were also examined for potential avulsions. We made a note of the frequency of the number of avulsions observed from the historical imagery, record in tables that accompany this publication. Channel avulsions that we mapped in areas that show a history of channel migration and cover relatively short distances are more likely to occur than channel avulsions mapped across very large areas and in areas where channel avulsion has not been previously noted.

2.2.3.7 Flagged

Flagged stream banks are used to highlight areas with an increased risk for potential lateral migration or bank instability in the immediate future. In this study, we flagged stream banks based on two potential characteristics: recent lateral migration or location directly adjacent to landslide deposits. These conditions may indicate potential unstable channel conditions, increased sources of sediment supply, or the possibility for future landslides or debris flows to confine or block channel flow which all could result in channel migration or avulsion.

We flagged stream banks where channel migration and stream bank erosion was observed between 1995 and the most recent aerial image. We used images available from the last 20-25 years 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 for much of Oregon. We also flagged AC stream banks that were located directly adjacent to landslide deposits. The flagged stream banks were annotated where one or both conditions were met. As the stream continued to change with time, we recognize the need to monitor and potentially update the flagged areas periodically, such as every 5 years and/or after a major flood event.

2.2.3.8 Channel Migration Zone CMZ

The channel migration zone (CMZ) is comprised of all areas within the AC, HMA, the 30-year and 100-year EHAs, and AHA. Because the 100-Year EHA encompasses all areas within the AC, HMA, and 30-Year EHA, the CMZ was created by combining the 100-Year EHA and the AHA.

Future conditions including changes in hydrology due to climate change, sediment supply, land use, riparian vegetation, and human modifications to the river and watershed may result in migration beyond the mapped CMZ. As a result, we recognize the potential need to monitor and periodically update the CMZ every 30 years and/or after a major flood event.

3.0 RESULTS

The results of the study include new riverine flood and change maps, GIS datasets, and tables of channel migration zones and flood depth. The flood depth map results are included in the Benton_County, Marion_County, and Morrow_County_flood geodatabases that accompany this report. The CMZ map results are available in Appendix A. The CMZ GIS results are available in the Benton_Co_CMZ, Marion_Co_CMZ, Morrow_Co_CMZ, and Washington_Co_CMZ geodatabases. Descriptions of the CMZ river segments (RSs) are summarized in the Benton, Marion, Morrow, and Washington County CMZ Excel Tables.

3.1 Flood Depth Maps

These maps provide a representation of flood depths based on the WSEL modeled from the currently effective Flood Insurance Study cross section and lidar data. Although the vertical accuracy of the lidar data, WSEL, and resulting depth maps is ~0.5 feet, there are limitations on the resolution and accuracy of the boundaries of the depth maps. For example, although the topography for hydraulic models used to calculate the flood elevations is based on accurate surveyed elevations along each cross section, our approach relies on interpolating the WSEL between adjacent cross sections. Thus, the flood zones are fit to the topographic data available at the time, guided by the elevations at the cross sections. As a result, the flood zone boundaries are generalized and may not accurately reflect the intersection of the WSEL and the actual ground surface. The difference rasters produced in this study depict the intersection of the WSEL and the ground surface. Once the negative values (locations where the ground surface is higher than the WSEL) are set to Null values, the raster is a considered a depth map. Although the boundary of the unclipped depth map usually closely matches the FIRM flood zone, there are areas where the map extends beyond and falls short of the FEMA flood zone boundary. This is the expected result of combining two datasets with different topographic resolution. Where the edge of the depth map does not reach the flood zone that more accurate edge is retained. Where the edge of the depth map extends beyond the flood zone, it is clipped to the flood zone boundary, to avoid any confusion with the regulatory flood areas. Since there are no flood zone boundaries for the 10- and 50-year floods, the depth maps for those floods are clipped to the 100-year flood extent.

Three areas were identified as having highly complex parallel floodplains that required iterative attempts to accurately map the flood depths. These areas included the Mill Creek floodplain near Salem in Marion County; the confluence of the Mary's River with the Willamette River in Benton County; and the Thornton Lakes Overflow area. We iteratively adjusted the length and orientation of the cross section extensions in these areas to better fit the depth maps to the flood zones. As a result, the final flood depth maps for these areas closely matched their respective flood zones.

A small section of Marion County flood zone near Mill Creek and Beaver Creek was recently re-mapped using lidar data. The flood depth map boundary for that area, which used the same lidar data, was nearly identical to the revised flood zone boundary. This provides confidence that our mapping methods accurately represent the FEMA flood zones in areas that were mapped without lidar.

In Benton and Marion Counties, the depth maps show that the Willamette River makes up most of the floodplain area and that all agricultural levees built along the Willamette River would be overtopped by 100-year flooding. Patterns in the depth maps of the Willamette River shows ancient channels which indicate a long history of channel migration. Potential additional flow paths that differ from the main course of the Willamette River are likely at the 100 and 500-year floods.

On the Mill Creek floodplain near Salem there are differences between the flood zone and the depth map. These differences are not caused by lower resolution topographic data, but rather land use and land cover changes caused by development in the floodplain in the years since the flood model and flood zone were revised in 2003. In areas of rapid development, the validity of stream models decreases over time making new stream modelling necessary to accurately depict the flood risk.

The depth maps in Morrow County shows floodplains that are simple and tightly constrained to the narrow river canyons. The depth maps for tributaries to Willow Creek show the greatest potential for flood damage in Morrow County.

3.2 Channel Migration Zones

This study mapped CMZs along a total of 464 river miles across 20 rivers. Across the four counties, there was a wide variety of channel forms, geologic conditions, and erosion rates observed. Detailed CMZ maps can be found in Appendix A. In the accompanying Excel spreadsheets, we provide the various stream morphologic characteristics including channel length, average width, water surface slope, and sinuosity for each river segment (RS), along with brief descriptions of the channel pattern, noted recent migration, 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 overarching findings. For unfamiliar terminology, please review the definitions provided in **Section 2.1.1.**

3.2.1 Benton County

In Benton County, we mapped CMZs along 66 river miles of the Alsea River, North Fork Alsea River, Marys River, and Tumtum River (**Figure 3-1**, **Figure 3-2**, and **Appendix A** for detailed maps).

- The mainstem of the Alsea River (River Segment (RS)01-RS11) is predominately a single thread (i.e. one active channel), low slope, relatively straight channel that is heavily incised and has shown minimal channel migration during the last 65 year. Throughout the study area, the channel is confined within erosion-resistant terraces that are 15-30 ft above the water surface elevation. In RS01-RS05, the stream is further confined within a very narrow valley bottom, between valley walls comprised of sedimentary and volcanic bedrock and landslide deposits. Although the EHA is very narrow and no areas were mapped for the AHA, we recognize the potential for landslide-induced channel change in the future and flagged areas should be monitored for possible future change.
- The North Fork Alsea River (RS01-RS07) is a single thread, moderately low slope channel with intermittent sections of modest channel migration. RS01, RS02, and RS07 showed the greatest channel change during the period of observation since the 1950s and the widest HMAs relative to the active channel. RS03 - RS06 show little to no channel change and narrow floodplains; RS03 and RS04 are incised within the valley bottom alluvium. Landslide deposits are common along the valley walls but are not as frequently located directly adjacent to the active channel as in the Alsea River study area.
- The Marys River study area (RS01-RS27) includes a transition in river conditions from unconfined, regularly migrating highly sinuous channel lower in the watershed to confined, steeper slope, straighter channels that have experience minor or intermittent channel migration higher in the watershed. RS03-RS09 are comprised of very low slope, highly sinuous channels that flow through the unconfined Willamette Valley bottom and show signs of recent, rapid channel migration. RS11-RS15 and RS24-27 are heavily confined within a narrow valley by volcanic and sedimentary bedrock walls and show little evidence of having experienced any recent channel migration. RS16-RS23 are moderately confined with limited historical channel migration; some RSs are adjacent to large landslide deposits that appear to narrow the overall valley width.
- The Tumtum River (RS01-RS08) is a single-thread channel with moderate to high sinuosity that is moderately confined by the sedimentary bedrock walls. RSs show moderate to no channel migration during the last 65 years. There are landslides that consistently line the valley walls, and

some lie directly adjacent to the active channel. The EHA is relatively narrow along most of the Tumtum River indicative of it having experienced limited historical channel migration.

Figure 3-1. Alsea River and North Fork Alsea River segments, CMZ areas, and labeled counties.

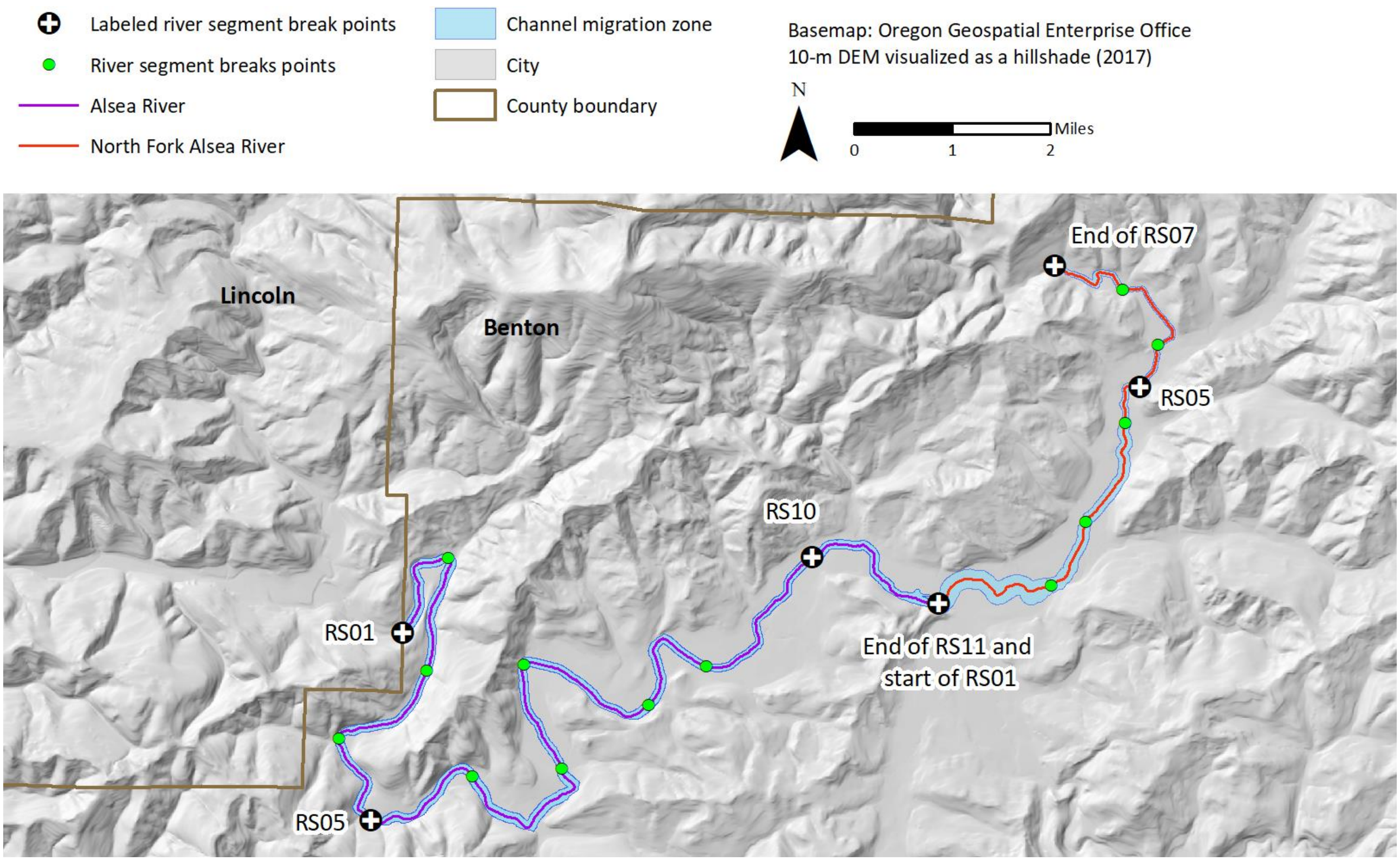
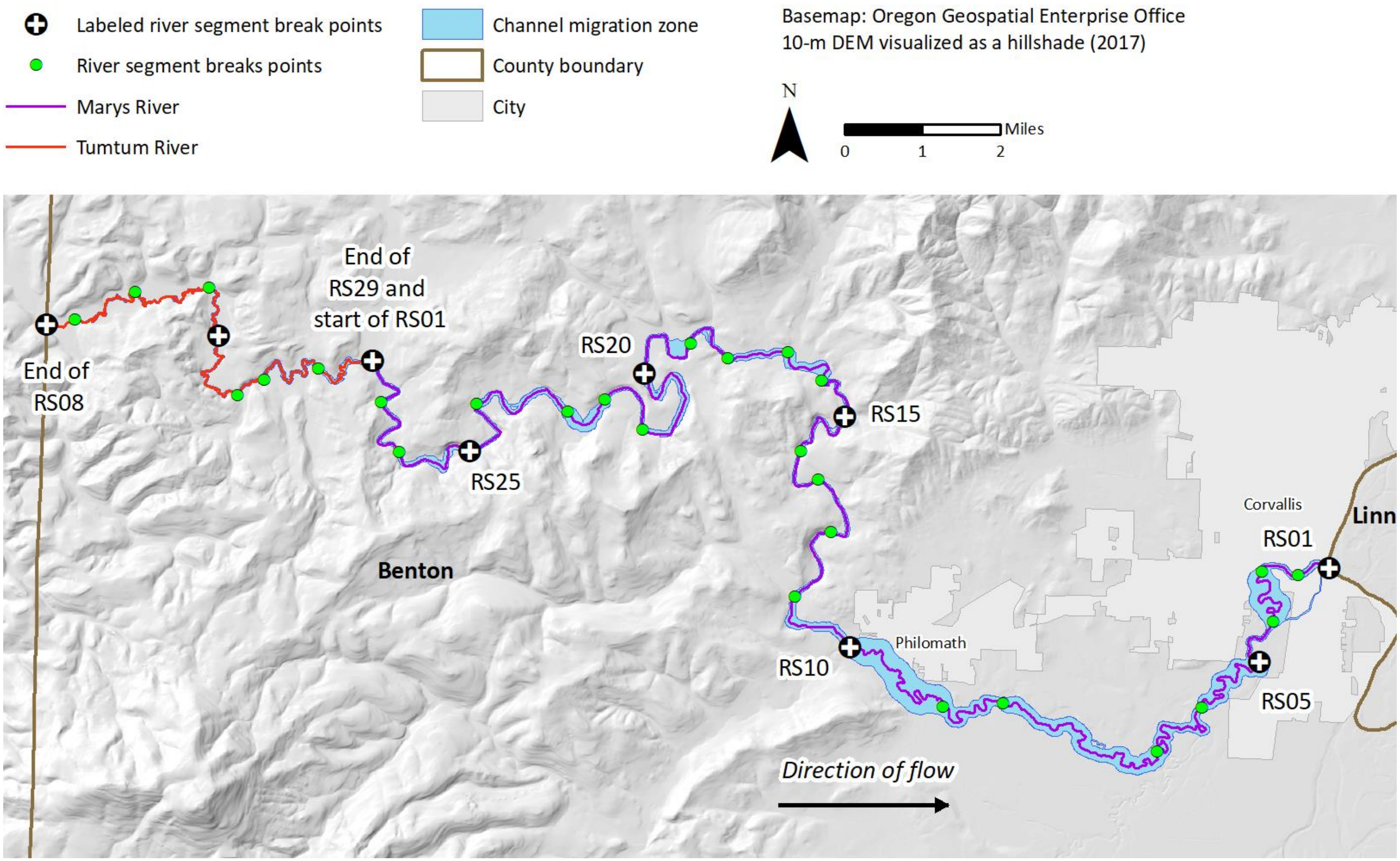


Figure 3-2. **Marys and Tumtum River segments, CMZ areas, and labeled counties.**



3.2.2 Marion County

In Marion County, we mapped CMZs along 136 river miles along Santiam River, North Santiam River, and Pudding River (**Figure 3-3**, **Figure 3-4,** and **Appendix A** for detailed maps)

- The mainstem of the Santiam River (RS01-RS06) is predominately a single-thread channel with low to moderate sinuosity and very low water surface slopes flowing generally unconfined in the bottom of the Willamette Valley. We observed moderate historical migration, recent channel narrowing, and a few channel avulsions in this study area. Since 1995, only two of the six river segments showed signs of recent lateral erosion.
- The North Santiam River is a major tributary to the Santiam River and can be divided into lower and upper sections by the Detroit Dam and Lake.
    - The lower North Santiam River (RS07-RS33) flows west from the Detroit Dam and Cascade Mountain Range into the Willamette Valley where it joins the Willamette River. The channel varies greatly in form across the study area. RS07-RS15 includes single channel, multi-thread, and braided river segments that flow, often unconfined across the Willamette Valley bottom. Most of these river segments have shown historical and recent channel migration and erosion; some river segments have experienced frequent channel avulsions (e.g.). In RS16-RS28, the river becomes partially confined by bedrock, older terraces, and landslide deposits. The lower reaches, including RS16-RS18 are multi-thread and have experienced historical and recent channel migration, but segments above RS19 are typically single thread and show much less historical channel migration. RS29-RS32 have single thread channels confined by bedrock and landslide deposits and show no evidence of channel migration during the last 65 years.
    - Upstream of Detroit Lake, the upper North Santiam River (RS34-RS40) is confined by narrow valley walls composed of bedrock, landslide deposits, and Quaternary glacio-fluvial deposits within the Cascade Mountain Range. The channel is predominantly a single channel with relatively little evidence of channel migration during the last 65 years. None of the seven river segments show signs of recent lateral channel migration, but six of the seven have sections where the active channel flows directly adjacent to a landslide deposit.
- The Pudding River (RS01-RS34) typically consists of a moderately to very highly sinuous, single-thread channel. The greatest historical migration has occurred in the lower reaches (RS01-RS04). With the exception of human channel modification in several upstream reaches, there is both progressively less channel migration and the channel is more commonly incised within its banks in the river segments upstream from RS05. Of the 34 river segments within this study area, only 9 show signs of recent channel migration since 1995 and avulsions are historically very rare.

Figure 3-3. **Santiam and North Santiam River segments, CMZ areas (including valley-scale AHA polygons appearing as thin blue lines), and labeled counties.**

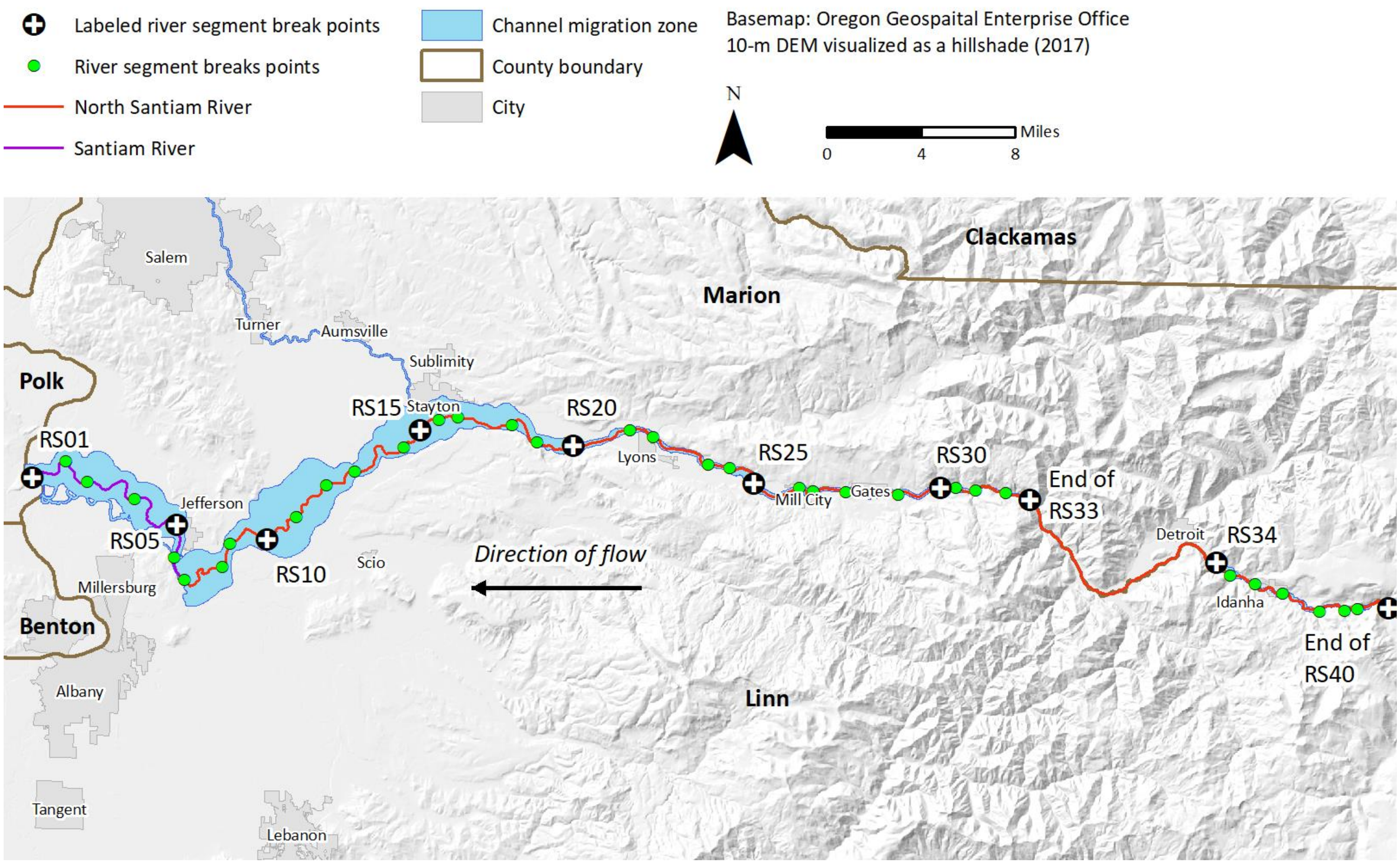
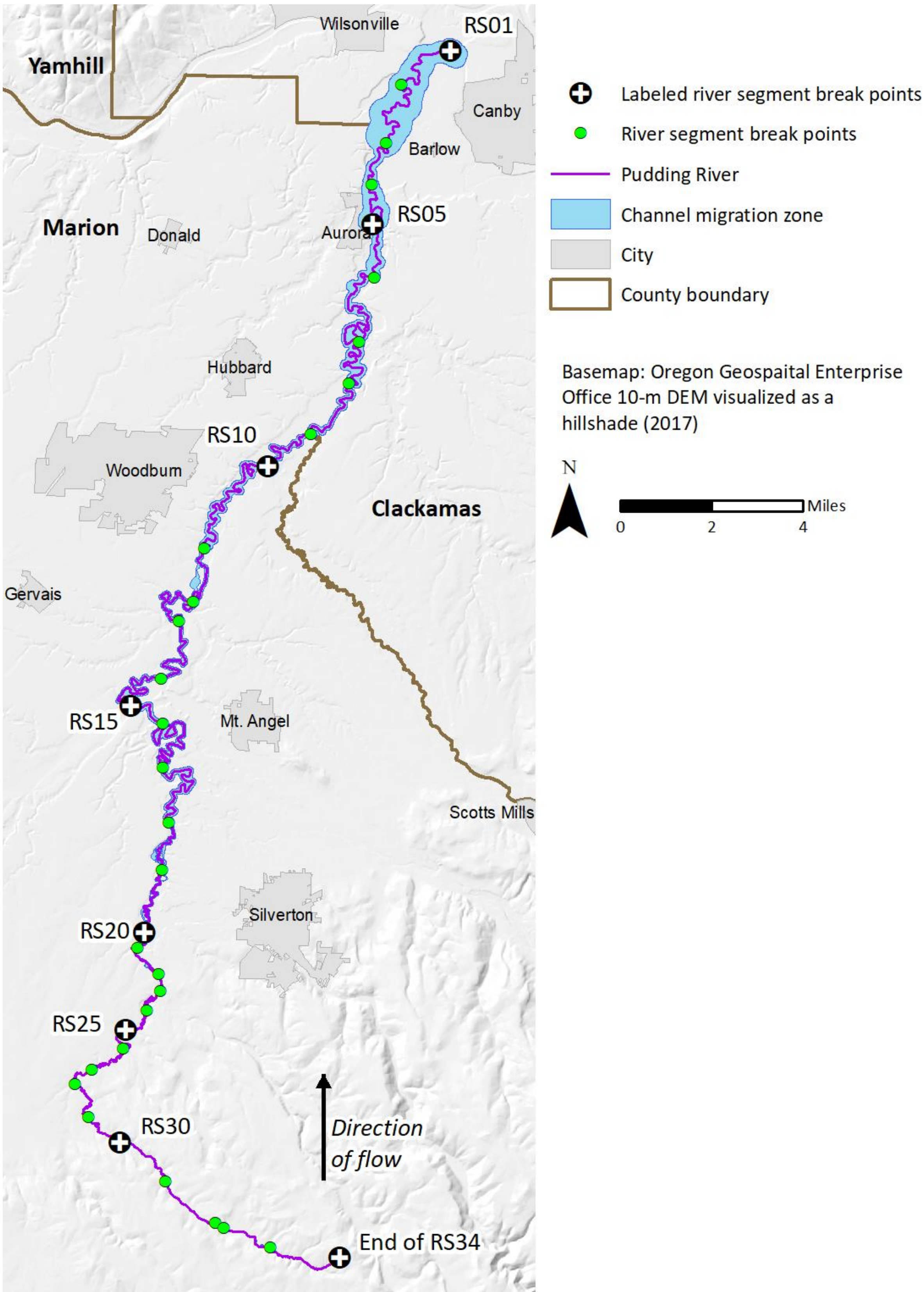


Figure 3-4. Pudding River segments, CMZ areas, and labeled counties.



3.2.3 Morrow County

In Morrow County, we mapped CMZ along 78 river miles along Hinton Creek, Rhea Creek, and Willow Creek (**Figure 3-5**, **Figure 3-6**, **Figure 3-7**, and **Appendix A** for detailed maps).

- Willow Creek is divided by the Willow Creek Dam into lower and upper sections.
  - Lower Willow Creek (RS01-RS29) is a single thread channel with moderately low slope and low to moderate sinuosity. The channel flows broadly unconfined in RS01-RS05 and RS12-RS18, moderately confined in RS19-29, and confined in RS06-RS11. Most of the river segments show minor to moderate channel migration with the greatest recent channel change having occurred in RS01, RS02, RS06-RS14, RS16-RS18, and RS21-RS26. Some channels have been straightened or modified including RS15 and RS29. Landslide and debris flow deposits commonly line the bedrock valley walls.
  - Upper Willow Creek (RS30-RS07) flows above the Willow Creek Dam and is a single thread, predominantly straight channel with a moderately steep slope. Minor to moderate channel migration has occurred and there is evidence of some channel straightening since the 1950s. The channel is moderately confined by bedrock valley walls and landslide and debris flow deposits.
- Hinton Creek (RS01-RS07) is a predominantly single thread, moderately straight channel and moderately steep slope. The bedrock valley walls and landslide and debris flow deposits intermittently partially confine the channel. In RS01, RS02, RS06, and RS07 there is very little change in the channel position and the active channel appears be narrower in some locations than in past imagery. In RS03-RS05 the channel appears to have changed location although it is unclear how much of this change is due to lateral erosion, avulsion, manmade straightening, or a combination of all three.
- Rhea Creek (RS01-RS14) is a single thread, partially confined channel with a low to moderate slope. The sinuosity varies across the river segments ranging from straight to highly sinuous; RS04, RS09, and RS012 appear to have been modified and straightened. All the river segments show a history of channel migration, and RS01, RS05-RS08, RS10, RS11, RS13, and RS14 show the greatest amount of recent channel migration,

The 1950s-2020 photographs show evidence of large-scale avulsions, channel straightening by humans, lateral erosion, and channel migration along Willow, Hinton and Rhea Creek. There are also large areas of the floodplains that lie 1-2 feet above the water surface elevation. As a result, we mapped the potential for avulsion hazards for wide areas on the floodplains of all three streams. However, it is difficult to predict the timing and frequency of future avulsions.

Figure 3-5. Willow Creek segments, CMZ areas downstream of Willow Creek Dam, and labeled counties.

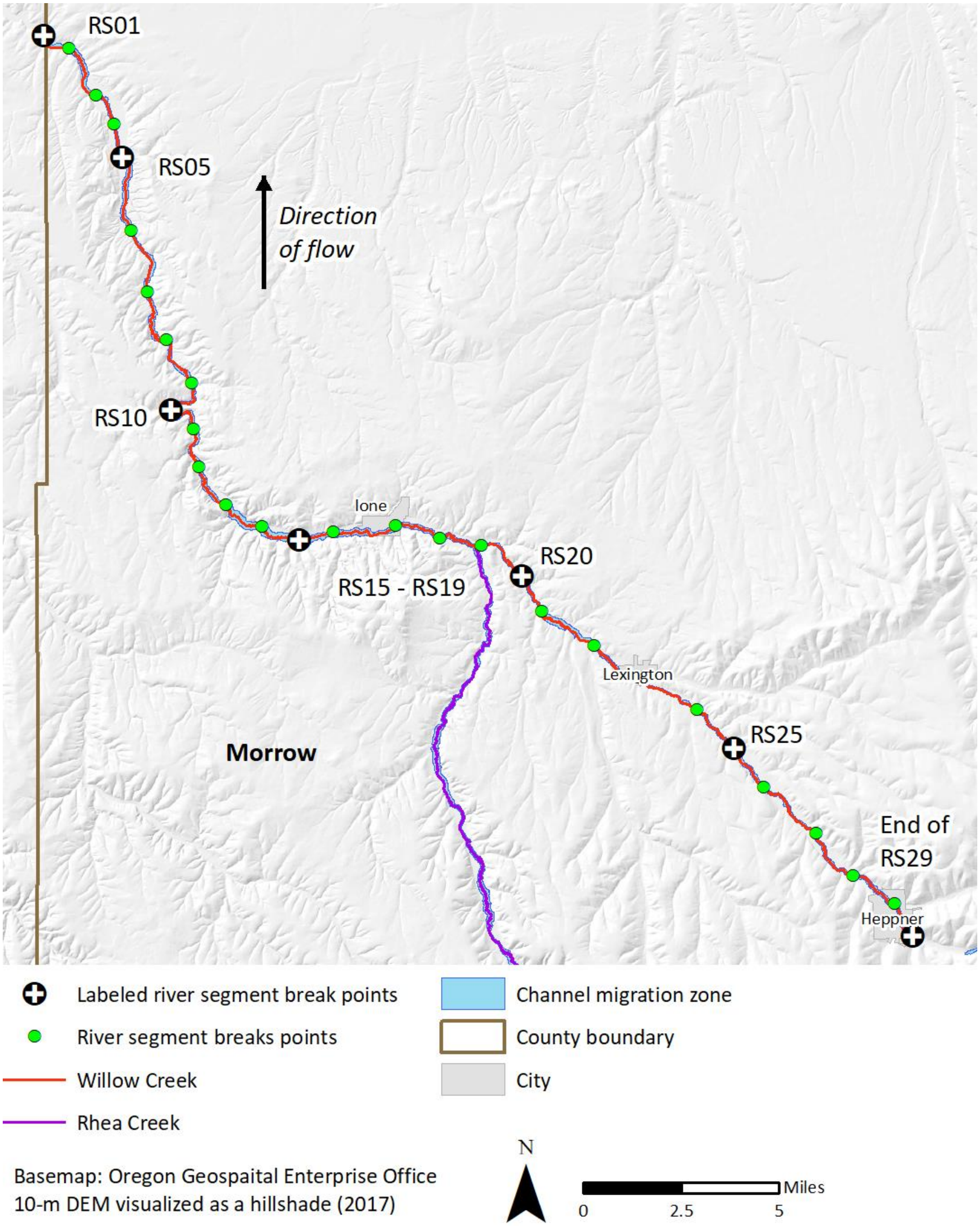


Figure 3-6. Hinton and Willow Creek segments, CMZ areas upstream of Willow Creek Lake, and labeled counties.

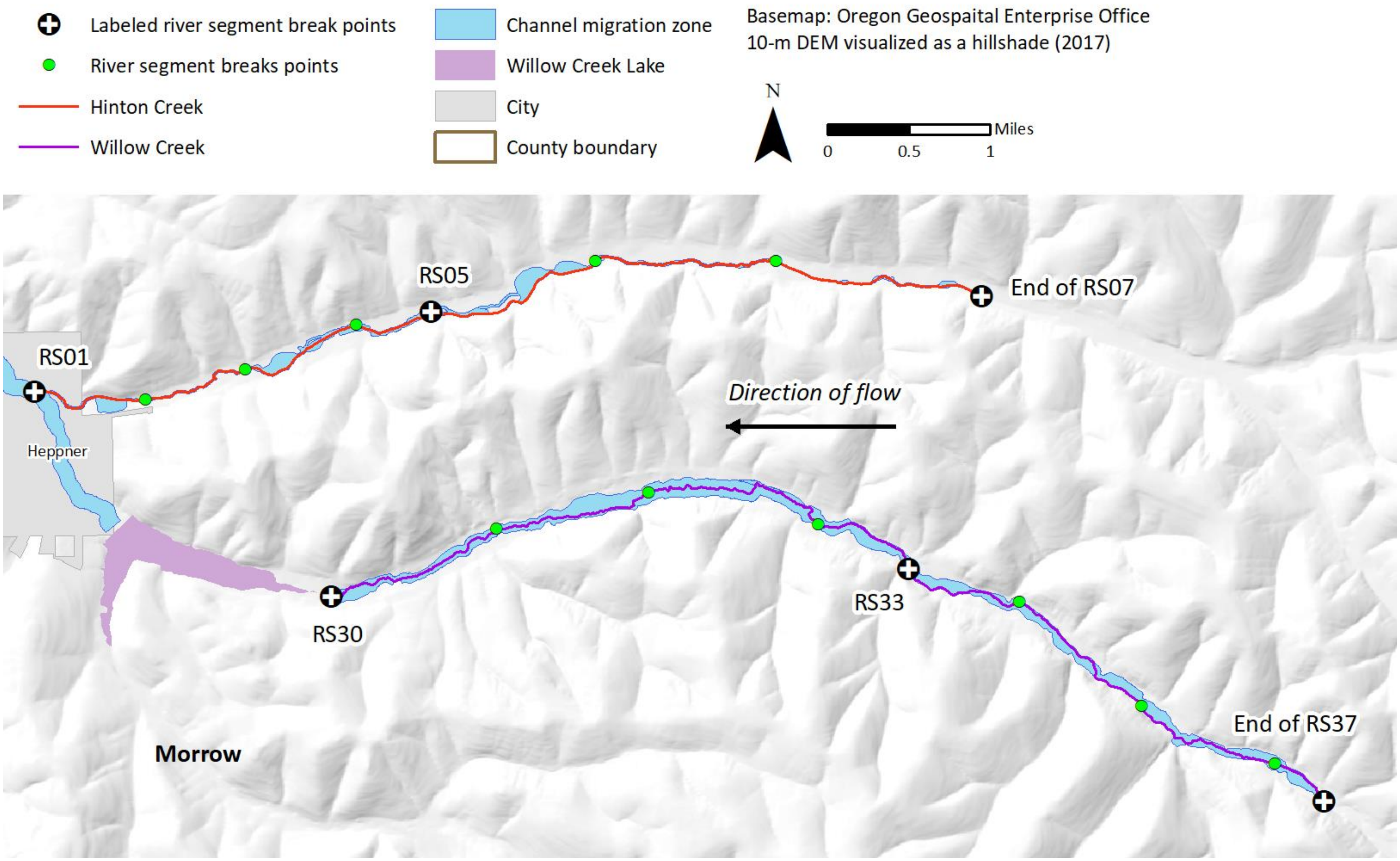
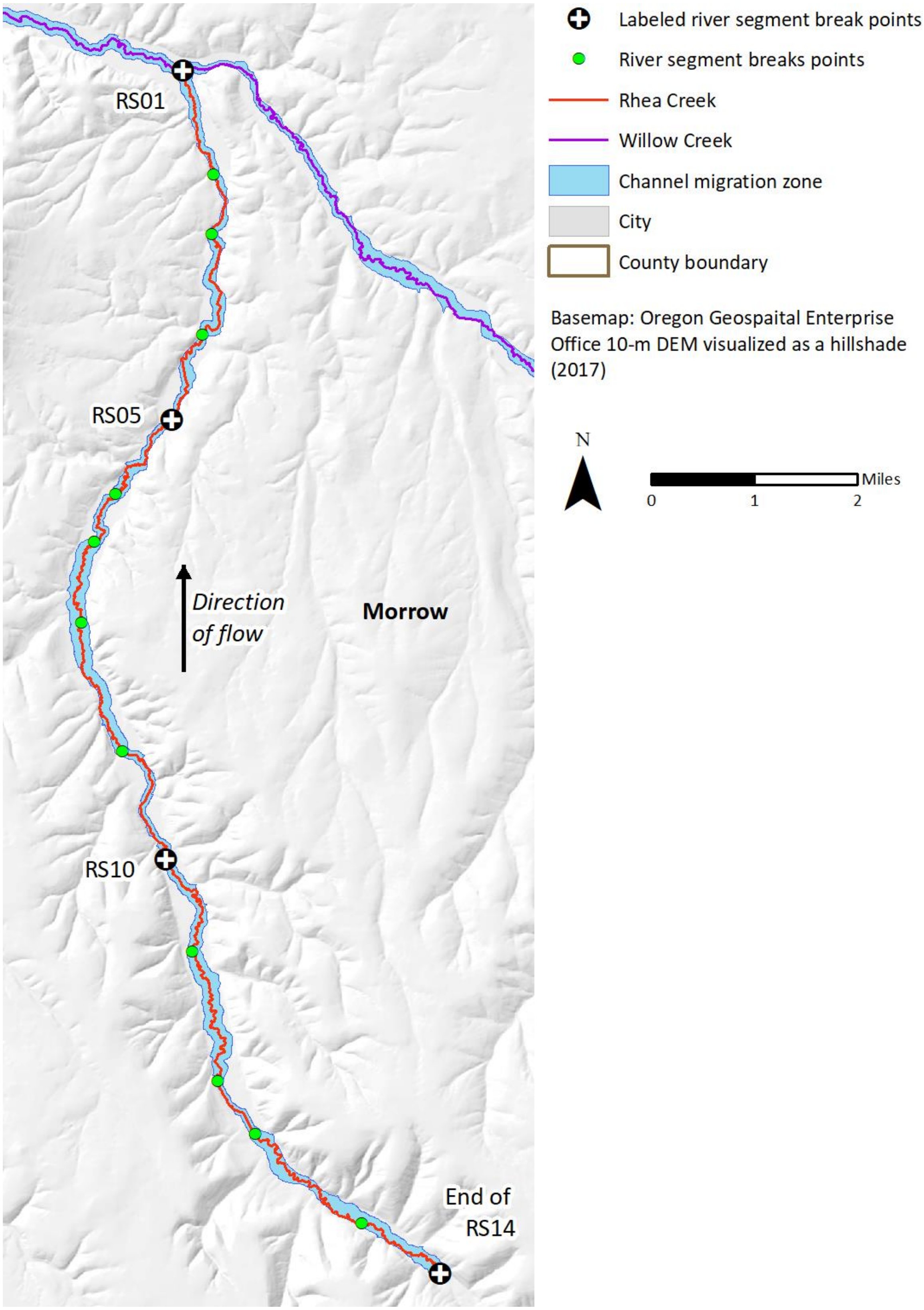


Figure 3-7. Rhea Creek segments, CMZ area, and labeled counties.



3.2.4 Washington County

In Washington County, we mapped CMZ along 225 river miles (**Figure 3-8, Figure 3-9, Figure 3-10, Figure 3-11, Figure 3-12, Figure 3-13,** and **Appendix A** for detailed maps).

- The Tualatin River (RS01-RS42) is a single-thread channel with a very low to low slope. Our mapping indicate that the sinuosity, channel confinement, and amount of past channel migration are highly variable throughout the study area. RS01-RS03 and RS17 are straight channels and RS06, RS08, RS09, RS11, RS18, RS19, RS22, RS27, RS28, and RS30 are highly sinuous. Tualatin River RS31-RS40 are unconfined and RS24-RS30 and RS41-RS42 are partially confined. RS01-RS23 are confined by Missoula flood deposit, bedrock, landslides, and artificial fill. RS01-RS32 are incised into the Missoula flood deposits. Historical aerial imagery shows no or minor channel change in RS01-RS37 and rapid and recent channel change in RS38-RS42. RS36 has been heavily modified by humans. There are small landslide deposits adjacent to the active channel distributed throughout the study area, as well as several large landslides in RS37, RS40, and RS41.
- Beaver Creek (RS01-RS12) is a single-thread channel with highly variable sinuosity, including straight and highly sinuous segments. All segments are characterized with having very low to low slope except RS12 which has a steep slope. RS01-RS04 are unconfined and RS05-RS12 are partially to fully confined by the valley walls composed of bedrock and landslide deposits. RS01-RS10 show no visible channel migration and RS11 and RS12 show minor change.
- Beaverton Creek (RS01-RS11) is a single thread channel in an urbanized area, confined by valley walls composed of Missoula flood deposits, artificial fill and other manmade materials such as bridge abutments. The slope is very low and the sinuosity varies from straight to highly sinuous, becoming generally straighter in the upstream segments. Minor or no change was observed in the historical record between 1950s-2018.
- Dairy Creek (RS01-RS08) is a single-thread channel incised into Holocene floodplain deposits with a very low slope and no observed history of channel migration in the last 65 years. The channel has moderate to very high sinuosity. RS01, RS03, and RS04 flow unconfined and RS02 and RS05-RS08 are partially confined by the valley walls composed of Missoula flood and landslide deposits.
- East Fork Dairy Creek (RS01-RS15) is a predominantly single-thread channel. RS01-RS11 have low slopes and most are moderate to highly sinuous; RS12-RS15 have moderate to steep slopes and are straight or slightly sinuous. Most of the segments are unconfined or only partially confined by the valley walls except RS12-RS15 which are confined by valley walls composed of bedrock and landslide deposits. RS01-RS06 and RS12-RS15 show little to no historical channel migration, but the channels within RS07-RS11 have shown recent channel migration. In RS03-RS08, the main channel is surrounded by natural levees and is perched higher than the valley's lowest point.
- Fanno Creek (RS01-RS14) is a predominantly single-thread channel with a low slope in a highly urbanized area. Although sinuosity varies greatly throughout the segments, most segments are partially or fully confined by valley walls composed of Missoula Flood deposits, artificial fill, and other man-made materials such as bridge abutments. RS07-RS09 and RS12 RS13 have areas where the active channel flows into or adjacent to wetlands and ponds. Most but not all segments have observed historical channel migration occurring between 1950s-1995, but few changes have occurred since 1995. RS06 includes a restoration site characterized by a constructed new meander in the stream channel morphology.
- Gales Creek (RS01-RS20) is a single-thread channel. Except for the highly sinuous RS01-RS03, most segments in this study area are low to moderate sinuosity. The channel is characterized with

predominantly low to moderate slopes, except RS15-RS20 which have moderately steep slopes. RS01-RS11 are unconfined and most show evidence of a history of channel migration. RS12-RS20 are partially or fully confined by the valley walls composed of bedrock and landslide deposits and show no to moderate historical channel migration. RS01-RS05 and RS12-14 are heavily incised with banks located approximately 10-16 ft above the water surface.

- McKay Creek (RS01-RS15) is a predominantly single thread channel with a moderate to high sinuosity. The channel migration has been very limited since the 1950s. The channel slope is very low in RS01-RS13 and quite steep in RS14-RS15. The channel is commonly confined by valley walls composed of Missoula Flood deposits, landslide deposits, artificial fill, and other man-made materials except for RS09-RS12 which is unconfined.
- Rock Creek (RS01-RS26) is predominantly single thread channel with a low slope. Most segments in this study area are moderate to high sinuosity and show little to no channel migration. The channel is most commonly partially or fully confined by valley walls composed of Missoula Flood deposits, bedrock, landslide deposits, artificial fill, and other man-made materials. However, RS11 and RS12 are unconfined, the main channel is surrounded by natural levees is perched higher than the valley's lowest point, and there are ponds and wetlands in the valley bottom.
- West Fork Dairy Creek (RS01-RS21) is a predominantly single thread channel with several multi-thread sections (RS02 and RS03). The lower unconfined reaches (RS01-RS10) and the partially confined reaches (RS11-RS16) have low to moderate slopes and the confined reaches (RS17-21) are steeply sloped. In RS02-RS08, there are drainage ditches constructed in the valley bottom and the channel appears to have been straightened in the past in some areas. In RS02-RS15, the main channel is surrounded by natural levees and is perched higher than the valley's lowest point. Overall, there is very limited channel movement since the 1950s, and much of the channel relocation in the lower segments is likely due to human construction.

Figure 3-8. Tualatin River and Fanno Creek segments and CMZ area.

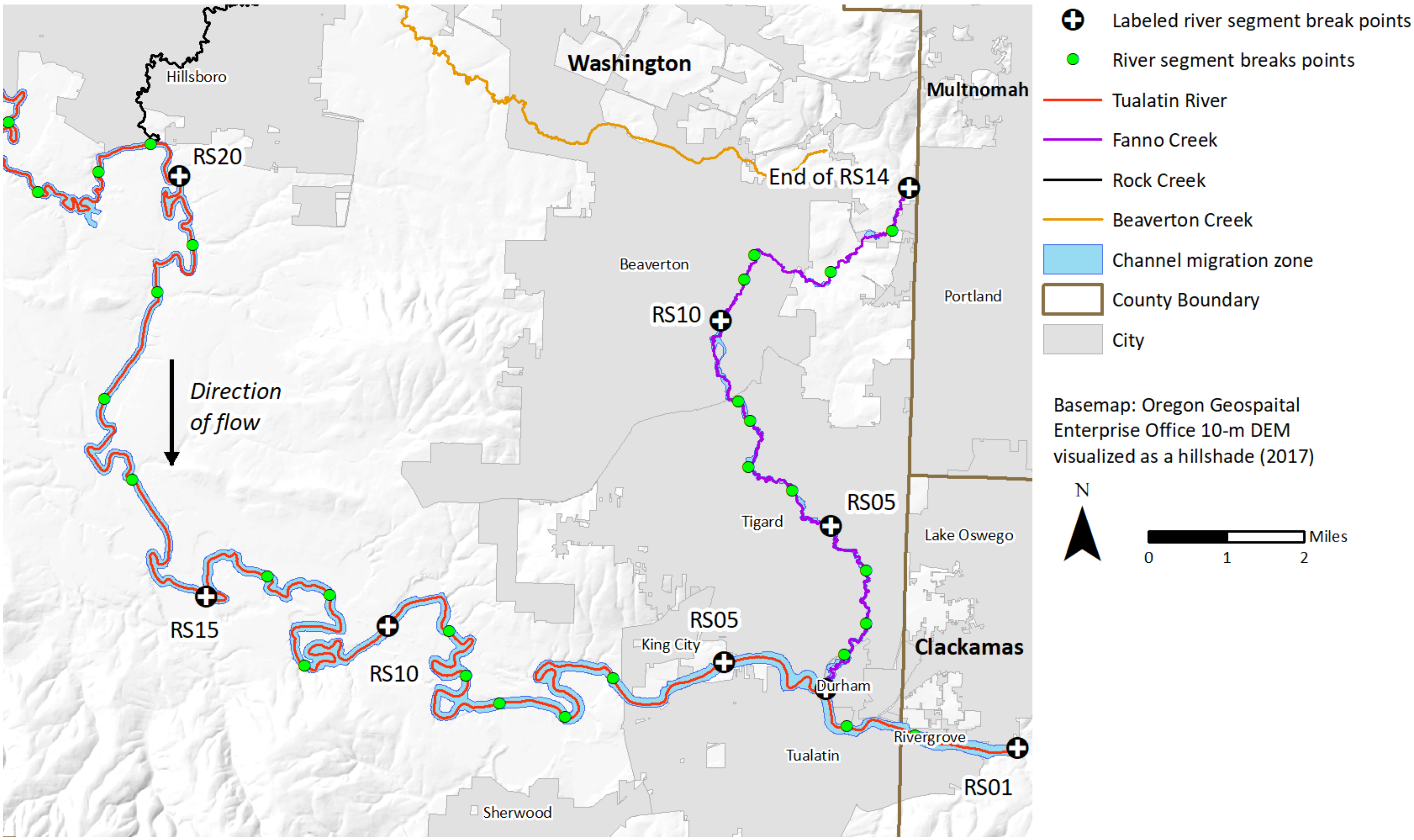


Figure 3-9. Tualatin River segments, CMZ area (including valley-scale AHA polygons appearing as thin blue lines), and labeled counties. The location of the confluence with Gales Creek location is shown in purple; the detailed map of Gales Creek is shown in Figure 3-13.

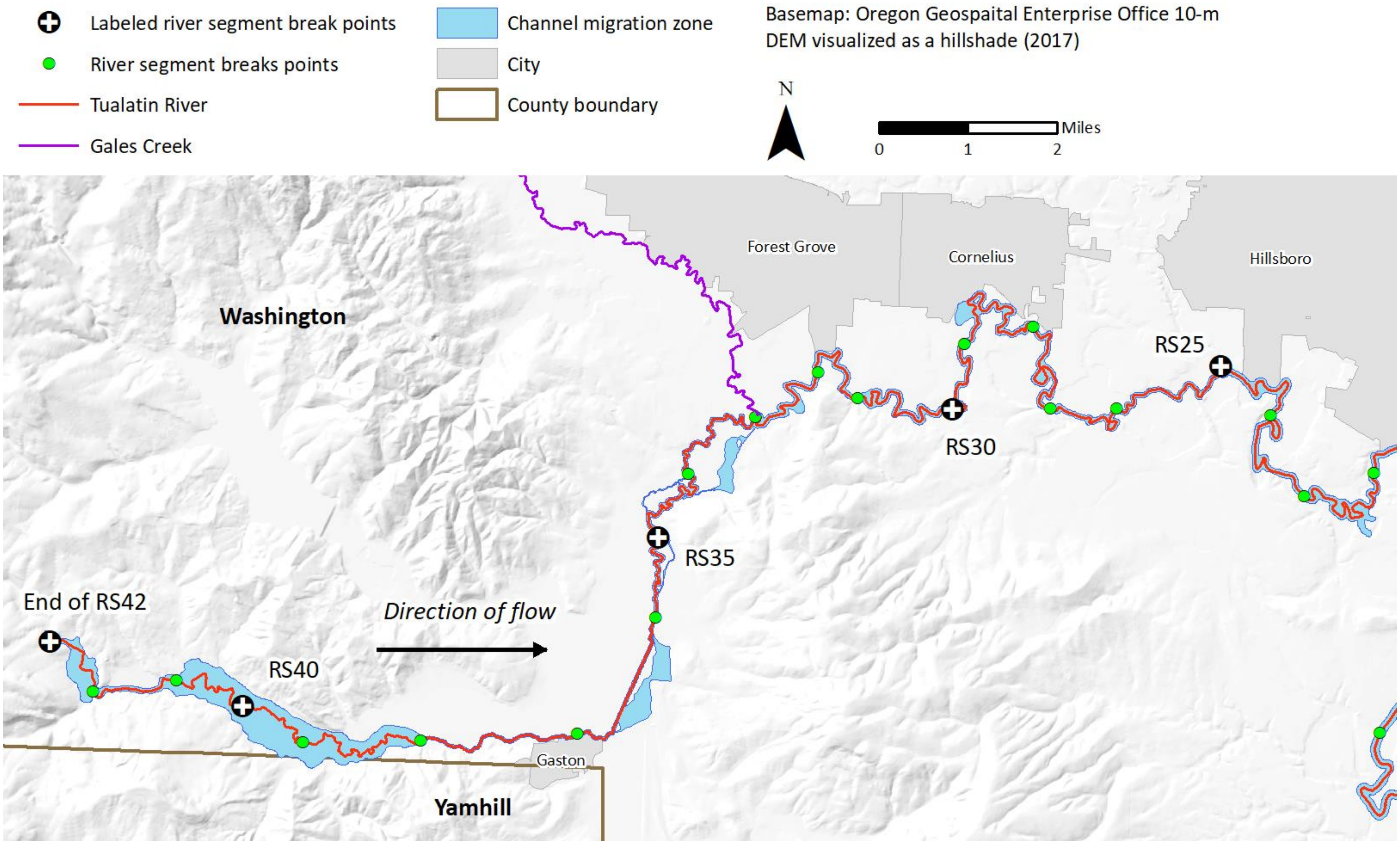


Figure 3-10. Beaverton and Rock Creek segments, CMZ area (including valley-scale AHA polygons appearing as thin blue lines), and labeled counties.

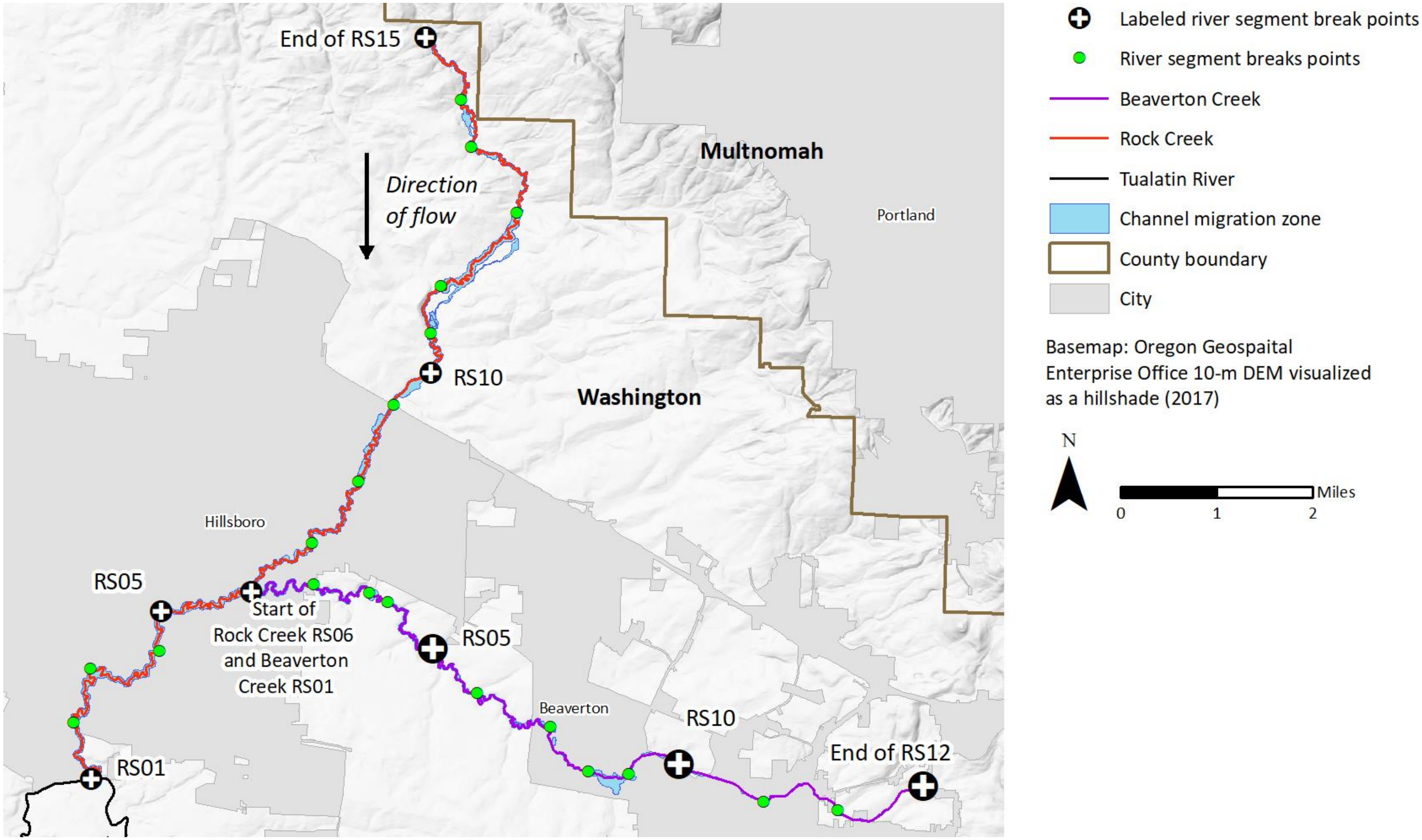


Figure 3-11. McKay, Dairy Creek, CMZ area (including valley-scale AHA polygons appearing as thin blue lines), and labeled counties. The location of the confluence with East Fork Dairy Creek location is shown in red; the detailed map of East Fork Dairy Creek is shown in Figure 3-12.

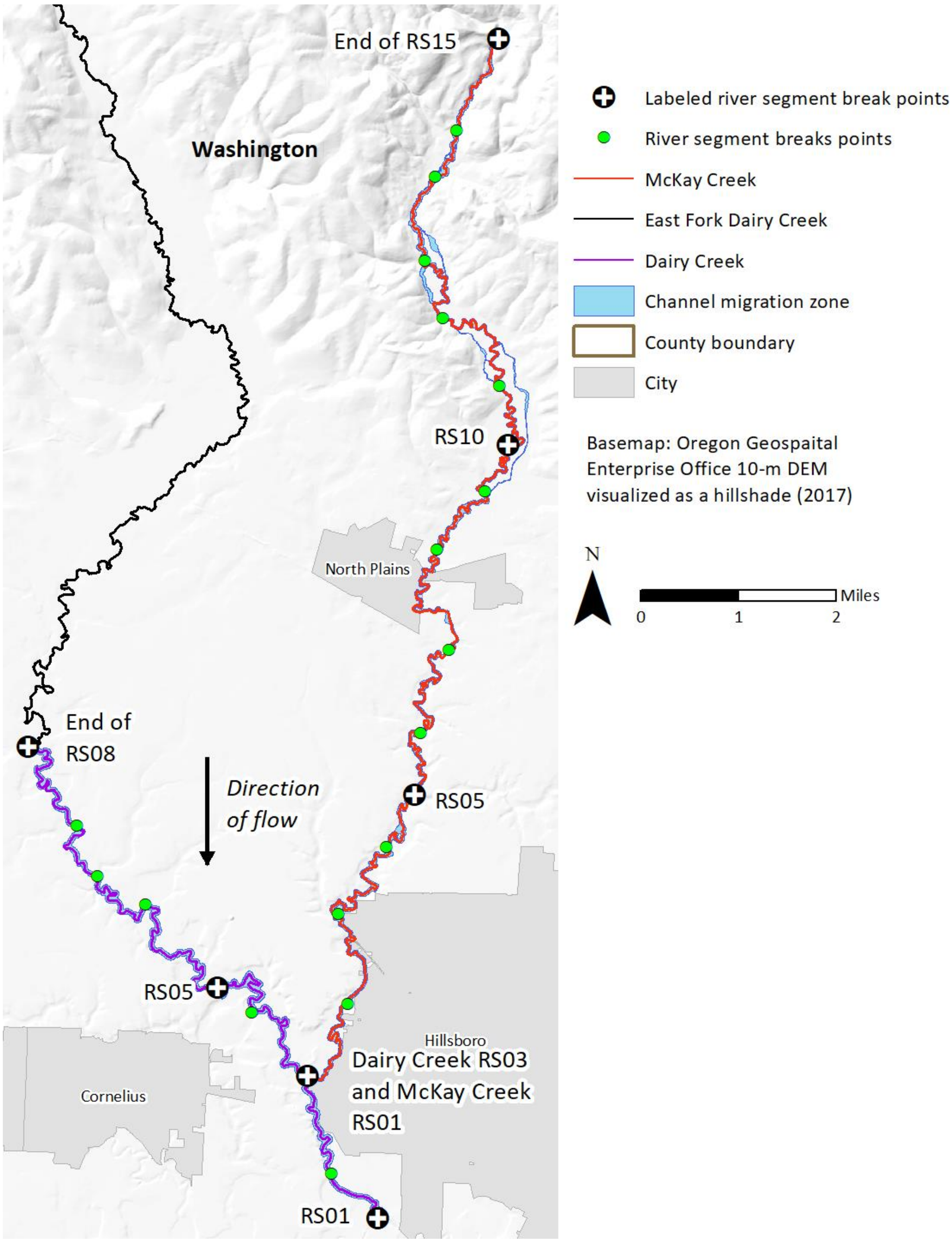


Figure 3-12 East and West Fork Dairy Creek segments, CMZ areas (including valley-scale AHA polygons appearing as thin blue lines), and labeled counties.

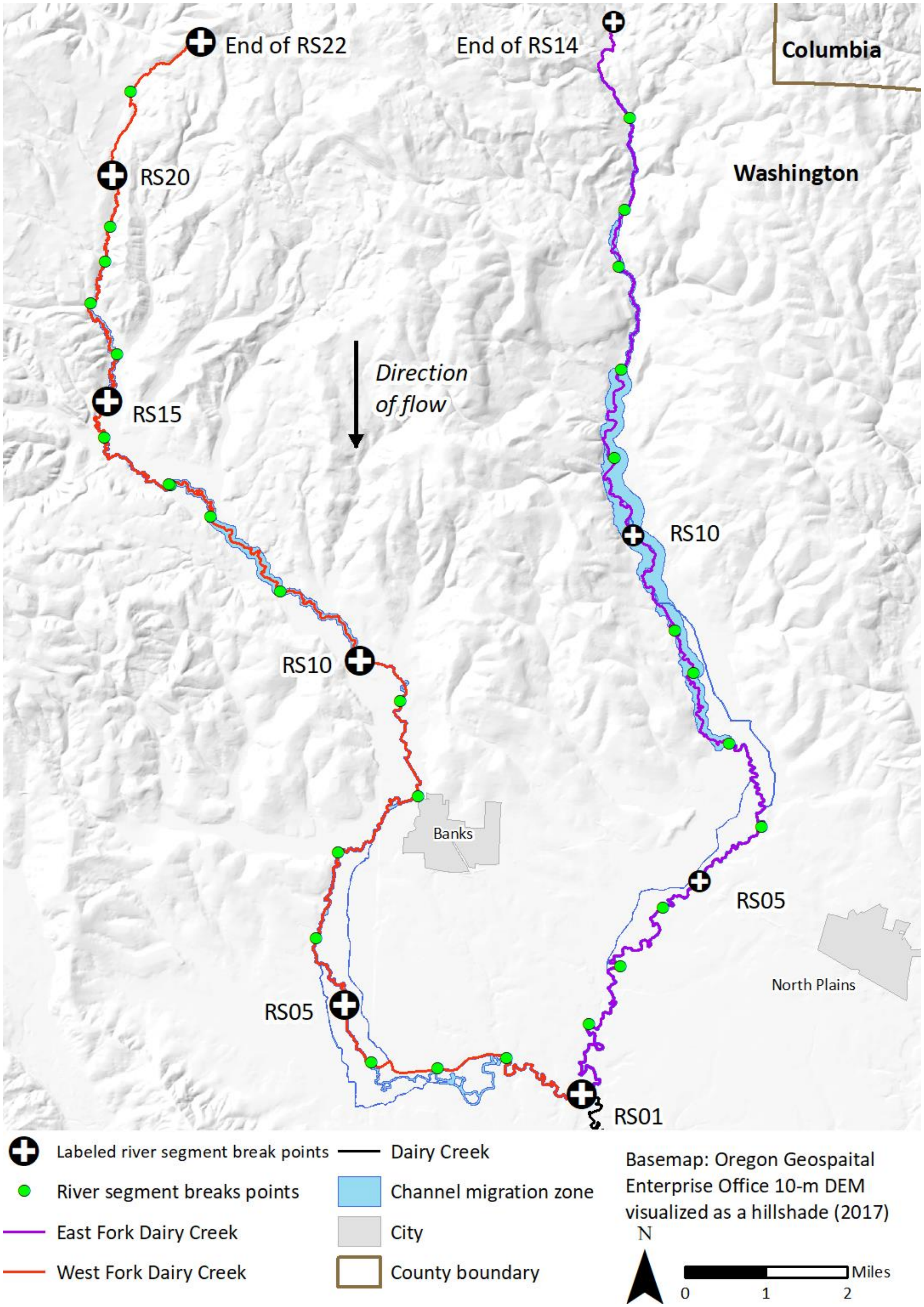
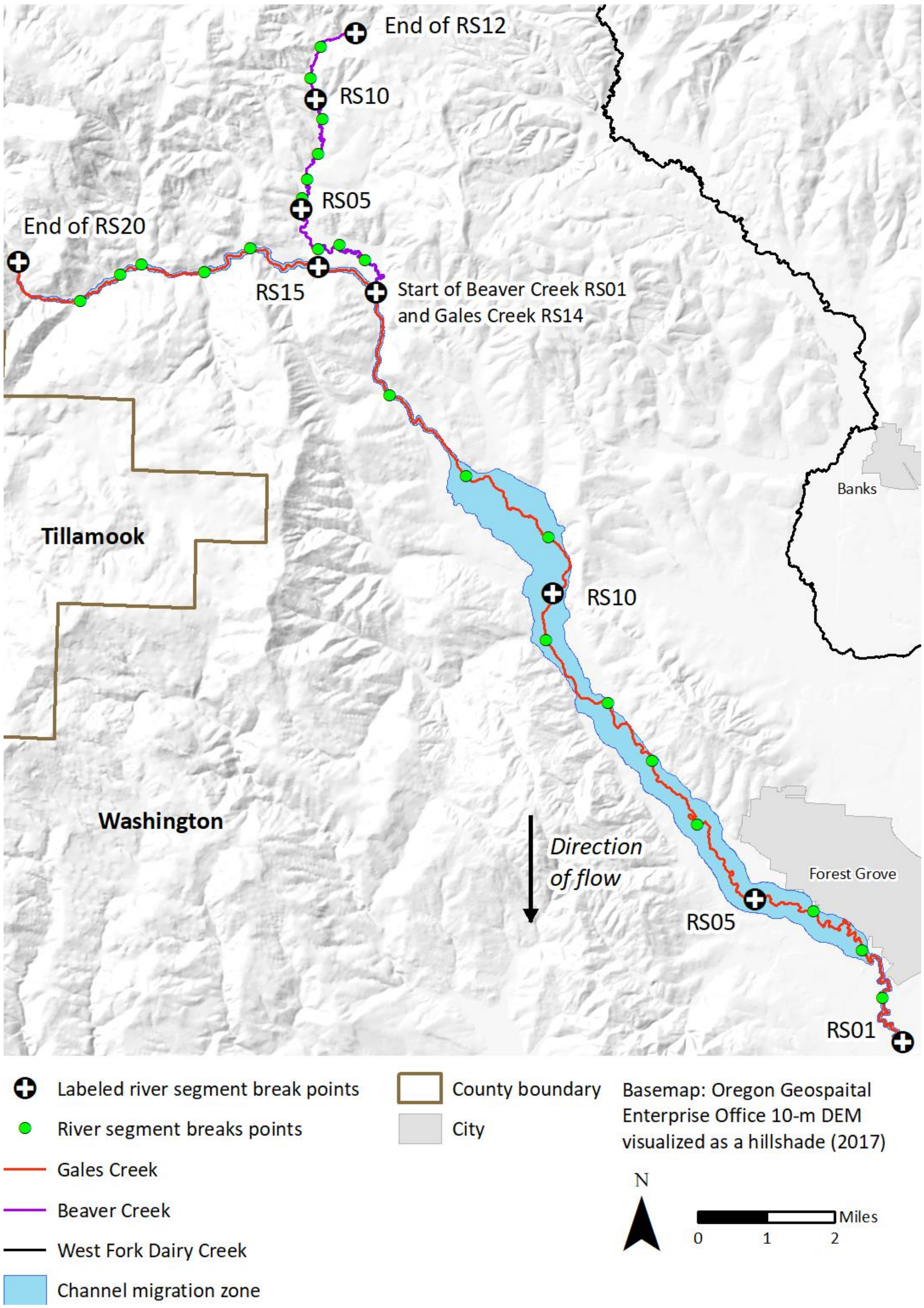


Figure 3-13. **Beaver and Gales Creek segments, CMZ area, and labeled counties.**



4.0 DISCUSSION AND RECOMMENDATIONS

4.1 Applications of Data and Maps

- **Risk Assessments and Risk Reduction**: The flood depth and CMZ maps produced in this study are designed to be used to perform risk assessments, including identification of buildings, critical facilities, infrastructure, and transportation lines that are potentially at risk of flooding. This information can then be used to estimate the potential financial impact of future flooding and channel migration and the number of people who may be at risk or displaced due to these hazards. Furthermore, both maps can be used to perform exposure analyses and Hazus-MH software can be used to estimate economic losses due to building damage based on the flood depth maps. 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.
- **Education and Awareness**: The flood depth and 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 flood insurance.
- **Planning and Decision Making**: The flood depth and 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 Natural Hazard Mitigation Plans and Comprehensive Plans and can also help stakeholders decide where the greatest need for flood map updates exist.
- **Other:** This work can also be applied for uses beyond immediate hazard mitigation. For example, by establishing current channel erosion rates, we will be able to track changes in future erosion rates that may occur because of climate and land use change. The 10-year flood depth maps and CMZ maps are especially useful for identifying areas best suited for riparian habitat conservation and potential ecological restoration. By including CMZ maps in the land use and development planning process, communities will increase their resilience to climate change.

4.2 Limitations of Data and Maps

4.2.1 Flood

- **Study area extent**: Although this study only produced flood depth maps for areas where FEMA FIS exist, flooding can occur in additional areas within each county. Creating maps only in areas with studied streams may give the false impression of a reduced risk in other areas.
- **Changing conditions**: Climatic, hydrologic, and land use changes that have occurred after the FEMA FIS study or will occur in the future will change the extent and depth of flooding. These flood depth maps may not accurately reflect future flood conditions in areas where there has been or will be significant change in climatic conditions, hydrology, and/or land use change. In addition, as we gather more flood data in the future, the statistical models that define the specific discharges associated with a 10-, 50-, 100-, and 500-year flood may need to be updated. As a result, new flood zones and depth maps may need to be established.
- **Topographic data accuracy**: Although FEMA uses detailed, surveyed cross-section information, most off the FEMA FISs used in this study were developed based on low-resolution topographic data

and not based on modern lidar data. As a result, these datasets may be less accurate in their flood depth maps.

- **Cross section interpretation**: Cross sections should ideally be drawn perpendicular to flow. However, there are cases where this is difficult to do, such as areas with wide, complex floodplains and highly sinuous channels. Drawing cross sections in these cases is based on the interpretation of the terrain and may lead to errors in the WSEL raster.

4.2.2 Channel migration

- **Changing future conditions:** Although commonly practiced, using historical patterns to predict future channel migration may be inaccurate if key conditions change. For example, changes in sediment supply, precipitation patterns, or land use, may result in different bank erosion rates than in the past. Climate change, wildfires, human channel modifications, and changes in riparian vegetation, sediment supply, land use, landslides, infrastructure can lead to unprecedented patterns in channel migration. The maps we produced represent predictions based on the last 60 to 70 years of history. As key condition change in the future, these maps are expected to change as the forcing conditions change.
- **Historical observation:** Studies have shown that after construction of many flood control structures between the 1930s-1970s in the Willamette Valley, the Willamette River's channel migration patterns changed significantly (Wallick and others, 2007). To more accurately predict future channel changes, we limited our window of observation to post-flood regulation conditions. For most of our study area, this meant we based our CMZ mapping on aerial photographs that span the period from the 1950s to the present day. During this period, the various rivers can be expected to have changed geomorphically as they adjust to a new equilibrium status in response to changes in the flood-controlled hydrologic regimes. The disadvantage of using a limited, approximately 60-70 year widow of observation is that we may miss long-term trends, the impacts of infrequent storm events, and other natural variability of a river's behavior.
- **Method validation**: Our mapping method, including similar efforts undertaken in Oregon, have not been rigorously validated based on multiple decades of channel migration data. Our aim here was to produce maps that are both reasonable based on current channel conditions and past migration patterns, while leaning towards the higher end of estimating future migration (e.g., applying the highest possible erosion rate for a river segment). In this study, we have not quantified our uncertainty in CMZ mapping, instead having focused on the potential maximum extent of possible bank retreat.
- **Study area extent:** For reasons previously explained, we mapped CMZs for major rivers within each county, but we did not include the Willamette River nor its smaller tributaries. Channel migration along unstudied rivers may impact communities within each county and should be considered for future study.
- **Local conditions and site-specific analysis:** This study does not replace the need for site-specific analyses. For any point along a mapped river segment, there may be local conditions that change the migration pattern at that location such as bedrock outcrops, revetment, or bridge abutments. Without site specific analysis, detailed hydraulic modeling, and geotechnical knowledge of infrastructure, we cannot assume the infrastructure has been designed and constructed in a way to resist erosion and migration stresses. Including infrastructure in CMZ areas serves to highlight the need to construct and potentially maintain these structures to withstand CMZ impacts.

4.3 Recommendations and Future Studies

- **Risk assessments:** As discussed in **Section 4.1**, the flood depth and CMZ maps are designed to be used in risk assessments. Risk assessments that utilize the flood depths and CMZ maps can provide estimates of the costs of building damage due to different flood risk scenarios, as well as in exposure analysis to determine which structures may be at risk from channel migration during the next 30- and 100-years.
- **Update flood depth maps**: As new FIS models and new lidar topographic information are developed, new flood depth maps can be produced. This will be particularly useful in areas where the FIS studies are not originally based on lidar and for streams that were not previously included in a FIS.
- **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 30-years 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 in Oregon. In particular, a multi-county scale Willamette River mapping effort that leverages ongoing work by the U.S. Geological Survey would be particularly useful since there are numerous communities in the Willamette Valley at risk of flooding or potential channel migration.
- **Advancing the CMZ method**: As discussed in **Section 4.2.2**, multi-decadal validation of our CMZ mapping methods is needed, particularly as it relates to quantifying the uncertainty inherent in the mapping approach. Also needed is an established method to quantify ways of assigning risk categories (i.e., low, medium, and high risk) to each of the CMZ components. Of importance, is the need to compare the CMZ method here to newer mapping techniques that are being developed elsewhere, such as those employed by Colorado (Blazewicz and others, 2020).
- **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 wish to answer questions such as:
    - Which river segments and what overall proportion of rivers in Oregon experience channel migration over interannual to interdecadal time periods?
    - 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 likely to have on channel migration and erosion rates in Oregon?

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