MASS WASTING IN THE YAKIMA RIVER CANYON, WASHINGTON:
AN INVENTORY AND HAZARD ASSESSMENT

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ABSTRACT

MASS WASTING IN THE YAKIMA RIVER CANYON, WASHINGTON: AN INVENTORY AND HAZARD ASSESSEMENT

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Mass wasting events pose a significant human hazard to residents, travelers, and recreationalists in the Yakima River Canyon (YRC) of Central Washington. Potential hazardous areas for mass wasting events in the YRC including debris flows, rockfall, and landslides had not been thoroughly investigated prior to this study. I identified, mapped, and classified mass wasting features, produced several mass wasting hazard maps, and provided land management recommendations for the YRC transportation corridor based on findings. Flow, fall, rotational slide, translational slide, and complex slide-flow totaled 225 features cover 22% of the study area. Most flow movements occur in steep-sloped ephemeral and perennial drainages. Areas prone to rockfall consist of areas of very steep slopes and cliff faces; especially near the State Route 821 and the Northern Pacific Railroad where over-steepened slopes have been created during construction of these routes. Rotational slides, translational slides, and complex slide-flows have the highest probability of occurrence near sedimentary interbeds with steep slopes. Shallow translational slides are most prone to steep ephemeral drainages and eastfacing slopes. Development in the Yakima River Canyon should be limited to areas of low or very low hazard areas.

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CHAPTER I

INTRODUCTION

Research Problem

Drylands cover approximately 30% of the Earth’s surface with areas of significant human inhabitance in these regions (Cooke & Warren, 1973). Landscape evolution in dryland regions has been well studied and documented in many aspects (Bierman et al., 2005; Blissenbach, 1964; Canfield, Lopes, & Goodrich, 2001). However, mass wasting in dryland regions is not well understood, especially that which occurs on rock-mantled slopes. Mass wasting is a general term that can be simply defined as “the movement of a mass of rock, debris, or earth down a slope” (Cruden, 1991, p.1). Another definition is “the downslope movement of soil and rock material under the direct influence of gravity” (Bates & Jackson, 1987, p. 314).

The high angle, rock-mantled slopes in Central Washington's Yakima River Canyon (YRC), spanning from Ellensburg to Selah, have the potential for human hazards in the form of debris flows, rockfall, and landslides. For example, a severe thunderstorm passed over the Manastash Ridge east of the YRC dumping more than 3 inches of rain in approximately one hour in 1998 (Kaatz, 2001; Figure 1). This storm initiated several debris flows that covered Canyon Road and fanned out well into the Yakima River. Kaatz (2001) identified the importance of summer thunderstorm events and their relationship to the initiation of debris flows, but the frequency and potential hazardous areas for mass wasting events in the YRC, such as debris flows, rockfall, and landslides, have not been thoroughly investigated.

Figure 1. Debris flows covering State Route 821 from the 1998 thunderstorm event. Photo from Washington State Department of Transportation, South Central Office.

Mass wasting inventory maps have been produced around the world for land use planning purposes. However, less than half of the states in the U.S. have complete, or even partially complete, landslide inventories. With increasing urban growth and sprawl, landslide inventories are of major importance to urban planners, developers, and the residents and travelers in these areas. Inventory maps can be very basic, displaying only the spatial distribution of landslides, common with standard geologic maps. Inventories can also be very complex, which may add many other variables such as state of activity, geology, land uses, hydrologic data, seismic data, and even socio-economic factors of landslide occurrence (Parise, 2001; Wiezoreck, 1984). Other parameters that have been used are slope classes, landforms, and soils (Soeters & van Westen, 1996). Complex inventories often involve many other disciplines and are very time consuming. Nonetheless, even the most basic inventories are useful since many landslides are reactivated from older slide areas (Casagli et al., 2004).

A mass wasting inventory is an important first step to determine causative factors for landslide distribution in any given area. When the causative factors for mass wasting have been identified, this can effectively lead to hazard mapping. Hazard maps are useful tools that can reduce the socio-economic costs and losses of mass wasting. The costs of preventing mass wasting or not developing where mass wasting could potentially occur is less than the cost of correcting mass wasting after an event has occurred (Turner & McGuffy, 1996). Hazard maps and relative slope stability maps have been created in areas of Central Washington that are prone to mass wasting, but no hazard maps have been created for the YRC (Artim & Campbell, 1977; Hays & Schuster, 1987).

Mass wasting can be difficult to manage, but if done correctly it can save much time and effort for maintenance crews. Each time a mass wasting event occurs in the YRC that impacts State Route 821, a maintenance crew is sent out clear the debris (Personal Communication May 05, 2010). Current mitigation measures in the YRC are not completely preventing mass wasting from impacting S. R. 821. Enhancing mass wasting mitigation in the YRC could prevent much of the mass wasting that impacts the highway. This would ultimately reduce the amount of mass wasting related accidents in the YRC and would reduce maintenance costs.

Research Objectives

I investigated mass wasting in the YRC. Specifically, this study consisted of four parts: 1) identifying, mapping, and classifying mass wasting features, and creating a mass wasting inventory; 2) identifying mass wasting control variables; 3) developing mass wasting hazard maps; and 4) developing management recommendations.

Research Significance

Events such as the 1998 debris flows in the YRC pose a significant human hazard. Although no damage occurred to homes during this event, there is potential for more destructive events to occur. Areas of the YRC have similar geologic conditions to the Nile Valley Landslide of the Naches River Valley. Identifying these prone areas could influence land use decisions and produce more rapid and efficient emergency response efforts. Rockfall also poses a major hazard for travelers. To identify where and when rockfall is occurring will lead to more effective mitigation strategies. The production of an inventory map and hazard maps for the YRC will not only lead to effective land use and mitigation strategies, but more efficient emergency alert systems and responses. Since the YRC is a major transportation corridor and recreational area, and is experiencing increased human development, the production of these maps will help mitigate travel and future development incidences.

These processes can also have a significant effect on river systems such as the Yakima River. The debris flow fans from the 1998 event are still identifiable in the river today. The YRC serves as an ideal study area because significant, recent mass wasting events have occurred, and it has high potential for future events. This study will expand the knowledge of mass wasting in basalts and rock mantled slopes and it will benefit land use planners. Since it serves as a major transportation route for recreationalists, travelers, and residents, this mass wasting inventory will provide direction for management action and will help deter future incidents.

The Columbia River Basalt Group (CRBG) has been extensively mapped and researched (Campbell, 1976; Tabor et al., 1982; Reidel, Campbell, Fecht, & Lindsey, 1994). Mass wasting in the CRBG especially, within the more arid regions of the Columbia Basin has been somewhat neglected. Documented mass wasting in these semi-arid regions is mainly in the form of geologic maps, with mass wasting features largely unclassified (Bentley & Powell, 1984; Reidel, 1988; Reidel & Fecht, 1994). Creating a detailed mass wasting inventory for the YRC of Central Washington will identify and provide a better understanding of the types of mass wasting that occur in semi-arid regions of the CRBG.

Mass wasting events in general are common processes in almost any environment containing large elevational differences and steep slopes. By examining arid land geomorphic processes, such as weathering, slope processes, channel processes, and alluvial fan development in semi-arid lands, much can be learned about the significance of mass wasting in these landscapes. Mass wasting events such as debris flows in arid environments have a major influence in arroyo incision and the development of alluvial fans (Blissenbach, 1964). Rockfall produces talus slopes which provide the foundation for the formation of more gentle hillslopes as the talus get filled in with finer sediments. Landslides alter drainage pathways on a hillslope and can drastically alter the flow path of a river or creek.

CHAPTER II

LITERATURE REVIEW

Mass wasting inventories are the first step in creating quantitative and qualitative data to better understand mass wasting. The organization of these data allows planners, developers, and land managers to make informed decisions about major projects such as road building, housing developments, irrigation systems, and forest harvesting. This chapter will provide an introduction to mass wasting inventories and examine different techniques used to mitigate the social and economic impacts of mass wasting.

Identifying, Mapping, and Classifying Mass Wasting

Identifying Mass Wasting

Mass wasting features can be identified by aerial photo interpretation, digital image interpretation, ground survey, and existing databases of historical mass wasting occurrence (Soeters & van Westen, 1996; Wieczoreck, 1984). Features are identified based on three main factors: morphology, vegetation, and drainage (Cruden & Varnes, 1996). Since these variables differ with climate and lithology, the development or manipulation of decision rules are necessary for different geology and climates.

Types of Mass Wasting

Mass wasting can be separated into five major classes with many different subtypes, some of which can fall into multiple categories. For this inventory, the three major classes are flows, falls, and slides. The other type of mass wasting are spreads and topples.

Flows

Flows have been subject to many different types of classification but are generally based on composition and velocity. The most common and widely accepted classification system was developed by Varnes (1978) and revised by Cruden and Varnes (1996) with four common types of flows: debris flows, mudflows, debris avalanches, and earth flows.

Three subtypes of debris flows can be delineated: 1) debris flows caused by the mobilization of shallow landslides that occur on steep slopes (Costa & Fleisher, 1984; Cruden & Varnes, 1996). These types of debris flows are uncommon in mountainous arid environments due to lack of antecedent moisture in the regolith that mobilize a shallow landslide into a flow (Abraham & Parsons, 1994); 2) open-slope debris flows that form their own path down a hillside; and 3) debris flows that occur by surface runoff, entrenching flow paths and creating scoured channels (Larsen, Pederson, & Schmidt, 2006). Coe, Kinner, and Godt (2008) identify the relationship of flows that occur by surface runoff in the semi-arid Chalk Cliffs of Colorado. Regardless of the subtype, debris flows form a flow path and a distinct fan where the final deposition occurs.

A mudflow consists mainly of clay or other fine materials that liquefy. Mudflows are generally a rapid form of mass movement, but can range in velocity depending on the slope, clay content, and amount of moisture. Mudflows also form fan deposits, but are usually much thinner and wider due to the nature of the material being deposited (Cruden & Varnes, 1996).

Debris avalanches are a very rapid form of mass movement. These flows are a type of open-slope flows, typical on steep slopes with shallow soils underlying bedrock. Debris avalanches are generally composed of coarse-grained materials consisting of large rocks, earth, and debris. These form hummocky, debris-filled deposits with a flow-like appearance (Cruden & Varnes, 1996).

Earth flows are the fourth type of flows which contain less moisture and are composed of mostly fine-grained soil. These are set apart from debris flows and mud flows because they lack internal deformation, which occur mainly on the sides of the earth flow (Cruden & Varnes, 1996). Earth flows are rare in semi-arid to arid environments due to shallow regolith (Abraham & Parsons, 1994).

Cluer (1987) proposed a fifth type of flow termed a leveed boulder flow which occurs in basalt-capped arid lands. These differ from previously classified flows because they contain little or no fine-grained sediments. Velocities of leveed boulder flows can range from slow to rapid, and can resemble fluid-like flows, slumps, or block-like structures with distinctive shear planes. The 1998 debris flows of the YRC resemble these flows, containing mostly large rocks and boulders with little or no fine grained materials (Kaatz, 2001). It is debatable whether or not these flows are truly devoid of fine material or that the fines are just flushed out during late stage surges of water.

Rockfall

Rockfall is a significant form of mass wasting. Rockfall is significant because it is one of the most common and frequent forms of mass wasting. These are very rapid events that can be very large or as small as a single rock falling. Talus is the landform associated with these events. These deposits consist of unsorted angular rock forming slopes of approximately 45 degrees (Cruden & Varnes, 1996). Dry raveling, a subtype of rockfall is a term used for sediment transport of rock in semi-arid to arid environment (Gabet, 2003). Transport mechanisms include falling, bouncing, rolling, and sliding. This process is known to be a dominant sediment transport process in steep-sloped, semi-arid to arid lands (Gabet, 2003). Rockfall is a frequent process in the incised, basaltic canyons of Central Washington. A study by the WSDOT (2007) attributed rockfall in Central Washington to adversely jointed columns in the basaltic cliffs due to faulting and folding. Unpublished WSDOT data from the South-central Office, in Union Gap has identified 54 unstable slopes in the YRC. These slopes were rated for hazards based on the Rockfall Hazard Rating System developed by Pierson (1991). Parameters used for determining the hazard include; material, average daily traffic, posted speed limit, rate of rockfall, and several others.

Slides

A slide is a downslope movement of soil or rock mass on a distinct shear plane (Cruden & Varnes, 1996). Slides are classified by type of movement: rotational slides, translational slides, and complex slide-flows.

A rotational slide or “slump” happens when shearing takes place on a well-defined, concave-upwards surface producing a backward rotation in the displaced mass (Cruden & Varnes, 1996). The head of slide can move almost vertically downwards producing a nearly vertical scarp face. The body of the displaced mass often produces a hummocky topography with lakes, wetlands or a depression at the base (Lillquist, 2001).

Rotational slides can occur at very slow rate of inches per year or can happen rapidly, on the order of meters per second. Rotational slides are common within the Pacific Northwest's Columbia Basin where the geology is dominated by the Columbia River Basalt Group (CRBG) (Reidel, 1988). Safran, Anderson, Mill-Novoa, House, and Ely (2011) mapped many large rotational slides in geologically and climatically similar areas of central Oregon. These slides were attributed to weak sedimentary and volcanoclastic layers underlying coherent rock including the CRBG.

A translational slide, also called a rock or earth slide, is the most common of sliding phenomena. Such slides occur on planar shear planes and tend to produce linear, narrow scarp faces at the upward extent of slides. Translational slides often occur on planar slopes and tend to be shallower than rotational slides. During movement these slides can become wedged at the toe which leads to folding of the body beyond the toe of the slide (Cruden & Varnes, 1996). Deposits of the body often create hummocky topography but with longer runout zones. Translational slides can occur at very slow rate of inches per year or can happen rapidly, on the order of meters per second. These slides have been mapped in several areas of central Washington including the Saddle Mountains and the Rattle Snake Hills (Reidel, 1988).

Complex slide-flows are a type of mass movement that exhibit more than one type of movement, usually a slide with a flow at the end of the toe. This generally occurs when the slide block is composed of weak or loose materials that disintegrate or liquefy while sliding occurs (Cruden & Varnes, 1996). These are most common as rotational slides with a flow at the end of the toe. These movements are usually rapid to very rapid, which are consistent with flows. Lillquist (2001) identified, mapped, and classified many these features in the nearby Swauk Watershed along the CRBG margin of Central Washington.

Spreads

Spreads are a less common type of mass wasting. Unlike slides, flows, and falls spreads occur on more gentle slopes and are associated with soft sediments such as clay or wet sand. Geomorphic conditions for spreading usually include a fractured, cohesive layer overlying softer sediments that are prone to liquefaction (Cruden & Varnes, 1996).

Topples

A topple is the forward rotation of a mass on a slope. This process can range from slow to rapid. Topples can result in a fall or a slide depending of shape on the slope from where the disrupted surface occurred. Columar-jointed volcanic rocks often are subject to this process, which is characteristic of the CRBG (Cruden & Varnes, 1996).

Mapping Mass Wasting

Mapping mass wasting usually leads to the creation of a mass wasting inventory. These inventories can vary in scale ranging from small-scale (1:100,000 to 1:1,500,000) to large-scale (1:5,000 to 1:15,000) (Soeters & van Westen, 1996). Historically, mass wasting inventories were created and stored as hand-drawn maps by the geomorphologist conducting the inventory, but advances in technology such as the development of geographical information systems (GIS) have allowed these data to be mapped and stored digitally. Bentley and Powell (1984) produced hand drawn, unpublished maps for the majority of the geology in the YRC. The southern end was mapped by (Bentley, Campbell, & Powell, 1993). These maps included some of the large, distinct mass wasting features in the canyon, but were coarsely mapped and mass wasting features were not classified in any way. A small scale map of the East Half of the Yakima Quadrangle has also been produced at the 1:100,000 scale which is a compilation of the two geologic maps that were made for the YRC (Bentley & Powell, 1984; Bentley, Powell, & Campbell, 1993; Schuster, 1994). No detailed mass wasting inventory has been done for the YRC.

Mass Wasting Activity

Mass wasting events are typically further classified within inventories. This includes all identified mass wasting features with attribute information including state of activity, certainty of identification, depth (shallow or deep-seated), and known dates of activity (Wieczoreck, 1984). The most common classification scheme for state of activity is either active or inactive (Cruden & Varnes, 1996; Wieczoreck, 1984). Inactive landslides can be classified by morphology with indicators such as scarp weathering, vegetation growth, and drainage development (Cruden & Varnes, 1996; Flageollet, 1996; Lillquist, 2001; McCalpin, 1984).

Mass wasting events and features are classified by depth. All types of mass wasting can be classified as deep-seated or shallow. In the case of slides, the majority of shallow events are translational (Cruden & Varnes, 1996). Shallow events occur within the rooting depth of trees and vegetation, occurring in rock, soil, or regolith (Cruden & Varnes, 1996). Deep-seated mass wasting is often tens of meters in thickness and typically located below the maximum rooting depth of trees and other vegetation. Deep-seated slides are generally rare in arid to semi-arid environments due to shallowness and general aridity of the regolith, but can occur in areas with ground water seepage (Abraham & Parsons, 1994).

Mass wasting events are also classified by material in which they occur. The two main material types for classification are rock and soil. Soil can be further classified into earth and debris, which is dependent on grain size. Materials are considered to be earth if 80% of the grains are less than 2 mm and debris consisting of materials in which 80% of the materials are greater than 2 mm (Cruden & Varnes, 1996). This classification can become confusing with flows. A fine-grained debris flow or a mud flow consists of earth materials, but is different from an earth flow as described above. The term mud flow is used when 50% or more of the material is 2 mm or less, making these flows much more viscous (Cruden & Varnes, 1996). It is necessary to use different names so that these two different forms of mass wasting can be distinguished more accurately, since they vary greatly in composition, internal deformation, and velocity (Cruden & Varnes, 1996).

Mass Wasting Control Variables

Overview

Mass wasting events are generally initiated by the crossing of a threshold. This occurs when the shear stress on the material exceeds the material’s shear strength. Shear strength is a material’s ability to withstand a certain amount of stress without failure. Shear stress is a force applied to an area. Threshold conditions can be met in several different fashions. Independent of which event caused the threshold to be crossed is the saturation of the soil or regolith, increased pore pressure, and overland flow (Lee et al., 1997). Increased pore pressure decreases the shear strength of the substrate while increasing the shear stress by adding water weight to the area or landmass, while the overland flow has much higher velocity than interflow (Lee et al., 1997). Interflow is the lateral and vertical movement of water through a substrate such as soil or regolith. This allows for the mobilization of overlying sediments, which increases the viscosity of the flow. Increased sediment to water ratio adds more friction between the two surfaces, thus increasing shear stress.

Geologic Factors

Mass wasting features vary spatially depending on geology, slope angle (degrees), slope convexity, slope aspect, and slope elevation (Weizoreck, 1996). Geology or incompetent geologic units are likely the most dominant controlling factor of mass wasting (Soeters & van Westen, 1996). Incompetent units include weathered materials, weak interbeds, and soft materials (Soeters & van Westen, 1996). Factors such as jointing and fracturing of rock are important for mass wasting processes. This is especially true if the jointing is parallel to the strike of the hillslope (Lee, Odum, & Lee, 1997). After water flows into rock fractures, it freezes, expands and opens the fractures further. This action is repeated until the rock is dislodged from the rock face and falls. A study by Norikazu and Sakai (1999) found that maximum rockfall activity occurs on average about 10 days after the snow melts out of a steep rock face. This is due to the presence of water in the rock and spring freeze/thaw conditions.

Slope angle is a major contributing factor for mass wasting. With every degree a slope increases, the shear stress increases (Lee et al., 1997; Soeters & van Westen, 1996). Slope convexity can increase stability convex slopes have higher shear stress due to the weight of the unsupported slope (Jimenez-Peralvarez et al., 2009). Convex slopes are susceptible to instability since they accumulate surface runoff (Baeza & Corominas, 2001). Slope aspect can play an important role for mass wasting, especially in mountainous regions. North-facing slopes hold moisture longer and have higher rates of weathering (Jimenez-Peralvarez et al., 2009). This can lead to increased pore pressures and weakened materials which reduce stability of the slope. Slope elevation or altitude is an indirect case for mass wasting, but still potentially significant. Areas of large elevation differences can have differences in precipitation, freeze/thaw cycles, soil development, and vegetation (Jimenez-Peralvarez et al., 2009).

Slopes in arid lands can be classified into three distinct types with different types of mass wasting pertaining to each type. These are gravity-controlled slopes (fall face), debris-covered slopes (foot slope), and wash-controlled slopes (toe slopes) (Cooke et al. 1993; Mabbutt, 1977). Gravity-controlled slopes are characterized by steep slopes typically greater than 45 degrees, but normally over 65 degrees. These can also consist of rock outcrops where rockslides and falls are the dominant erosional processes. Debris-covered slopes are gentler slopes ranging from 20-45 degrees, and are often an accumulation zone consisting of thin debris mantles deposited by the gravity controlled slopes (Cooke et al., 1993; Mabbutt, 1977). Landslides and debris flows are the dominant form of mass wasting on debris-covered, foot slopes. Wash controlled, toe slopes are runoff dominated slopes fewer than 20 degrees in slope that may result in a variety of deposits from fine-grained to very coarse-grained depending on the intensity of the energies of the environment and available sediment transport (Cooke et al., 1993; Mabbutt, 1977). Wash-controlled slopes provide a depositional area for landslides and debris flows. The Yakima Canyon is a classic example of these arid slopes with different mass wasting characteristics pertaining to each slope type.

Erosional processes are often linked to landslide occurrence. Fluvial undercutting destabilizes slopes by increasing slope angle and removing materials that increase the weight on the slope (Cruden & Varnes, 1996). Flooding with subsequent water level decrease also provides conditions for landsliding (Cruden & Varnes, 1996). High water not only increases erosional processes, but also saturates materials below and directly above the flood line. The result is increased pore pressures from high water levels that cause increased shear stress and decreased shear strength which leads to slope instability (Wieczoreck, 1996). The deposition and concentration of loose debris in shallow hillslope gullies and chutes are also known for instability. These are known as inner gorges and colluvial bedrock hollows (Slaughter, 2009). Inner gorges are geomorphic features found adjacent to stream channels. These are formed by fluvial erosion and shallow landsliding. These features contain slope angles typically over 30 degrees ("Factors Affecting Landslides," 1999). Colluvial bedrock hollows are generally well-vegetated, shallow soils above bedrock. These are generally where water accumulates, such as the head of drainages ("Factors Affecting Landslides," 1999).

Climate and Weather Events

Climate and its relationship to moisture is one of the most important factors for mass wasting. Wetter climates generate higher frequencies of mass wasting. Although wetter climates can have high frequencies of events, mass wasting events can be attributed to weather events in arid to semi-arid lands. Wieczorek, Lips, and Ellen (1989) stated that the majority of historical debris flows in Utah's Wasatch Range were initiated by intense rainfall events, but the debris flows of 1983 and 1984 were initiated by rapid snowmelts on partially detached landslides. Summer thunderstorms are perhaps one of the most important triggers in the initiation of mass wasting events in arid lands. Cluer (1987) described a mass movement called a leveed boulder flow that occurs in the basalt-capped slopes of the Sonoran Desert in Arizona. These flows were found to be initiated by intense summer thunderstorms that are capable of transporting large boulders. Kaatz (2001) also highlighted the importance of summer thunderstorms in relation to the initiation of debris flows in the semi-arid YRC of central Washington.

Earthquakes

Earthquakes have historically been known to produce mass wasting events throughout the world (Wiezoreck, 1996). Seismic shaking can trigger large failures in rock and cause liquefaction of soils and sediments producing large slides and flows. From 1872 to 1980, fourteen earthquakes have been documented as mass wasting triggering events in Washington. A group of researchers suggest that the Ribbon Cliffs rockslide and several other events in North-central Washington were triggered by the 1872 earthquake, the largest known earthquake in the history of Washington ("1872 North Cascades," 1976).

Land Use

Land use has the potential to increase mass wasting hazards. Forestry and logging practices have been well known to increase mass wasting, but other uses can increase mass wasting susceptibility directly and indirectly. The construction of roads and railroads can create instability. For example, a landslide occurred during the construction of I-205 in Northern Oregon. The excavation of the hillslope exposed the Vantage Member interbedded in the Columbia River Basalts, which allowed the mass to slide ("Slope Stability Evaluation," 2010). Roadcuts also create over-steepened slopes that are prone to rockfall (Wyllie & Norrish, 1996). Roads that have been cut through old landslides can permit reactivations due to increased stress on materials above the cut. Railroads and highways also bring an increased frequency of wildfires due to vegetation loss and the creation of hydrophobic soils. This increases the frequency of mass wasting, especially soon after the fire occurs (Turner, 1996).

Hazard Mapping

Mass wasting- human interactions have occurred throughout time. Mass wasting events have been documented for centuries in Europe and Asia. The earliest useful descriptions of landslide investigations do not occur until after the beginning of the Industrial Revolution (Turner & Jayaprakash, 1996). Since then, recording and analyzing mass wasting events has become of great importance with ever-growing populations and the expansion of development into marginal areas for mass wasting. Many countries now keep records of these events along with detailed inventories to reduce the socio-economic impact of mass wasting (Schuster & Kochelman, 1996).

Many techniques of landslide hazard zoning have been created and implemented for land use planning. Four main groups of zoning techniques overlie several different subtypes of zoning. The use of each technique varies with scale, available data, and preference of the mapper. These techniques are the landslide inventory approach, heuristic approach, deterministic approach, and statistical approach (Soeters & van Westen, 1996).

Landslide Inventory Approach

The landslide inventory is the most basic form of landslide hazard mapping. This type of method involves aerial photographic interpretation, ground survey, and database development of historical mass wasting events that have occurred in the area. The inventory alone serves as a preliminary hazard map showing the spatial distribution of landslides and their relationship to factors such as slope, lithology, and landuse. A landslide inventory also serves as a baseline for most other landslide hazard mapping techniques. Casagli et al. (2004) used the inventory-based approach to determine landslide susceptibility by using multi-scale aerial photographs and field survey to identify potential landslide areas. Hays and Schuster (1987) applied this technique in the Ringold Formation along the Columbia River in Central Washington, identifying hazardous areas based on past landslides. The basic landslide inventory is limited because it does not assess temporal changes in landslide activity (Soeters & van Westen, 1996).

Landslide inventories can become more informative by creating landslide activity and density maps. Landslide activity maps are created by using multitemporal aerial photographic interpretation. These maps are essential for analyzing temporal changes in mass wasting frequency for factors such as land use. Landslide density maps can also be used to illustrate landslide distribution, usually in the form of isopleths or the formation of terrain units (Soeters & van Westen, 1996). One shortfall of these maps is that they do not assist in explaining control variables associated with mass wasting (Soeters & van Westen, 1996). These maps are best suited for small-scale inventories and will not be used in the analysis of the YRC.

Heuristic Approach

The heuristic approach to landslide hazard zoning relies on the expert opinion of the mapping geomorphologist. This technique is becoming a common approach for landslide hazard mapping in the literature (Castenllanos & van Westen, 2008; Ruff & Czurda, 2008). The heuristic approach can be further classified into two similar approaches: geomorphic analysis and qualitative map combination. Geomorphic analysis is a site-specific, field-intense survey in the area of interest. The mapping geomorphologist essentially maps the hazards in the field. This technique has questionable reproducibility with decision rules being difficult to develop due to site specific conditions that result in a certain hazard rating (Soeters & van Westen, 1996). Artim and Campbell (1977) used a method similar to this in the hills surrounding

Yakima, in central Washington by combining slope classes with lithology to produce a relative slope stability map. A qualitative map combination also relies on the expertise of the mapping geomorphologist. With this technique, the geomorphologist assigns weighted values to classify the hazard areas. Parameters are grouped into all possible combinations and the weighted values of each parameter are totaled, which are then grouped into appropriate hazard classes. The problem with this method is subjectivity of weighting values, which can lead to skewed results (Praise, 2001; Soeters & van Westen, 1996).

Deterministic Approach

The deterministic approach uses quantitative, mathematical models to delineate landslide hazards. These models are usually a combination of slope stability and groundwater models. The infinite slope model is one of the more common deterministic approaches used and was developed by Ward, Ruh-Ming, and Simmons (1982). These models are generally only applicable for geologically homogenous areas and can easily be oversimplified.

Statistical Approach

The statistical approach uses combinations of factors associated with landslide occurrence to assess the landslide hazard. This approach to landslide hazard zonation is data driven and therefore much more objective than other practices such as the qualitative map combination and geomorphic analysis. This approach can apply either bivariate or multivariate statistics to analyze hazard zoning. The bivariate method essentially combines a landslide distribution map to the appropriate causative factors (slope, aspect, and lithology) and weights them according to the landslide densities that are calculated for each parameter class. This method was first developed by Carrara (1983) by combining landslide densities of a slope map and geologic map together. GIS-based methods are becoming very common for bivariate methods in landslide hazard mapping (Iragaray et al., 2007; van Westen, 2001). The GIS matrix method (GMM), a type of bivariate statistical analysis takes the most important causative factors and intersects every combination of causative factors and crosses these combinations with a landslide distribution map to form a matrix (Iragaray et al., 2007; Jimenez-Peralvarez et al., 2009). The combination of factors that have produced landslides in the past are identified in other areas that do not presently have landslides. This method is different from other bivariate methods because causative factors are weighted within the GMM than by landslide density.

Multivariate statistical analysis involves sample relevant factors on a large grid basis or by morphometric units (Soeters & van Westen, 1996). With these data, a matrix is formed and combined with landslide distribution to identify attributes of landslide distribution such as slope angle, lithology, and slope aspect which is similar to bivariate methods, but is analyzed by multiple regression or discriminant analysis to determine the significant causative factors. These types of analysis are best implemented for homogenous areas or areas with few causative factors (Soeters & van Westen 1996).

Landslide hazard zoning can be very complex and time consuming, often resulting in adverse cost-benefit ratios. More simplistic descriptive statistics and GIS models, especially with the implementation of LiDAR can be just as useful in landslide hazard zonation as complex statistical analysis. The Washington Department of Natural Resources implements such techniques. A method developed by Slaughter (2009) applies 2 m resolution LiDAR for detecting potential initiation points of shallow landslides. These initiation points are landforms known as bedrock hollows and inner gorges. These terms are not typical geomorphic terms, but were developed for the field of resource management, primarily for timber harvesting, road construction, and other land development. The Washington Department of Natural Resources is currently applying these methods the ongoing Landslide Hazard Zonation Project for the state.

Mass Wasting and Resource Management

Mass wasting is an under-recognized geologic hazard in terms of socio-economic cost (Schuster, 1996). The 2009 Nile Valley Landslide of the Naches River Valley of South-central Washington is a perfect example of this with the costs associated with the slide potentially totaling up to $50 million in highway costs alone (WSDOT, 2010). Although no lives were lost in this incident, many homes were destroyed along with a quarter-mile section of Washington’s Highway 410. Much of the public view these processes as very rare events that happen in sparsely populated, mountainous areas. This leaves government agencies, Indian tribes, and interested non-govermental organizations responsible for developing guidelines and maps for local governments and land use planners in order to reduce the socio-economic losses due to mass wasting.

Preventing Mass Wasting

Reducing the effects of mass wasting can be achieved by prevention and mitigation. Prevention of mass wasting in planning involves correct design of infrastructure such as roads, railroads, and other land uses such as mining or forestry. The problem with prevention is that much of this infrastructure was developed before proper prevention techniques could be established (Schuster & Kochelman, 1996).

Land Use Planning in Washington

The need for mass wasting assessment in mountainous terrain, forested slopes, and coastlines in Washington is a necessity for land use planning. Prior to 1959, no planning or zoning laws were in place in the state of Washington. The initial act to enable zoning ordinances could still not compete with Washington's rapid growth in the 1980's which resulted in poorly controlled sprawl (Brunengo, 1994). Washington's Growth Management Act of 1990 includes planning measures to reduce the socio-economic impacts of mass wasting. The Growth Management Act requires a comprehensive plan for the fastest growing and largest jurisdictions (Brunengo, 1994). The plan essentially mandates the collection of physical, social, economic, political, and land use determinants such as logging, mining, road construction, and irrigation practices. The physical determinants include the natural landscape, particularly the hazards associated with them.

Mass Wasting Mitigation

Mass wasting has major effects on infrastructure and lives, especially in areas more prone to landsliding. To reduce these socio-economic impacts, proper planning should be implemented. Mass wasting mitigation can be very destructive to the natural environment, especially the more effective methods, so areas of high susceptibility should be avoided at all costs (Holtz & Schuster, 1996). In transportation corridors or densely populated regions, avoiding susceptible areas may not be completely possible, which will require mitigation strategies. Mitigation techniques must be applied to these areas where improper design has led to unstable conditions. The YRC provides an example of this with Canyon Road which was built in 1924. Sections of this road have been built through old landslides, while other sections have seen intense blasting which created unstable slopes which require mitigation. The two types of mitigation strategies used are passive and active (Holtz & Schuster, 1996).

Active mitigation consists of one of three measures: reducing the driving force (i.e. shear stress), increasing the resisting force, or increasing the internal strength (i.e., shear strength) (Holtz & Schuster, 1996). Reducing the driving force is essentially reducing the gravitation pull of the material. The main way this can be done is by slope reduction. Techniques involved with slope reduction include flattened slopes, benched slopes, reduced excavation depths, surface and subsurface drainage, and lightweight fill (Holtz & Schuster, 1996). Increasing the resisting force involves techniques such as constructing toe berms or installing anchors. However, if not set on a firm foundation these techniques may not be effective on deep-seated slides. Increasing internal strength in potentially unstable slopes require techniques such as using reinforced backfill or biotechnical stabilization. Biotechnical stabilization could require irrigation which does not make it ideal for arid regions. Measures like chemical and thermal treatments have been used to stabilize slopes, but these treatments are costly and can be reversible over time (Holtz & Schuster, 1996).

Mitigation of rockfall in transportation corridors are handled in two different manners, stabilization measures and protection measures (Wyllie & Norrish, 1996). Each measure implemented or recommended should be site-specific and dependant on the type of events that occur. For example, a transportation corridor confined by a river and steep walls may not provide an area for the construction of a catchment area. Different measures should be taken for small more frequent events that damage tires versus larger events that could result in the loss of human lives.

Stabilization measures consist of either reinforcing rock or removing rock from an area. Common measures for reinforcing rock include rock bolting, shortcrete, buttresses, and drainage (Wyllie & Norrish, 1996). These measures can be used alone or used together in areas depending on suitability of area of concern. Rock bolts are best used for potential failure surfaces that can be anchored into sound rock past the potential failure plane. Shortcrete, a type of concrete, is typically used for areas of closely fractured rock, controlling smaller blocks and raveling that would potentially produce less stable overhanging faces (Wyllie & Norrish, 1996). One issue with shortcrete is that it only provides surface protection and does not provide protection of sliding to the overall slope (Wyllie & Norrish, 1996). Buttressing is applied to areas where rockfall has created a cavity in the slope face, to prevent the collapse of the overhanging rock below the cavity. This is done by filling in the cavity with concrete which protects the area of weak rock and bears the load of the overhang (Wyllie & Norrish, 1996). Creating drainage is another method to reduce instability in rock slopes. This can be achieved by drilling drainage holes at the toe of the slope to release pore pressure from the slope (Wyllie &

Norrish, 1996). Removing unstable materials is also an option for transportation corridors. These measures can be implemented by resloping, trimming, or scaling slopes (Wyllie & Norrish, 1996).

According to Wyllie and Norrish (1996) many methods exist for the stabilization of slopes. Protective measures include catchment ditches, barriers, wire-rope mesh, catch fences, warning fences, rock sheds, and tunnels. Catchment ditches are regarded as a cost-effective way to stop rockfall if there is enough space for it. The size of the ditch, width and depth, should relate to the height of the face and the slope angle (Richie, 1963). For example, rockfall from slopes of 75 degrees or greater tend to land closer to the toe of the slope, where as slopes of 55-75 degrees produce rockfall that bounce and spin causing them to land further from the toe. Barriers are often used in conjunction with ditches to provide more area of catchment. These can be made of concrete or wire containers filled with rock. Wire-rope mesh is another widely used technique to mitigate rockfall hazard. The mesh can either be draped on the slope or in front of the slope hung by steel I-beams. Warning fences are similar to wire-rope mesh except that when a wire is broken by rockfall it triggers a warning sign that is placed well before the rockfall area, giving travelers enough distance to safely slow down and avoid the incident. Rocksheds are similar to snowsheds. These provide a sheltered area against rockfall for where rockfall is very frequent, such as the base of talus slopes. Tunnels through mountainous areas can avoid the rockfall hazard all together, but costs of tunnels are very high so this type of mitigation should be used when all other techniques have been exhausted (Wyllie & Norrish, 1996).

Passive mitigation concentrates less on saving infrastructure, but focuses more on saving lives (Schuster & Kockelman, 1996). Passive mitigation involves alert systems, restrictions on building, and codes for development (i.e., roads). Passive mitigation can even involve closing an area or road all together and rerouting traffic to a more stable or safe location. The development of a mitigation plan is an important economic and social factor for land management. One of the best examples of passive mitigation is in California where the National Weather Service and the United States Geological Survey have issued warnings for storms systems that are anticipated to produce mass wasting events (Keefer et al., 1987). A relative simple plan in the YRC can save lives and greatly reduce the costs of these natural disasters.

CHAPTER III

STUDY AREA

The Yakima River Canyon (YRC) lies between Ellensburg and Selah in Central Washington (Figure 2). The canyon spans nearly 38 km starting approximately five miles south of Ellensburg and ending approximately 3 km north of Selah. The canyon averages about 3 km in width from ridge crest to ridge crest and can reach depths of 600m. The highest point in the canyon is 980 m (Baldy Peak) and the lowest elevation is 380 m at the end of the canyon near Yakima. The Yakima River enters the canyon at about 440 m and drops about 1.5 m per kilometer through the extent of the canyon (Wenatchee Resource Area, 1988).

Geology and Geomorphology

The Columbia River Basalt Group (CRBG) flooded into the sedimentary basins of the Columbia Basin about 17 million years ago (Reidel et al., 1993). These continental flows erupted from fissures near the Washington, Oregon and Idaho border, filling the Columbia Basin with several different basalt flows until approximately 6 million years ago. The basalts of the YRC consist entirely of the Yakima Basalt Subgroup including the Grand Ronde, Wanapum, and Saddle Mountain formations (Bentley & Powell, 1984; Figure 3). These formations can be further divided by member. The Grande Ronde basalts are composed of several different flows, but the main two formations present in the YRC are the Grande Ronde R2, of reversed magnetic polarity and Grande Ronde N2 of normal magnetic polarity. Members of the Wanapum Formation present in the YRC are the Frenchman Springs, Roza, and Priest Rapids Members. The Pomona Member of

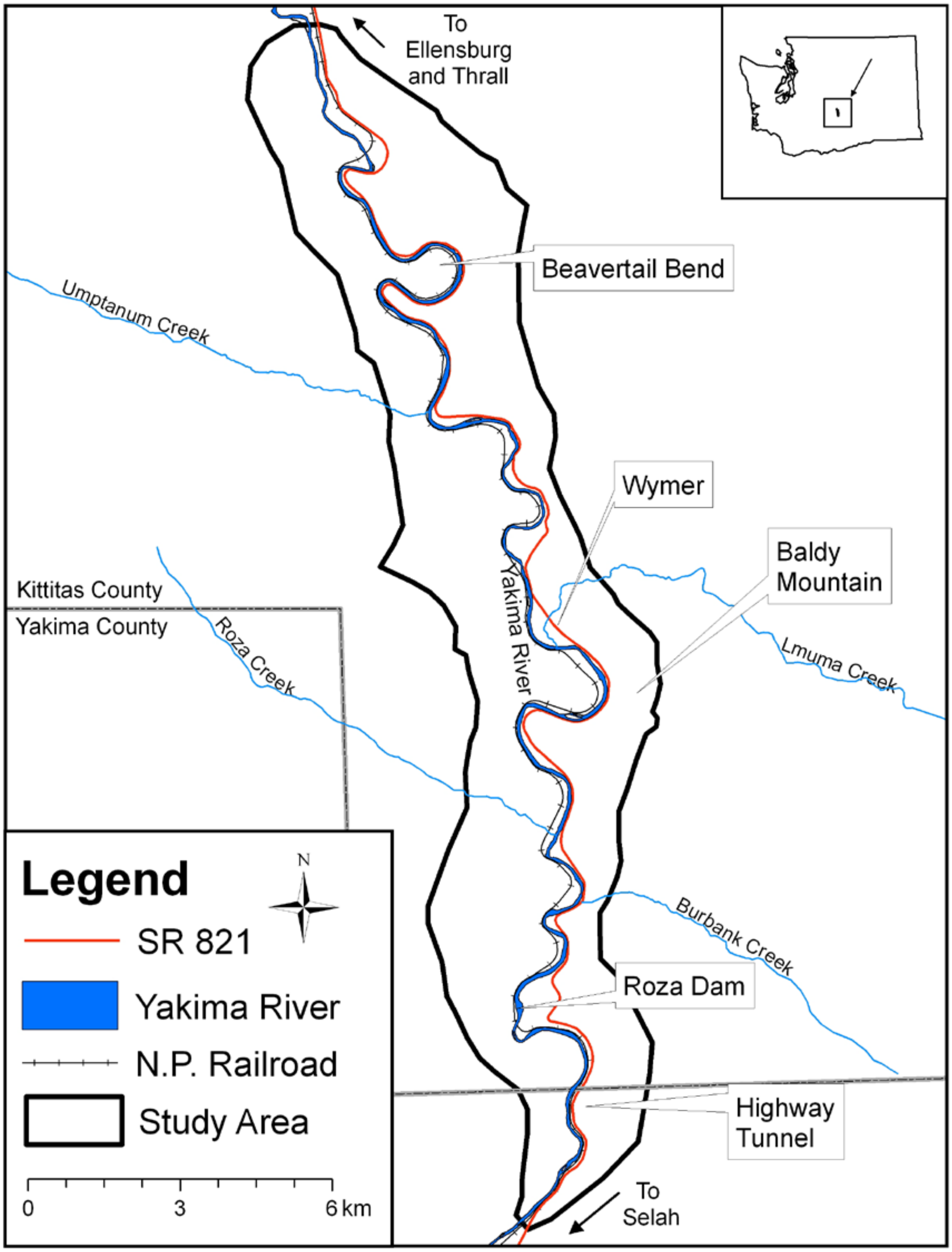
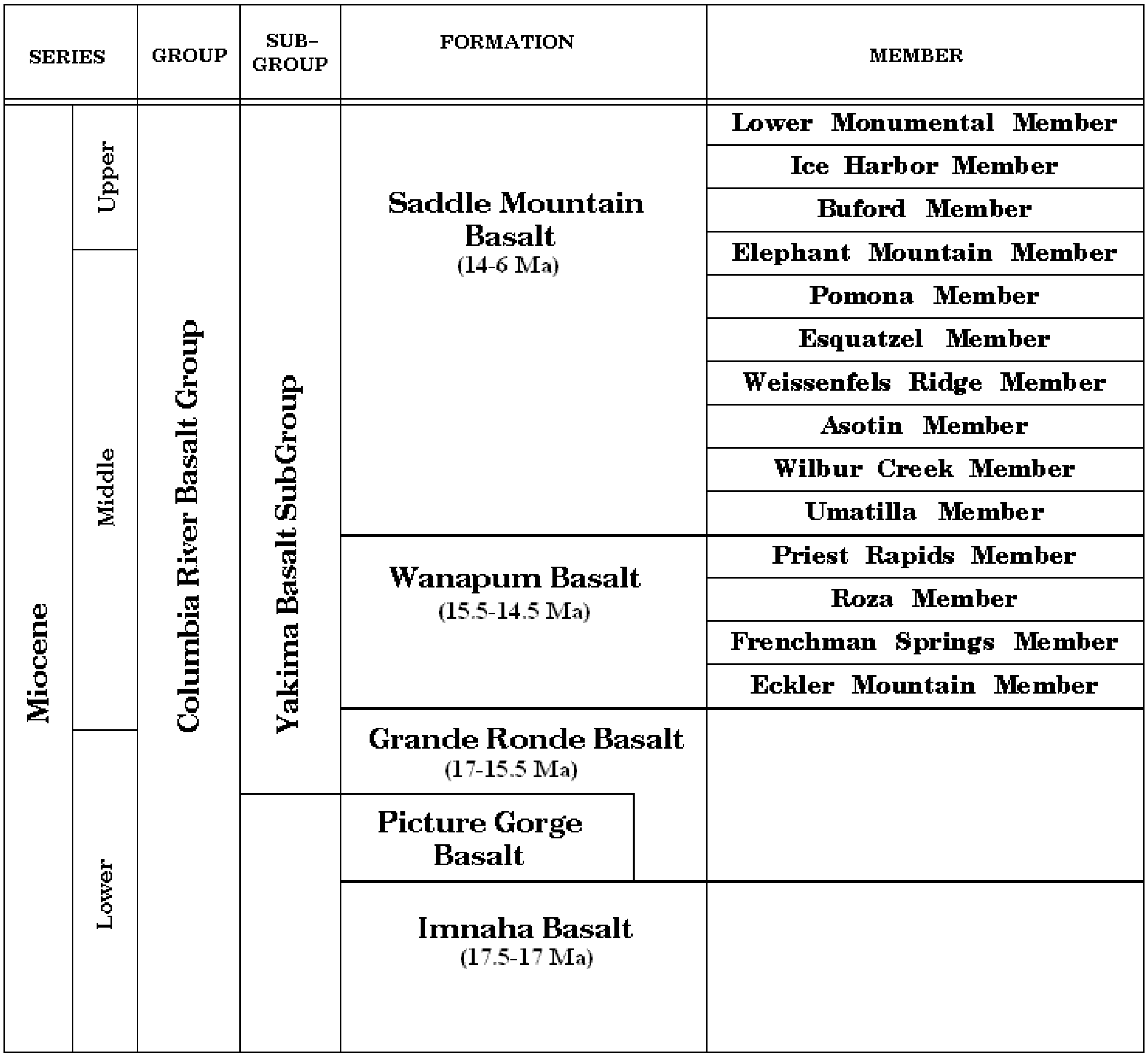


Figure 2. Generalized map of the YRC, Central Washington.



SERIES		GROUP	SUB-GROUP	FORMATION	MEMBER
Miocene	Upper	Columbia River Basalt Group	Yakima Basalt SubGroup	Saddle Mountain Basalt (14-6 Ma)	Lower Monumental Member
					Ice Harbor Member
					Buford Member
	Middle				Elephant Mountain Member
					Pomona Member
					Esquatzel Member
					Weissenfels Ridge Member
					Asotin Member
					Wilbur Creek Member
					Umatilla Member
				Wanapum Basalt (15.5-14.5 Ma)	Priest Rapids Member
					Roza Member
					Frenchman Springs Member
					Eckler Mountain Member
	Lower			Grande Ronde Basalt (17-15.5 Ma)	
				Picture Gorge Basalt	
				Imnaha Basalt (17.5-17 Ma)	

Figure 3. Stratigraphy of the Columbia River Basalt Group. Modified from Swanson et al. (1989).

the Saddle Mountains Formation is present in a small portion of the southern edge of the study area. Between flood episodes, central Washington was subject to local ponding, fluvial processes, and lahars, which led to the formation of relatively thin sediments known as the Coleman and Ellensburg formations. The most prominent member of the Ellensburg Formation in the YRC is the Vantage member. Other members include the

Selah and Lmuma sediments, which are only present in the very southern portion of the study area. These sediments became interbedded with each subsequent basalt flow.

This area of the YFB sits within the Olymipic –Wallowa Lineament (OWL). The OWL is a major topographic feature spanning across Washington and Oregon and dissecting the Columbia Basin. The origin of this structure is unknown and has not been associated with any individual structure (Reidel et al., 1993). The section of the lineament that intersects the Columbia Basin is known as the Cle Elum-Wallula deformed zone. The CRBG were subsequently subject to folding and faulting resulting in a series of anticlinal ridges, synclinal valleys, and thrust faults known as the Yakima Fold Belt (YFB). This area is characterized of N50°W trending anticlines (Reidel et al., 1993). The YRC sits in the middle of this portion of the YFB. As these ridges uplifted, the Yakima River dissected several anticlines including the Thrall, Manastash, Umptanum, and Selah Butte (Figure 4). Although the Yakima River is widely accepted as an ancetedent stream, it has been noted that the river chose a structural low where the anticlines plunge eastward from the Cascades (Baker et al., 1987). Interbeds of the Coleman and Ellensburg formation were exposed following the uplift of the Yakima Fold Belt by tectonic forces and fluvial downcutting, creating conditions for mass wasting (Tabor et al., 1982; Schuster, 1994).

Many types of Quaternary deposits exist within the canyon. The canyon began its formation with the deformation of the YFB about 10.5 million years ago, eroding through the anticlinal structures as they uplifted (Reidel et al., 1993; Smith, 1903). The YRC has not been subject to glaciations, but shows signs of periglacial processes. Periglacial loess deposits of the Palouse Formation have created intermittent pockets distributed

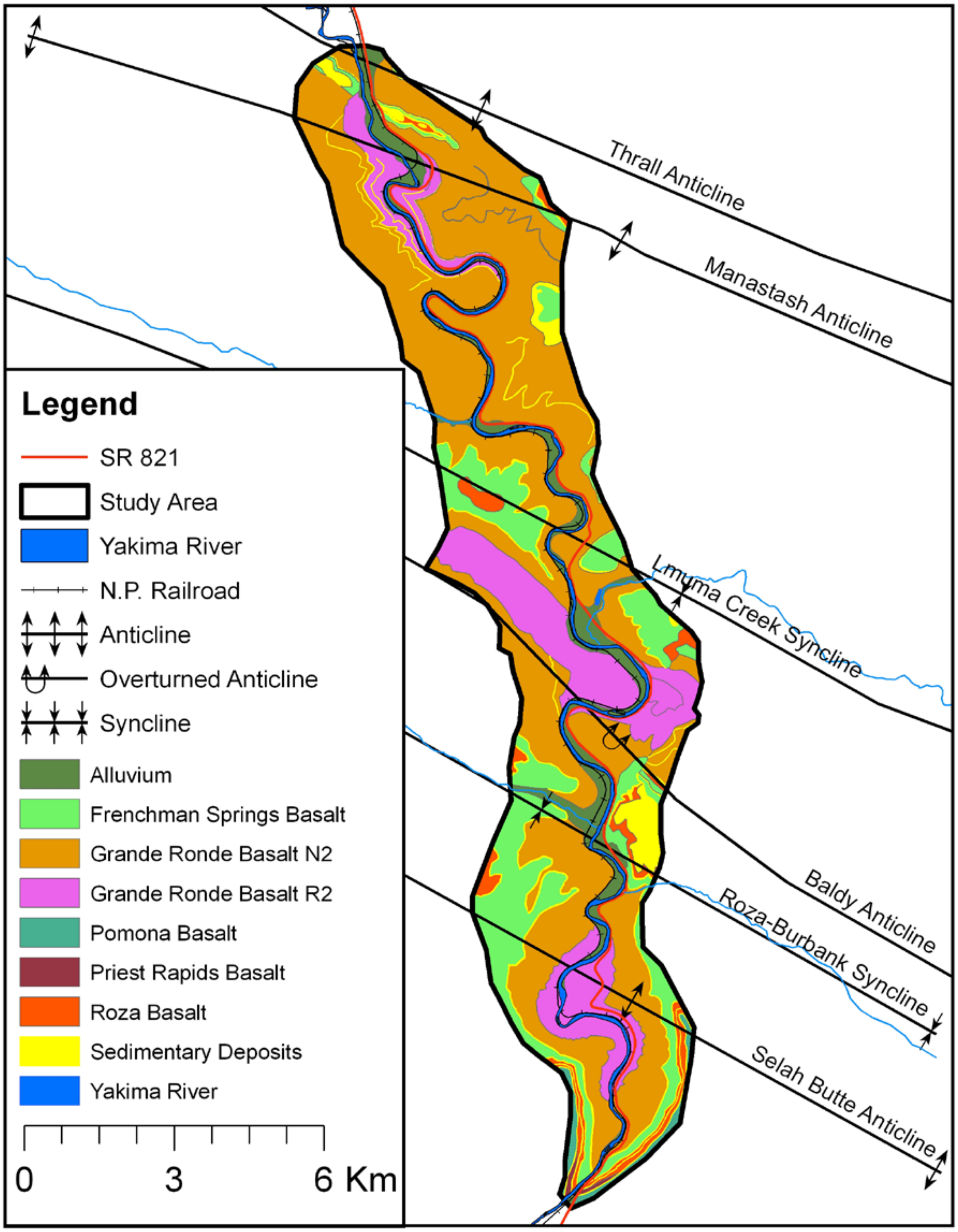


Figure 4. Geologic map of the YRC. Map drafted from Bentley and Powell, (1984); Bentley, Powell, and Campell, (1993); and Reidel, Campbell, Fecht, and Lindsey, (1993).

throughout the canyon (Campbell, 1979). Loess-like deposits on the canyon rims have formed into or deposited as a type of patterned ground known as mima mounds (Kaatz, 1959). Although the exact processes that have led to the formation of these mounds are unknown, many theories exist (Kaatz, 1959; Washburn, 1956,1988). Stone stripes, a different type of patterned ground is also present in the YRC (Kaatz, 1959).

Hydrology

The YRC lies within the Yakima River Watershed, which is part of the greater Columbia River Watershed. Steep ephemeral drainages and gullies dominate the YRC, but four major creeks drain into the canyon: Umptanum, Lmuma, Burbank, and Rosa Creek (Figure 5). The hydrology and hydrogeology of the canyon is linked to the tectonic forces that shaped the canyon. All of the creeks in the canyon are found within the synclinal valleys (Bentley & Powell, 1984).

The sedimentary interbeds of the Ellensburg and Coleman formations can create permeable layers above less permeable basalt, which may dictate the subsurface flow direction, especially if interbeds are dipping. Springs or riparian areas can be created if interbeds are exposed, with vegetation being a key in identifying these areas (Figure 6).

Climate

The YRC is located in Central Washington, approximately 80 miles from the Puget Sound and about 40 miles from the Cascade Crest. The proximity to the Cascades puts the YRC within the rainshadow created by the Cascades. This creates a semi-arid climate with a mild average temperature of 48 degrees Fahrenheit, based on climate data from the Ellensburg site south of Thrall. The lowest mean monthly temperature occurs in

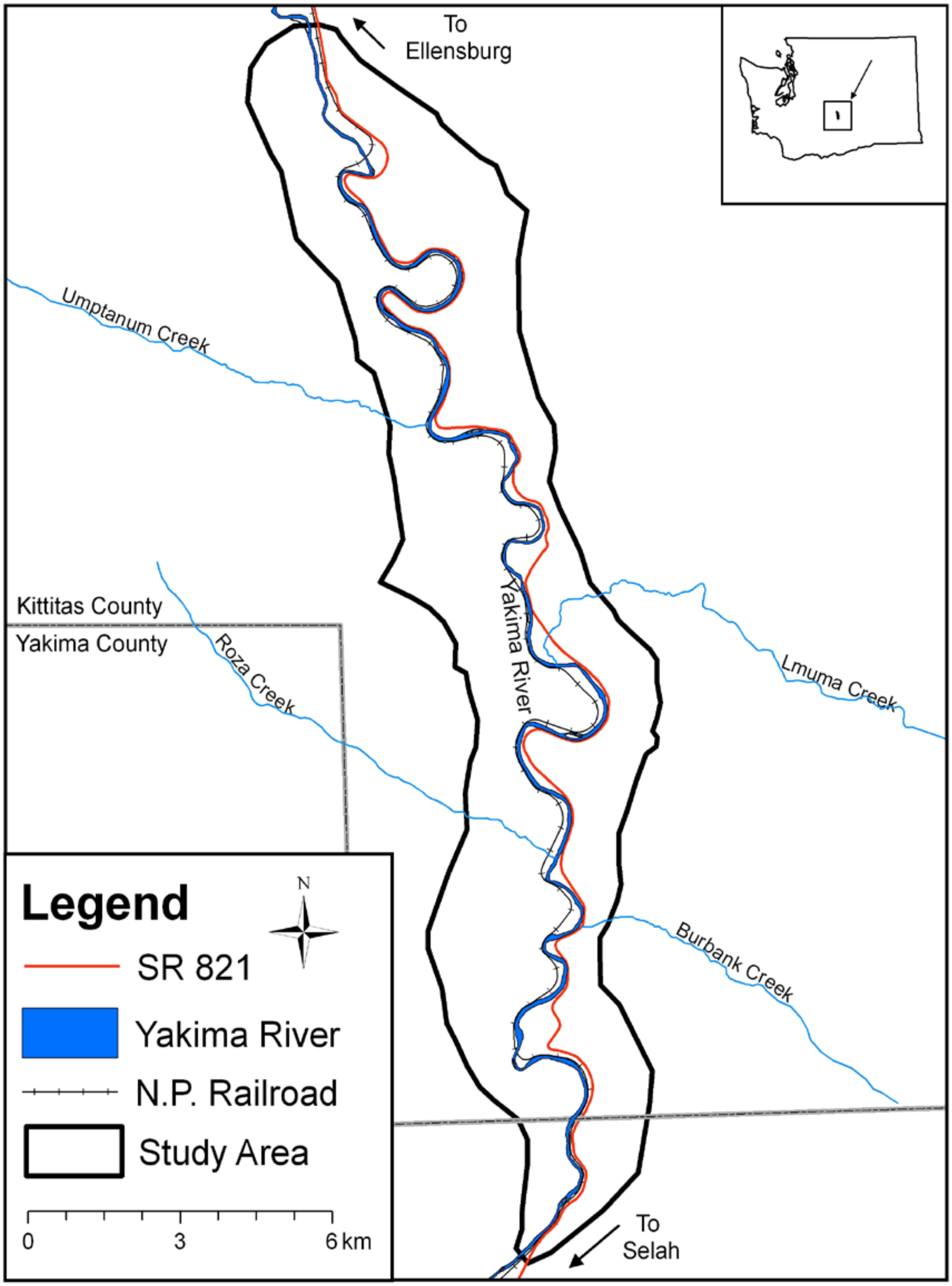


Figure 5. Map illustrating the four major creeks that drain into the Yakima River.

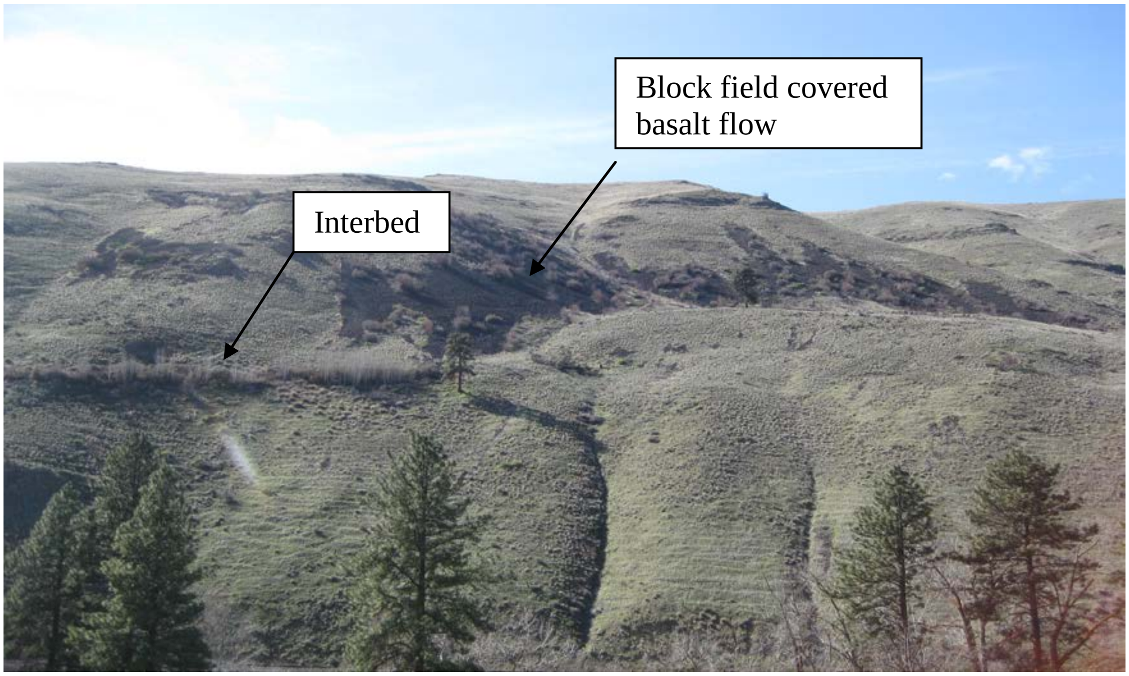


Figure 6. Exposed interbed of the Coleman Formation, North of Umptanum Recreation Area. Note the line of riparian vegetation present on the left side of the photo midslope.

January at 26 degrees Fahrenheit and the highest mean monthly temperature of 69 degrees Fahrenheit in July. The YRC has an average precipitation of ~9.0 inches annually with the majority of the precipitation occurring during the winter months (Western Regional Climate Center, 2011; Figure 7). In fall, winter, and spring the YRC is subject to freeze thaw conditions that promote rockfall. Winter storms are common in the Cascades. The most destructive of storms are known as rain-on-snow events which have caused mass wasting in the Cascades (Wemple, Swanson, & Jones, 2001). Although most precipitation is winter dominant the YRC has potential for sporadic and intense summer thunderstorms which have been attributed to debris flow initiation (Kaatz, 2001).

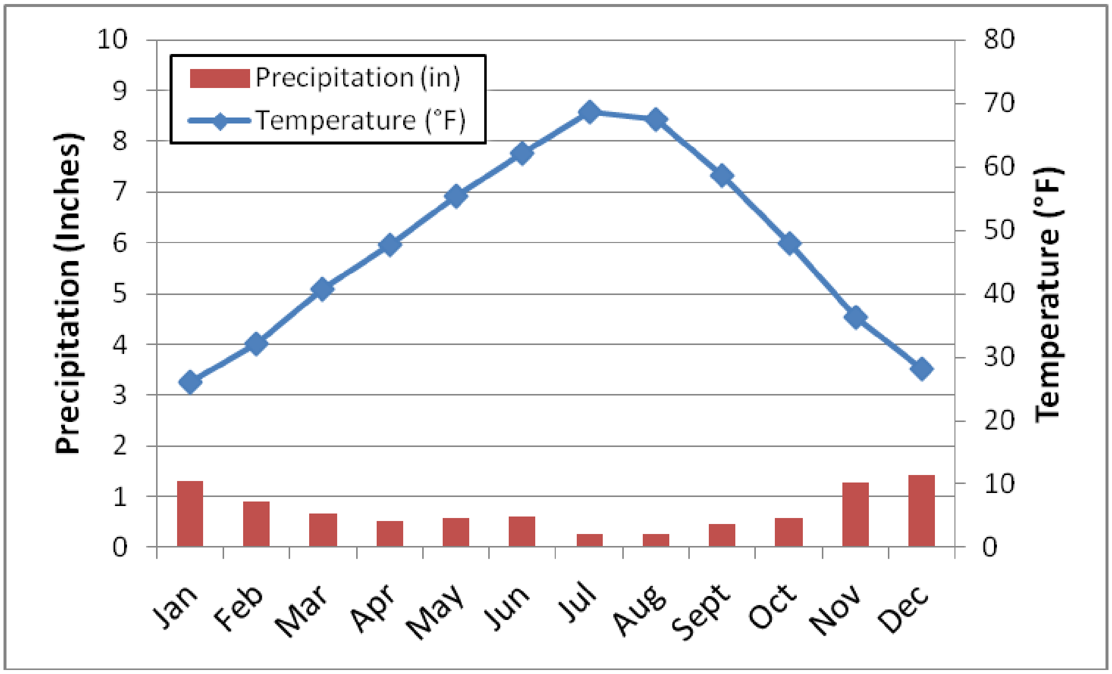


Figure 7. Climograph based on 1893-2010 climate record for Ellensburg, Washington, approximately 5 miles north of the mouth of the YRC. Data from Western Regional Climate Center.

Vegetation

The distribution of vegetation in the canyon is dependent on aspect, soil type, water availability (Sullivan, 2000). South-facing slopes typically are sparsely vegetated, composed mostly of grasses, while north facing slopes contain more shrubby vegetation. Vegetation in the YRC originally consisted of grass and sage brush communities (shrub-steppe) with cottonwoods and willows in the riparian areas. Cheat grass, an introduced species, is now a dominant species associated with sage in Central Washington (Sullivan, 2000). The canyon contains small pockets of ponderosa pine and quaking aspen where the aspect, elevation, substrate, and water supply are suitable for their growth. This vegetation is not characteristic of typical shrub-steppe environment, indicating that this area is transitional area (i.e., an ecotone).

Land Use

The YRC has been utilized by people, likely for thousands of years. Many archeological sites exist within the canyon (Bicchieri, 1999). Mass wasting deposits have even been used to store food because of the high insulation properties of talus. Native Americans have built several talus pits in the YRC which are still present in Umptanum Canyon (Bicchieri, 1999).

The settlement of the YRC began in the mid-to late-1800s, mainly for settlers wanting to raise cattle (Kittitas Centennial Committee [KCC], 1989). Prior to developments in the YRC, settlers had only one route between Ellensburg and Yakima known as the Shushuskin Trail, which is presently Umptanum and Wenas Roads (KCC, 1989). In 1882, Jacob Durr, with the help of local Native Americans, built a toll road to the west of the YRC known as Durr Road, which cost $25 for a yearly pass or $40 for a lifetime pass, becoming the easiest route to Yakima (KCC, 1989). Development in the YRC began in 1887 with the construction of the Northern Pacific Railroad, a land grant railroad which is still in use today as the Burlington Northern-Santa Fe line. The completion of the railroad allowed for small settlements to occur in the canyon. Residents of the YRC have traditionally made a living in the canyon by ranching livestock, growing hay, and even producing orchard fruits. The main two settlements were at the confluences of Umptanum Creek the Yakima River, and Rosa Creek the Yakima River (KCC, 1989) (Figure 8). Evidence of the Umptanum Creek settlement still exists near its junction with the Yakima River as old building foundations and fruit trees. In the early 1920s, the

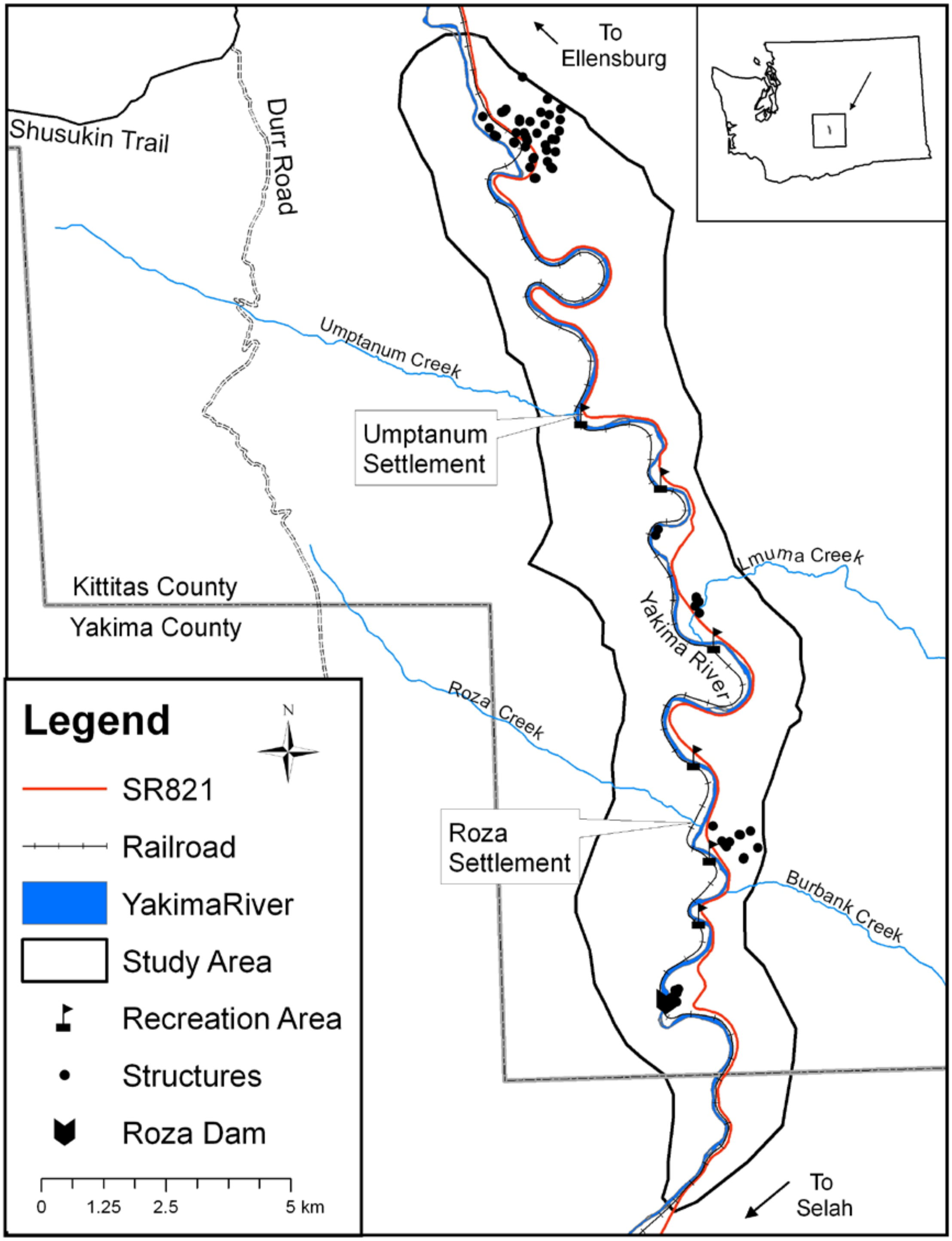


Figure 8. Approximate locations of early settlements at the confluences of Umptanum and Roza Creeks with the Yakima River (KCC, 1989). Also note S.R. 821 and the N.P. Railroad.

construction of Canyon Road began and was completed by September of 1924. This was a major transportation route, being the shortest and easiest route connecting Ellensburg to Yakima ("Canyon has New", 1924). This new route paved the way for development. Roza Dam construction started in the mid 1930's with completion by 1939 (Bureau of Reclemation, 2011). In recent years, developments of residential areas have increased in the YRC. Within the last 20 years housing developments have been constructed, mainly towards the head and mouth of the canyon, with some houses being in marginal areas prone to mass wasting events.

Three different ownership entities dominate the canyon: the state of Washington, U.S. Bureau of Land Management (BLM), and private landowners. The L.T. Murray Wildlife Area, owned by the state of Washington encompasses almost half of the study area.

In addition to being a transportation corridor, the YRC is a major recreation area. The Yakima River is considered a Gold Medal Fishery and is fished throughout the year with several companies that offer guided trips through the canyon. The canyon also is used for big and small game hunting. Permits for big horn sheep are highly sought after, with some people waiting many years to be able to hunt bighorns in the YRC. The BLM has developed several areas in the canyon to provide recreational access to many parts of the river and the canyon. Other recreational opportunities include hiking, birding, rafting, and canoeing. Rafting is perhaps the most intense recreational activity during summer months in the YRC. Rafters have many different entry and exit points available for public use including four different BLM recreation areas, a public fishing area owned by the

Washington State Department of Fish and Wildlife, and other privately owned boat launches.

CHAPTER IV

METHODS

This study of mass wasting in the YRC consisted of five steps: 1) data acquisition for the mass wasting inventory; 2) identifying, mapping and classifying mass wasting features; 3) identifying mass wasting control variables; 4) developing mass wasting hazard maps; and 5) developing management recommendations based on findings.

Data Acquisition

In order to start a mass wasting inventory, an initial data collection was needed. This involved gathering aerial photographs, digital topographic maps, geologic maps, and orthophotos. A set of 2001 natural color aerial photographic images were purchased from the Washington State Department of Transportation (WSDOT). As the scope of the study developed it became clear that sequential aerial photographic interpretation was necessary for identifying the presence and timing of historic mass wasting features, so an additional five sets of aerial photographic images were acquired. A total of six sets of aerial photographic images were used for this analysis including the years 1942, 1954, 1962-63, 1971, 1992, and 2001 (Table 1). These sets were purchased through the United States Department of Agriculture Western Aerial Photography Field Office, and borrowed from the Central Washington University's Geography Department. These photo sets ranged in scale from 1:20,000 to 1:24,000 which were well suited for this analysis of the YRC (Soeters & van Westen, 1996).

Six 1:24,000 topographic quadrangles were downloaded from the United States Geological Survey's (USGS) website. Hand-drawn 1:24,000 geologic maps were

Table 1

Aerial Photograph Sets Used for Landform Interpretation

Year, roll number, and county code	Photograph number	Scale	Natural color	Flight date
1942 USDA				
NJ-3B	159-168	1:20,000	No	Aug. 11
NJ-4B	3-16	1:20,000	No	Aug. 11
1954 USDA				
NJ-1N	42-54, 106-113	1:20,000	No	Aug. 7
NJ-1N	169-175	1:20,000	No	Nov. 26
1962 USDA				
FZ-2CC	137-144, 218-219 238-239	1:20,000	No	Aug. 24
1963 USDA				
FZ-3CC	153-162	1:20,000	No	Sept. 6
1971 USDA				
FZ-1MM	55-67, 138-148	1:20,000	No	May 25
FZ-2MM	265-269	1:20,000	No	May 23
1992 WSDOT				
24	378-380	1:24,000	Yes	May 15
25	395-403	1:24,000	Yes	May 15
2001 WSDOT				
24	08-12	1:24,000	Yes	Aug. 6
25	01-07	1:24,000	Yes	Aug. 6
26	45	1:24,000	Yes	Aug. 6

acquired from Washington State Department of Natural Resources geologist Jack Powell, who previously mapped the geology in the YRC. A digital 1:100,000 shapefile was downloaded from the WDNR’s website. A 2006 orthophoto constructed by the National Agriculture Imagery Program (NAIP) was obtained from Central Washington University’s Geography Department GIS data library.

Light Detection and Ranging Imagery (LiDAR) for the YRC became available January 2010. This imagery is an optical remote sensing technology that uses a laser to measure and record the distance of a target area with extreme accuracy, producing a very high resolution image (ESRI, 2007). Since the initial identification of mass wasting events had already occurred, this imagery was acquired to fine-tune the boundaries of mass wasting features mapped by aerial photography interpretation. LiDAR data was downloaded from Open Topography, which is funded through the National Science Foundation. Downloading the LiDAR consisted of downloading over 350 individual LiDAR images and mosaicking them together in ERDAS®. This initial preparation led to the development of a GIS-based inventory that was used for storing data and analyzing mass wasting in the YRC.

A historical inventory of mass wasting events aided in identifying mass wasting events. This involved internet research and library research. Google News Archive Search was used to find articles in the Ellensburg *daily record*. Library research was conducted in June and July of 2009. This involved looking at the front page of the Ellensburg *daily record* from 1886 to 1970. Records were viewed in microfiche format through a viewer in the Central Washington University’s Brooks Library. Since the canyon was a major transportation route any mass wasting affecting travel would likely be front page news, so only the front page of each newspaper was viewed. According to Gary Wolf of the WSDOT (Personal Communication May 05, 2010) no significant mass wasting events other than the 1998 event have occurred since 1970, which is why the archival search ended at that date. Each event found was printed out and an Excel® spreadsheet was created which recorded the data of the event, the trigger mechanism (if described), a description of the area, and the type (if distinguishable).

Data from the WSDOT South Central office in Union Gap was acquired to aid in identifying areas of historical mass wasting. The WSDOT Rockfall Hazard Rating System is a system that uses several parameters to assess the relative hazard associated with unstable slopes. Factors include posted speed limit, sight distance, catchment size, and fall frequency. The rating system identified 54 historically unstable slopes in the YRC that were known to produce at least one mass wasting event per year. These data were used to aid in the production of a rockfall hazard map.

Identifying and Mapping Mass Wasting Features

Mass wasting events were identified using four different methods: aerial photographic interpretation, LiDAR image interpretation, historical records, and field observation. All four data sets were compiled into shapefiles so features and attributes could be represented spatially. A shapefile is a digital file used in ArcMap® GIS used to display points, lines, or polygons for map making.

Aerial photographs were viewed with traditional stereoscopes and digitally. Aerial photographs were scanned into TIFF format. These were scanned at 1200 dots per inch and viewed digitally in ERDAS®, a spatial imaging program. Crystal Eyes, digital stereographic goggles were used in ERDAS® to view the images. The benefits of ERDAS® and Crystal Eyes® included easy and quick adjustment of parallax, stereo pairs that could be saved digitally, and the ability to view one set of images in stereo and have a full range of zoom unlike analog aerial photographic interpretation. Aerial photographs were analyzed along north to south flight lines.

Mass wasting features were identified based on morphology, vegetation, and drainage patterns. Other topographical features used for identification included head scarps, lateral flank scarps, scoured channels, hummocky topography, and differences in textures colors on the aerial photos (Cruden & Varnes, 1996). Each feature identified on an aerial photograph was digitized on top of a 2006 NAIP color orthophoto in ArcMap GIS.

Field observation was conducted in August and September of 2009. Field observations were carried out to test the decision rules applied for aerial photography and LiDAR image interpretation for mass wasting type, material, and state of activity (Cruden & Varnes, 1996) . This resulted in 60% of landsides, 58% of flows, and 30% of fall areas being field checked for accuracy.

Classifying Mass Wasting Features

Mass wasting features were classified according to the Cruden and Varnes (1996) classification (Table 2). The three variables used for this analysis were type of movement, material, and activity. Activity classes were modified from McCalpin (1984)

Table 2

Decision Rules for Mass Wasting Classification Through Aerial Photograph Analysis.

Movement type	Interpretive features from aerial photograph analysis
Fall	
Morphology	Debris covered slope; bedrock scarp
Vegetation	Sparse or devoid of vegetation
Drainage	No visible drainage
Flow	
Morphology	Entrenched channel or small circular scarp at head of channel; debris fan at toe of channel
Vegetation	Devoid of vegetation or sparsely vegetated
Drainage	Deranged drainage; distributaries
Translational Slide	
Morphology	Linear scarp; plane of failure parallel to slope; hummocky runout
Vegetation	Shrubs in depressions; scarps devoid of vegetation to grass covered
Drainage	Deranged drainage
Rotational Slide	
Morphology	Large scarp; back-tilted block; hummocky runout
Vegetation	Shrubs in depressions; scarps devoid of vegetation to grass covered
Drainage	Deranged drainage
Complex Slide-Flow	
Morphology	Large scarp; back-tilted block; flow at end of block
Vegetation	Shrubs in depressions; scarps devoid of vegetation to grass covered
Drainage	Deranged drainage

and Lillquist (2001). These variables were recorded for each mass wasting feature and stored within the mass wasting shapefile.

Type of Movement

The result of each mass wasting process was classified as a flow, fall, slide or spread. Mass wasting features were further classified to the subtype. Flows were classified as debris flows and earth flows. Falls were delineated between talus slopes and dry raveling. Slides were classified as rotational, translational, or complex slide-flow (Cruden & Varnes, 1996; Lillquist, 2001; McCalpin, 1984). Colluvial slopes are mass wasting deposits, but show no distinguishable features to further classify these features.

Material

Each mass wasting feature was classified by material: rock or debris. These classes were delineated through aerial photography interpretation (Cruden & Varnes, 1996). Data for each feature was entered into ArcMap® and stored within the mass wasting shapefile.

State of Activity

Mass wasting features were classified by state of activity, which was developed by McCalpin (1984) and modified by Lillquist (2001). Activity of each mass wasting feature in the YRC was classified by a set of decision rules in order to assign values in the most objective way possible (Table 3).

Identifying Mass Wasting Control Variables

The identification of mass wasting control variables was based on the compilation of data from GIS, field observation, and historical records. GIS analysis allowed visual

Table 3

Decision Rules for Mass Wasting State of Activity Class Used in This Study

Activity		Description
Active		
	Morphology	Sharp, exposed bedrock; visible cracks parallel to scarp; hummocky terrain; clear runout
	Vegetation	Disrupted; scarp devoid of vegetation
	Drainage	Closed depression
Inactive-young		
	Morphology	Weathered bedrock; talus formation; cracks are not visible; runout zone partially eroded
	Vegetation	Scarp partially overgrown; hummocky terrain partially overgrown
	Drainage	Closed depression
Inactive-Mature		
	Morphology	Weathered bedrock; talus formation; cracks are not visible; smooth hummocks runout zone partially eroded.
	Vegetation	Scarp partially vegetated; woody shrubs present
	Drainage	Depression partially filled; small drainages developed
Inactive-Old		
	Morphology	Scarp completely vegetated; smooth rolling topography
	Vegetation	Vegetation same as surrounding area
	Drainage	Completely filled depressions; fully developed drainage

Note. Adapted from Lillquist (2001) and McCalpin (1984)

representation and data quantification of mass wasting variables in the YRC. Attribute information was collected for debris flows, deep-seated slides and complex slide flows, and shallow slides. Attribute information collected included area, slope aspect, slope angle, altitude, slope convexity, and geologic data. Historical features from newspaper accounts were included in these data sets if they were positively identified and mapped. These data was not collected for rockfall. Since rockfall is distributed by cliff faces and very steep slopes an inventory alone can provide as a hazard map for rockfall. Aspect was calculated from LiDAR data. The LiDAR data was first converted from 0.5m resolution to 10m resolution for ease of processing in ArcMap®. Once the 10m DEM was created it could then be converted into vector format. Aspect for mass wasting events were grouped into classes and recorded within the mass wasting shapefile. Aspect was grouped into four classes of north facing, east facing, south facing, and west facing.

Slope classes were created by converting the LiDAR DEM into a 10 m DEM, which are standard landslide hazard zoning studies (Soeters & van Westen, 1996). A slope layer was created with Spatial Analyst in ArcMap®. The slope DEM was converted into vector format and each mass wasting event was categorized by slope class. Slope classes were reclassified to fit into clusters of mass wasting features, identifying common patterns. Three slope classes were created consisting of slopes of 0-15 degrees, 16-30 degrees, and greater than 30 degrees.

Elevation classes were created by converting the LiDAR DEM into a 10 m DEM. A vector layer was created with three elevation classes of equal interval: elevations less than 500 meters; elevations between 500 and 700 meters; and elevations greater than 700 meters. Mass wasting events were placed into the appropriate class and recorded within the shapefile.

Curvature was calculated by converting the LiDAR DEM into a 10 meter DEM. A curvature DEM was calculated by the Spatial Analyst Tool ArcMap®. Curvature was reclassified to either convex or concave slopes, the two main slope types. Mass wasting events were classified accordingly and were recorded within the inventory.

In order to identify geologic controls, a combination of unpublished and published geologic maps, and digitized geologic data from the WADNR was used to create a complete detailed geologic map for the YRC. Unpublished geologic maps were georeferenced and digitized so it could be added to the published data which improved the accuracy of the geologic boundaries (Bentley & Powell, 1984). Eleven different pieces were georeferenced to construct a complete map of the canyon. In order to guarantee accuracy, all maps georeferenced need to have a root mean square error less than 5.0 (Table 4; ESRI, 2007). The geologic map was used to classify all mass wasting features by lithology. The lithology type for each feature was recorded in the attribute table of the mass wasting shapefile. Deep-seated landslides that were within 200m of lithological contacts were also recorded in the inventory. This allowed for quantification of mass wasting feature by lithological unit which could was then used for statistical analysis.

After classes were delineated for each parameter mentioned above, statistics were used to determine significance for each parameter class and its relationship to mass wasting features (Jimenez-Peralavarez, Irigaray, Hamdouni, & Chacon, 2009; Soeters & van Westen, 1996). Tests were grouped by type of mass wasting. Four different test groups were assembled: 1) debris flows 2) deep-seated slides and complex slide-flows 3) shallow translational slides.

Table 4

Root Mean Square Errors for Georeferenced Maps, YRC.

Map ID	Quadrangle	RMSE
1003	Wymer	3.21490
1004	Ellensburg South/Kittitas	4.98940
1005	Wymer/Cottonwoods	3.82761
1006	Wymer/Cottonwoods	4.63661
1007	Wymer	4.66239
1008	Wymer	2.94929
1013	Wymer	4.67543
10111	Wymer/Cottonwoods	4.58110
10121	Ellensburg South/Kittitas	4.62662
101151	Ellensburg South/Kittitas	4.17982
101161	Ellensburg South/Kittitas	3.89135

Note. RMSE = Root Mean Square Error

Flows were tested individually due to the appearance of different control variables. Earth flows were not included for statistical analysis due to the appearance of different control variables. Deep-seated slides and complex slide-flows were grouped together due to the small sample size and the appearance of a similar geologic relationship. Shallow translational slides were also tested individually due to the size of the sample and the appearance of different control variables. Chi square tests were used because the data needed to be sorted into classes. Parameter classes including lithology, lithologic contacts, elevation, slope aspect, and slope convexity were tested with chi square (Table 5). Earth flows were not grouped with debris flows due to the appearance of different control variables and could not be tested individually due to the small sample size.

Chi square tests were based on mass wasting frequency. Expected values for each class were calculated by the percentage of area of each class of a parameter. This assumes that if there is no significant relationship for a specific parameter class, i.e., that the number of mass wasting features would be proportionate to the area of each parameter class. For example, 39 deep-seated slides and complex slide flows were grouped together for chi square. To test for a parameter such as geology, each geology type would be separated and the area calculated for each type. Once the area was calculated for each geology type, it can be converted into a percentage. If the Frenchman Springs basalt consists of 18% of the study area, then it should contain ~7 deep-seated mass wasting features creating an expected value (where 39 * .18 = 7). This was done for each geology type. The chi square test is (Observed value – Expected value)^2/Expected value). This provides a chi square value for each geology class. Each value for each class was then added together for the final chi square statistic. If this value was significant, then each individual chi square value for each geology class was analyzed to assess which class is the most significant (i.e. the highest individual Chi Square value). It is important to note that significant values can have two different meanings: 1) a parameter class is significant

Table 5

Control Variables Tested for Hazard Mapping.

Factor	Debris Flows	Deep-seated Slides and Complex Slide-Flows	Shallow Slides
Elevation	X	X	X
Distance to Anticlines and Synclines		X	
Distance to Faults		X	
Distance to Watercourses	X	X	X
Lithology	X	X	X
Lithologic Contacts	X	X	X
Slope Angle	X	X	X
Slope Aspect	X	X	X
Slope Curvature	X	X	X

because it has more mass wasting features than the expected value and; 2) a parameter class is significant because it has fewer mass wasting features than the expected value.

A Spearman Rank Correlation was employed to test for a relationship of basin area and slope to debris flow distribution. This was accomplished by using the Statistix® program available from Central Washington University's Geography Department.

Developing Mass Wasting Hazard Maps

Four different hazard mapping techniques were used in this analysis. Each major class of mass wasting has a different set of control variables in the YRC. Hazard maps were delineated for the following classes: 1) debris flows; 2) rockfall for the transportation corridor; 3) deep-seated slides and complex slide-flows; 4) shallow translational slides.

A hazard map for debris flows, deep-seated slides, and shallow slides was created from significant control variables tested for the study area. This form of hazard mapping is known as the statistical approach (Soeters & van Westen, 1996). Each parameter was sorted into classes. Each class was given a value of low = 1, moderate = 3, or high = 5 hazard based on the results of the statistical analysis. A low value was assigned if the observed value was less than the expected value. A moderate value was assigned if the observed value approximately equaled the expected value. A high value was assigned if the observed value was greater than expected value. These values were transferred to each parameter map for each significant control variable. Using the Raster Calculator Tool in ArcMap® each parameter map was added together. The resulting map was a raster layer that contained the sum of the parameter maps that were added together. Four classes were created by equal intervals: 1) very low hazard; 2) low hazard; 3) moderate hazard; and 4) high hazard.

A rockfall hazard map for the transportation corridor was also created for the YRC. This was done by using rockfall data acquired by WSDOT and from rockfall mapping that was done in the inventory. Rockfall areas within 50m of the road or railroad were labeled as high hazard, 100m within was labeled moderate, 250m was labeled low, and greater than 500m was labeled very low.

A second approach of hazard mapping was used for deep-seated landslides. This method, based on the bivariate statistical approach, was a landslide susceptibility model developed by Jimenez-Peralavarez, Irigaray, Hamdouni, and Chacon (2009) was modified and used to process the significant control variables within ArcMap®. These variables were cross tabulated in every possible way to identify areas with terrain and geologic conditions similar to where current mapped landslides have occurred. The relative hazard level was set to low, moderate, high, or very high depending on the amount of significant control variables present in a particular area.

A second approach was used for shallow landslide hazard mapping. This method follows Slaughter (2009) by using 2m LiDAR to identify potential shallow landslide source areas. In resource management terms these are colluvial hollows and inner gorges (Slaughter, 2009). This method was chosen because LiDAR data is the best available imagery. The high resolution of LiDAR data can be used to identify these features more effectively than 10m digital elevation models (Slaughter, 2009). This technique uses LiDAR data to calculate the slope and the plan curvature. Plan curvature calculates the convexity or concavity of a slope for the area of interest, used typically for the effect of terrain on water flow (ESRI, 2007). In order to be used for analysis, the

LiDAR data was first reclassified by using the Reclassify Tool in ArcMap®. Slope angle and plan curvature were calculated with the Spatial Analyst Tool. Once these layers were creating they were combined by using the Raster Calculator function in ArcMap® producing an image in a stretched value. Hazards classes were reclassified as very low, low, medium, and high. High values were applied to where historical mass wasting events have occurred, and moderate, low and very low values were set at equal intervals below the high hazard.

Developing Management Recommendations

Management recommendations were based on field observations, results of hazard mapping, and current techniques used to mitigate mass wasting hazards. The maps produced provide a preliminary template for land use management and illustrate what transportation areas are most at risk and possibilities to mitigate future incidences. Some of the most common mitigation techniques recommended in highway corridors include rock bolting, rock netting, draped mesh, shortcrete, installing barriers, maintaining or expanding catchment ditches (Wyllie & Norrish, 1996). Mitigation measures for the YRC could include draped mesh for most areas, due to their effectiveness of directing rockfall into catchment ditches (Wyllie & Norrish, 1996). Other places of high concern with potential for bouncing rockfall trajectories could include wire rope fencing to catch rocks to keep them from impacting the highway.

CHAPTER V

RESULTS AND DISCUSSION

Identifying, Mapping, and Classifying Mass Wasting Features

Mass wasting features encompassed ~22% of the total study area. These features are both historic and prehistoric, with some features that are likely of the late Pleistocene. Four types of mass wasting features were inventoried resulting from these events: flows, falls, slides, and complex slide-flows. A total of 248 mass wasting features were identified in the YRC through aerial photography interpretation, LiDAR image interpretation, and from historical record analysis, totaling 16 km^2 (Figure 9). The smallest mass wasting feature mapped was 42 m^2 which is a result of the high resolution imagery used in the inventory (Table 6). The largest feature mapped was over 2,000,000 m^2. The highest density of mass wasting features occurs at the southern end of the YRC in an area known as a water gap. The formation of this water gap created a narrow channel with steep-slopes which is most likely the reason for the high mass wasting density in this area.

Flows

Sixty-one debris flows were identified and mapped in the inventory. Debris flows ranged from 3,700 m^2 to 650,000 m^2. Flows were generally confined to channels with debris fans being deposited in or near the Yakima River. Debris flows occurred in almost every subgroup of the CRBs found in the YRC, excluding the Pomona and Priest Rapids basalts, which only account for a small percentage of the study area. Two types of flow features were delineated in the inventory: 1) flows that accumulated debris by upstream

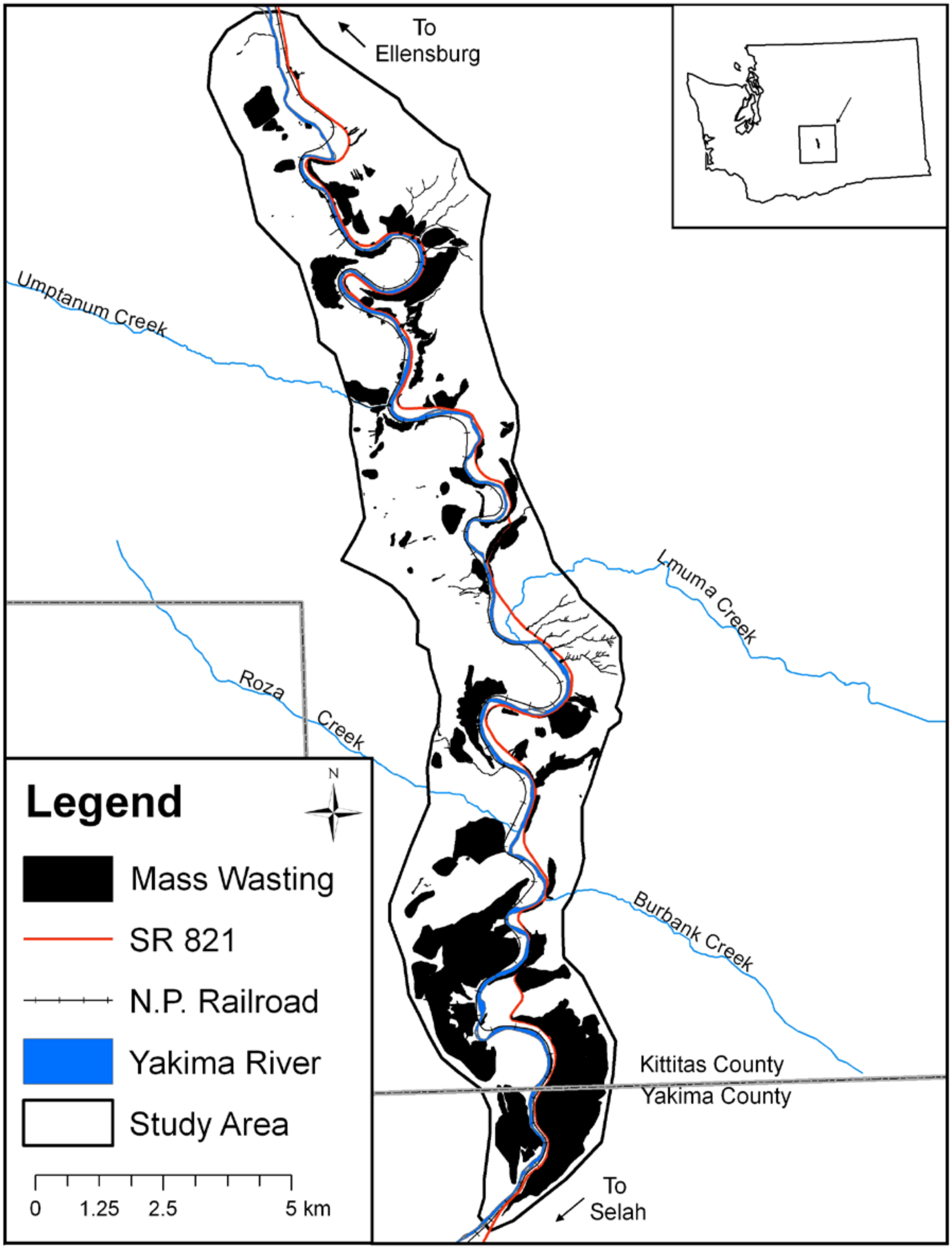


Figure 9. Overall mass wasting in the YRC.

Table 6

Descriptive Statistics for Mass Wasting Features in the YRC.

Type and material	Total Number	Total area (m^2)	Mean area (m^2)	Minimum area (m^2)	Maximum area (m^2)	Total mass wasting area (%)	Study area (%)
Fall							
Rock	91	9047847	98346	62	2195519	55.2	11.9
Flow							
Debris	61	1934736	37012	100	652200	11.8	2.5
Earth	3	21018	7006	741	11500	0.1	0.3
Slide-Flow							
Rock	6	2639693	377099	167844	854195	16.1	3.5
Rotational							
Rock	16	1248974	78061	8452	332217	6.6	1.4
Translational							
Rock	17	1472395	866611	8191	297600	10.0	2.2
Debris	35	24560	744	42	13043	0.1	0.3

channel entrenchment (Coe, Kinner & Godt, 2008); 2) flows that initiated from a shallow landslide that mobilized into a flow (Larsen, Pederson, & Schmidt, 2006; Figure 10).

Three earth flows were mapped in the inventory. These features ranged in size from 740 m^2 to 12,000 m^2. These were clustered and found exclusively in the northern portion of the YRC. These events occurred on an open slope, with distinct points of initiation.

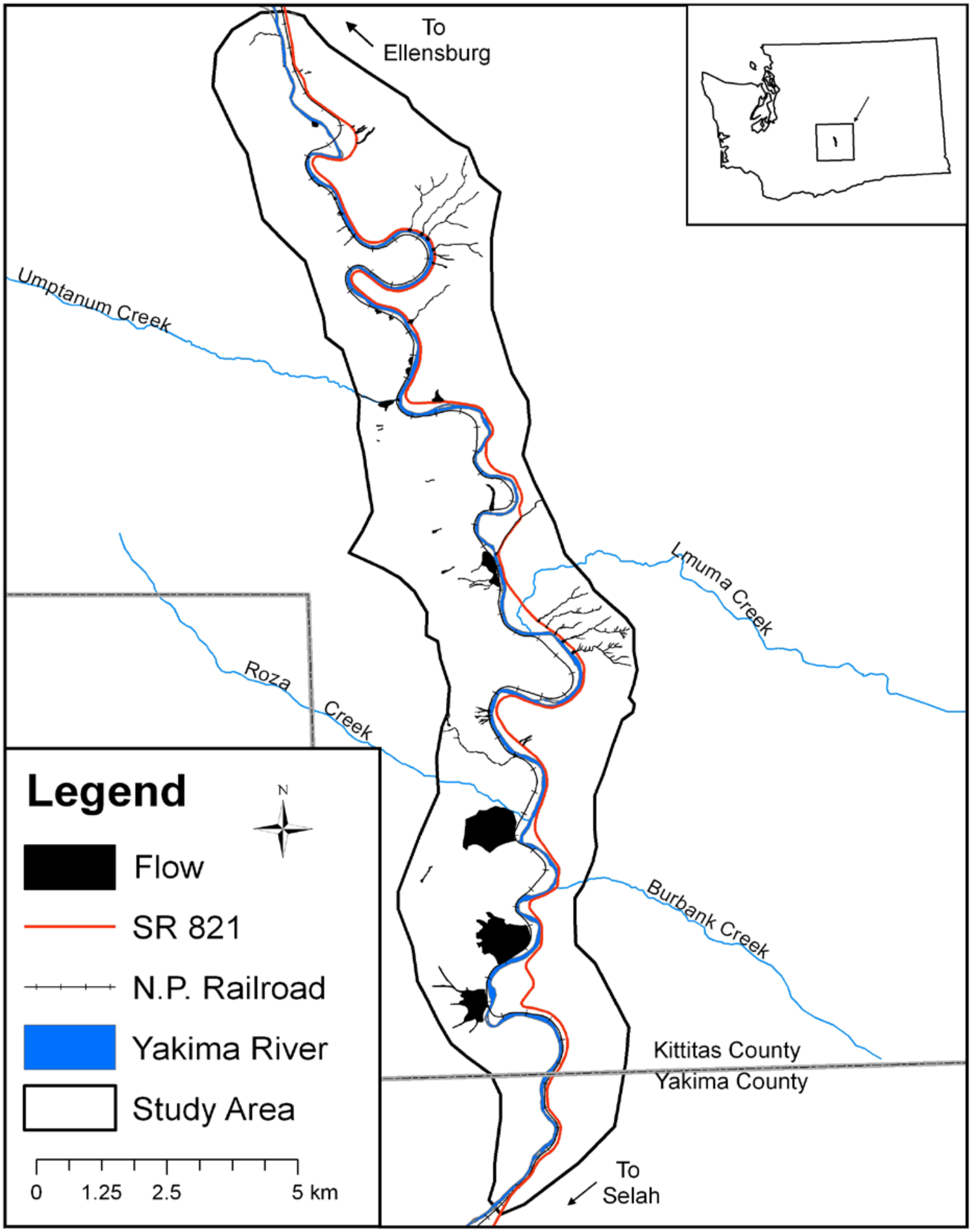


Figure 10. Distribution of flows in the YRC.

Falls

Rockfall is abundant throughout the canyon and is the most common mass wasting feature accounting for 55.2% of the total mass wasting (Figure 11). Ninety-one rockfall deposits were mapped in the YRC and ranged in area from 60 m^2 to over 2,000,000 m^2. Rockfall occurs in almost every subgroup of the CRBs found within the YRC. Rockfall deposits are distributed throughout the YRC, with large clusters of deposits in three areas of the canyon.

Slides

Slides, which include rotational, translational, and complex slide-flows movement types, are distributed in distinct clusters throughout the study area. This included deep-seated slides and shallow slides. Deep-seated slides included all three slide types while shallow slides were exclusively translational. Slides occur in most basalt types in the canyon including Grande Ronde N2, Grande Ronde R2, Frenchman Springs, and Roza subgroups of the Columbia River Basalt Group (Bentley & Powell, 1984). Spatially, the deep-seated slides are clumped in four areas of the canyon.

Sixteen rotational slides are found throughout the canyon and ranged from 330,000 m^2 to 8,000 m^2. Area of these features totaled over 1,000,000 m^2. These slides generally have large scarps and with hummocky topography. They occur in several locations including steep shoulder slopes and foot slopes, near the Yakima River (Figure 12).

Translational slides were the most abundant in the canyon with a total of 50. Of the total translational slides mapped, 18 were deep-seated rock slides and 23 were

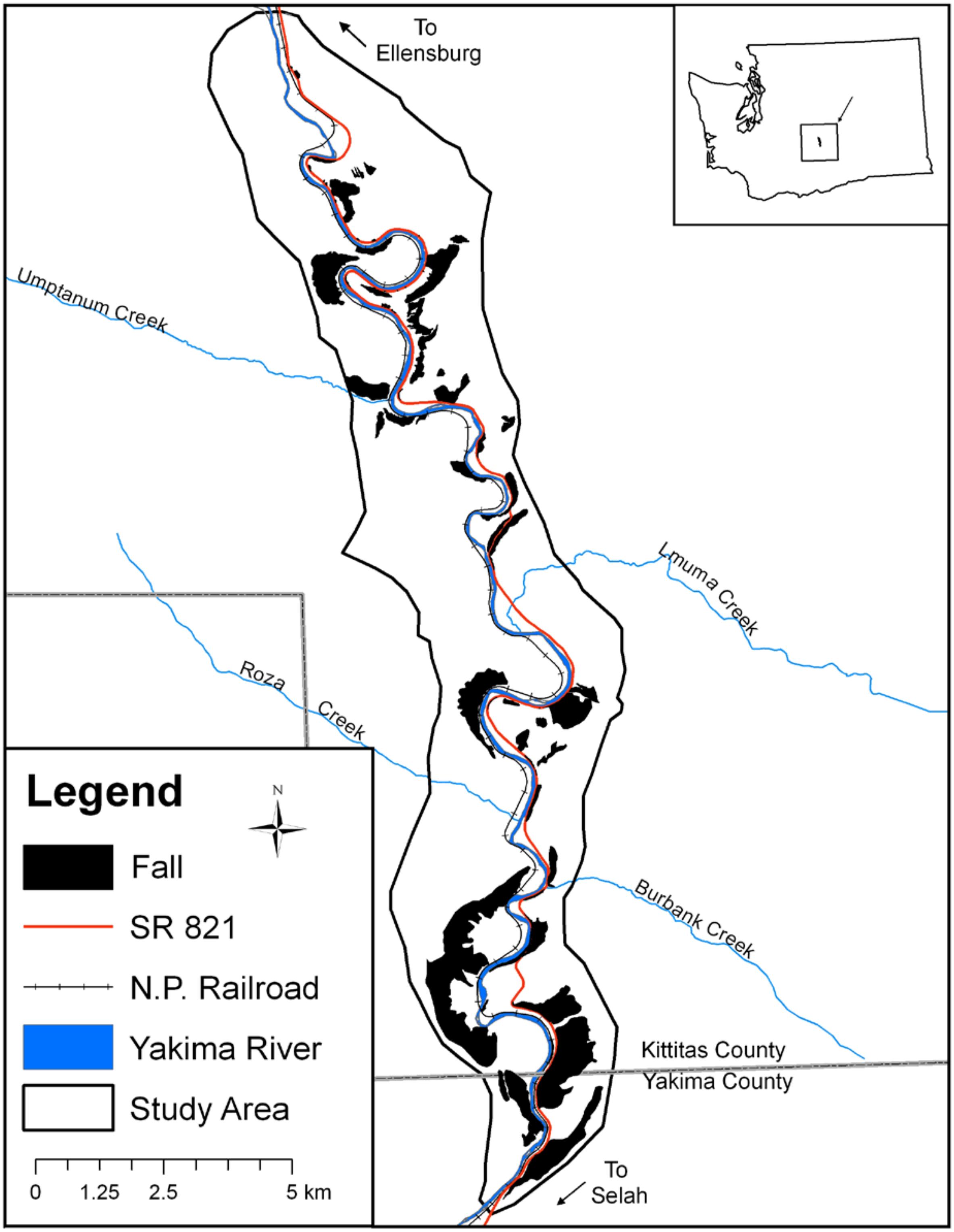


Figure 11. Rockfall distribution in the YRC.

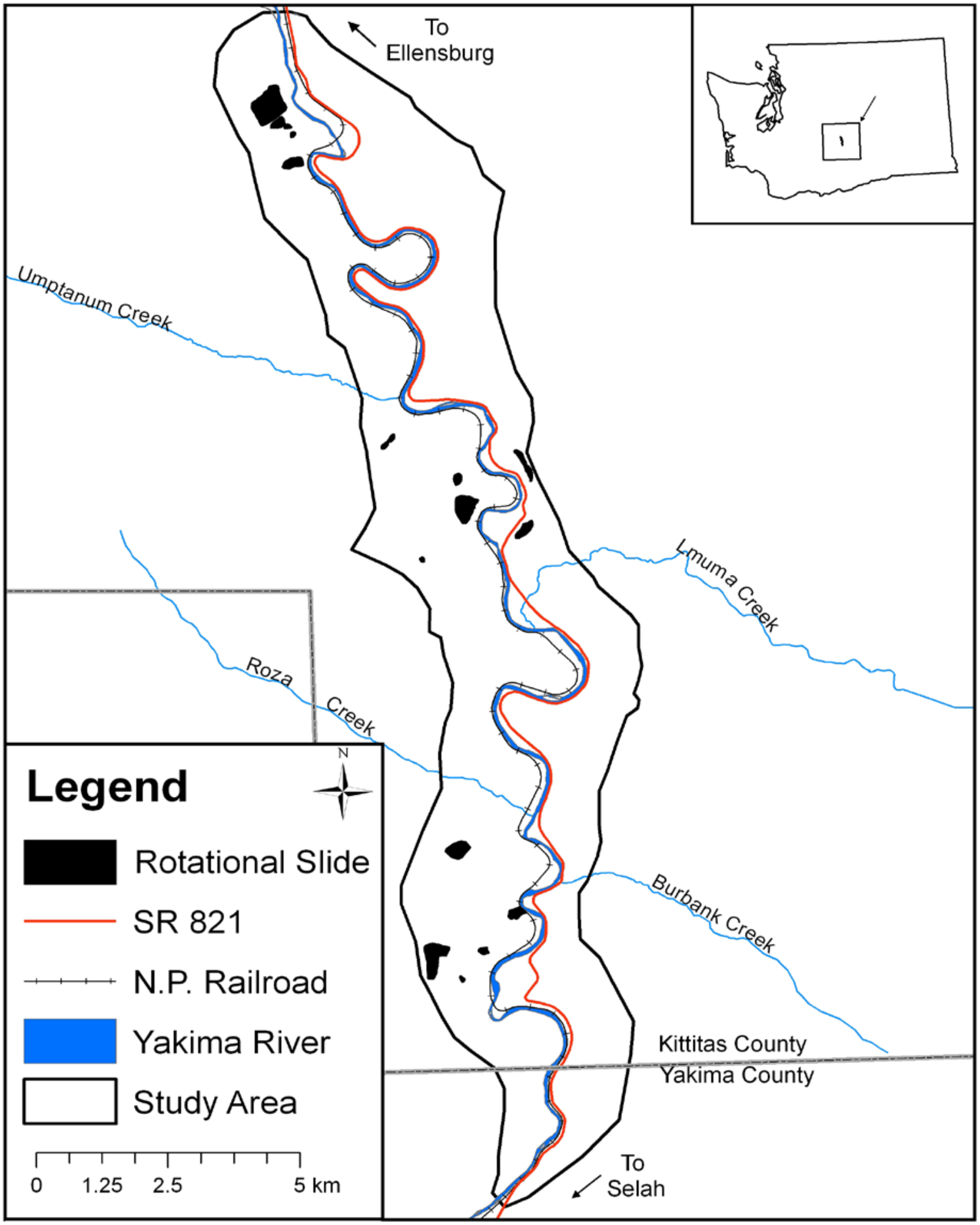


Figure 12. Rotational slide distribution in the YRC.

shallow debris slides. These have more narrow linear scarps with longer runout zones. These shallow translational slides in the YRC are much smaller in size compared to deep-seated slides. Translational slides ranged in size from 300,000 m^2 to 40 m^2. These slides were generally found in or near ephemeral drainages and on steep shoulder and foot slopes (Figure 13). Translational slides are generally the most common sliding phenomena. Due to the shallower, planar nature of these slides, they are much easier influenced by weather events. They do not require the deep infiltration and saturation of materials which is necessary for the triggering of deeper slides such as rotational slides and complex slide-flows.

Complex slide-flows are found exclusively on the southern end of the canyon. These were one of the least common mass wasting features in the YRC with a total of 6. All except for one of these features were clumped in an area of several basalt flows including the Grande Ronde N2, Frenchman Springs, Roza, Priest Rapids and Pomona. These are the largest overall mass wasting features ranging from 850,000 m^2 to 200,000 m^2 (Figure 14).

Identifying and Mapping Historical Mass Wasting

Using Ellensburg *Daily Record* newspaper articles, I identified 24 mass wasting events that occurred in the canyon between 1886 and 1970. These articles ranged from being very descriptive (including information such as location, description of movement, triggering mechanism, and size of the event) to providing little information. The newspaper likely did not use a proper classification scheme so descriptions needed to be

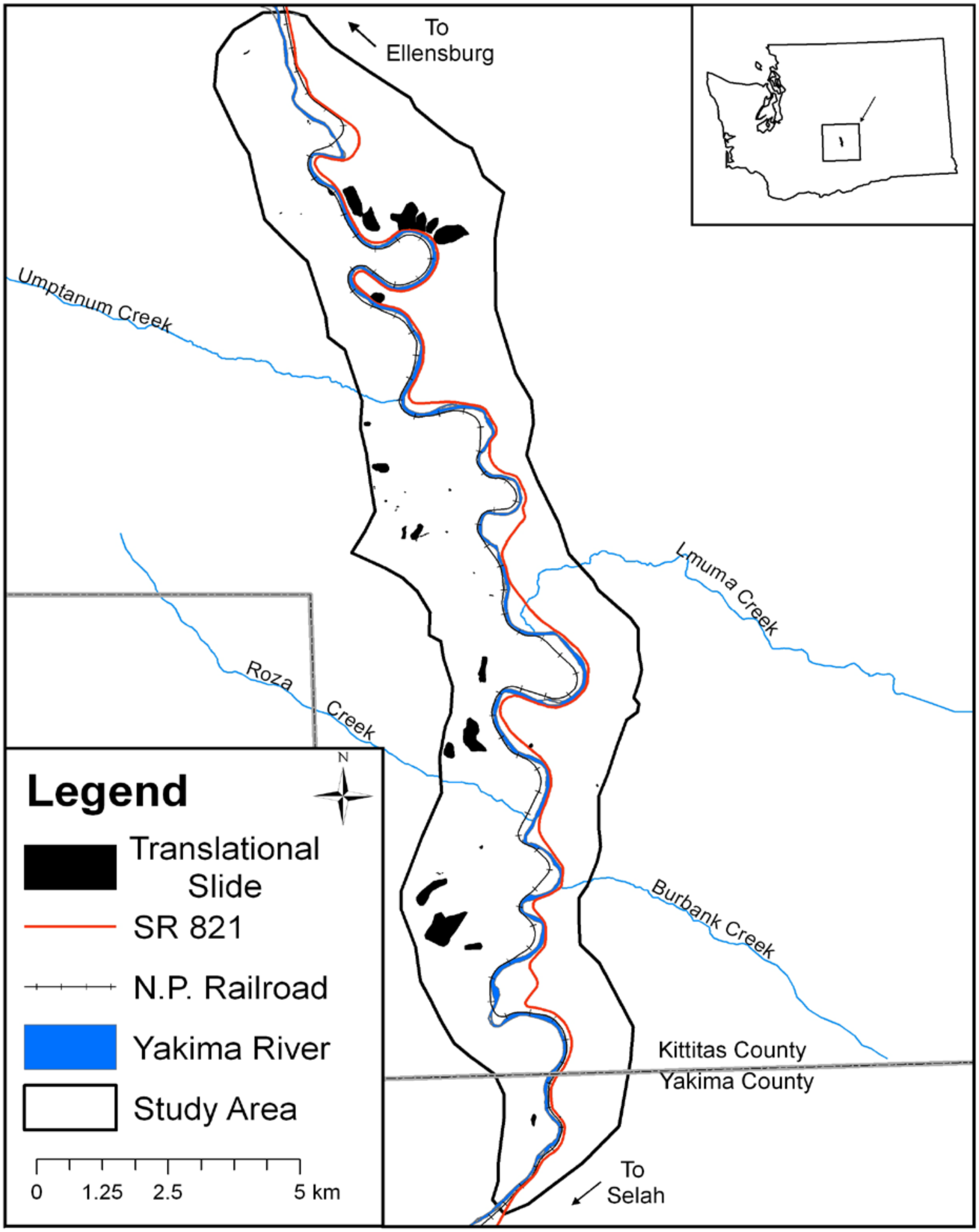


Figure 13. Translational slide distribution in the YRC.

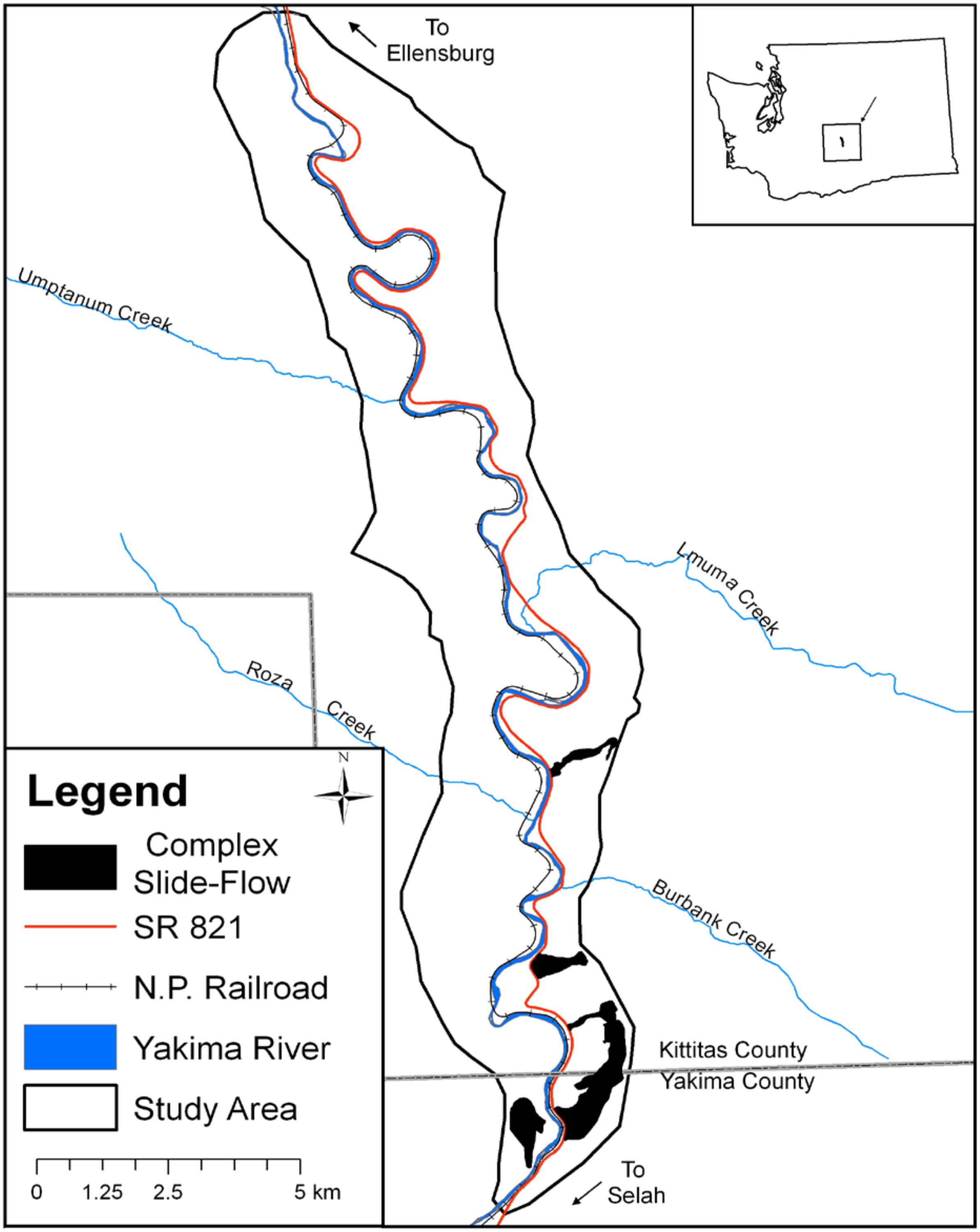


Figure 14. Complex slide-flow distribution in the YRC.

interpreted. Mass wasting events were interpreted by descriptions of newspaper accounts. Three different interpretations were made: 1) descriptions that involved thunderstorms creating wash outs from gullies and deposited fans were interpreted as debris flows; 2) descriptions of boulder falling onto the road were interpreted as rockfall; and 3) descriptions of long duration, moderate rainfall that deposited earth and rock onto the road or railroad were interpreted as shallow landslides. Historical mass wasting events found in newspaper accounts that occurred before 1942 were recorded in the inventory but not mapped. There was no way to positively link these events to the land surface accurately without aerial photographic images that occurred before and after the events. A few small events that occurred after 1942 were also not mapped, because of the small sizes, and the inability to positively identify them. Shallow slides and other smaller mass wasting events can be erased from the landscape within a few years due to erosion and vegetation, adding to the difficulty of identifying and mapping these older historical events (McCalpin, 1984).Out the 24 events found, 12 occurred in the warm season, May through September, and 12 occurred in the cool season, October through April. The descriptions of these events indicated that these events were shallow and were a combination of falls, flows, and slides (Table 7).

Of the 12 cool season events that were identified through newspaper accounts, most were shallow slides and rockfall. One was an earth flow event. It is difficult to determine whether these events were actually shallow slides or rockfall from aerial photographic interpretation. These events occurred along the highway and were described as slides. However, the earth flow that was recorded could be easily identified

Table 7

Historical Cool Season Mass Wasting Events in the YRC as Identified in Newspaper Accounts.

Date	Place	Type	Description
3/15/1929	?	Slide	Blocked 7 m of the highway
1/22/1941	19 km south of Ellensburg	Slide	Small slide blocked highway
1/221953	12 km south of Ellensburg	Earth Flow	765 m^3 of material, near record rainfall
2/16/1954	35 km south of Ellensburg	Fall/Slide	Rolling rocks followed by a slide
11/18/1955	Roza Dam construction area	Slide	Road blocked, 25 cm of snow
3/12/1957	1.6 km north of Highway tunnel	Fall/Slide	Large boulder with accompanying dirt covered highway
2/19/1959	?	Slide	Blocked one lane of highway
12/10/1965	1.6 km north of Roza Camp	Slide	Highway blocked for hour and half
1/261970	South end of canyon	Slide	Blocked both lanes of traffic, 22 cm of snow fell
1/29/1970	Wymer cut	Fall	One lane temporarily closed
2/9/1970	South of Roza cut	Fall/Slide	One lane temporarily closed
2/28/1977	?	Fall	Moderate rainfall

due to the large size of the event. Trigger mechanisms for cool season events were mostly long duration, moderate intensity rainfall events. Snowstorms were less common but also noted as triggering events within newspaper accounts.

One drawback of newspaper accounts is that they vastly underestimate rockfall occurrences in the YRC. Smaller rockfall events were not likely front page news and not every small rockfall that occurred in the YRC was documented in the newspaper. The small rockfall articles found were not front page, but were found because of the Google News Archive search engine. I am unsure whether Google Archive Search found all possible non-front page events; however, the goal of this research was to identify major events in the YRC. Even though this does not provide a complete list to minor rockfall in the YRC it does provide beneficial information on timing and trigger mechanisms. Rockfall is a frequent process in the canyon, which occurs during all times of the year. Washington State Department of Transportation data added to this inventory by identifying 56 slopes in the canyon that have been historically prone to yearly rockfalls. Many of these identified slopes have become unstable by cutting out the sections of hillslope to build Canyon Road, while others were naturally unstable.

These newspaper accounts were useful for capturing debris flow events in the YRC. These data indicated that 12 major debris flow events occurred between 1900 and 2000, and that all occurred during warm season months of May-September (Table 8). No debris flow events were recorded during the winter months. Most of these events are described as cloudbursts that washed rocks down hillsides and gullies that have fanned out onto S.R. 821 or the Yakima River. For example, the first recorded event was likely a

Table 8

Historical Warm Season Mass Wasting Events in the YRC as Identified in Newspaper Accounts.

Date	Place	Type	Description
1/4/1904	Lower YRC	Debris Flow	Debris filled half of the channel of the Yakima River
7/22/1905	0.5 km above Selah	Debris Flow	Heavy rain caused a flow and covered the railroad tracks
7/15/1908	Near Umptanum	Debris Flow	Nine slides, in two locations piled as high as 6 to 9 m
6/24/1918	Many locations	Debris Flow	Railroad covered in many places up to 1.2 m deep
8/16/1924	1.6 km north of Wymer	Debris Flow	Covered railroad tracks in two places
6/22/1930	Near Wymer	Debris Flow	Covered the highway in two places
6/7/1936	Near Wymer	Debris Flow	Covered railroad tracks at Wymer
9/14/1940	6 km south of Thrall	Debris Flow	Covered 6 m of railroad track
8/12/1952	between Wymer hill and the tunnel	Debris Flow	Highway and railroad covered in several places
6/20/1967	Beavertail Bend	Debris Flow	Debris from two gullies, 9 m wide and 1.5 m deep
6/22/1973	Many locations	Rockfall	Wind causing rockfall 17 -22 m/s
7/3/1998	Beavertail Bend	Debris Flows	Five major debris flows and several smaller flows north of Umptanum

debris flow due to the description of Lmuma Creek being a torrent for a short while. The article also describes ravines in other areas having torrents of water washing through them. This event occurred on July 9, 1904 in which a cloudburst caused a washout that filled half of the river channel with debris in the lower YRC. The debris also covered the railroad tracks and required 75 men, 12 hours to get the railroad back in working order. In 1905, a cloudburst caused a “landslide” in the lower YRC. This landslide was more likely a debris flow with boulders, sand, and gravel washing through gullies. The rest of the summer events were described as washouts, even sometimes noting that they came out of gullies, indicating that they were likely debris flow events. At least five of these events have deposited in the Yakima River. It is likely that more of these events have impacted the Yakima River, but many descriptions from newspaper articles, did not include whether or not a debris fans were deposited in the river. Many of these events were associated with warm summer temperatures, leading to the formation of convectional thunderstorms. These events were short in duration, mostly an hour or less and were character of sporadic short-duration thunderstorms that occur in arid to semi-arid lands (Abraham & Parsons, 1994; Cooke & Warren, 1973).

Through sequential aerial photograph interpretation, I identified 35 historical mass wasting features in the Yakima River Canyon (Figure 15). The newspaper inventory of the YRC aided in the identification of mass wasting events from aerial photographs. Features with an absolute date were identified from newspaper articles and features occurring between time periods were identified using air photograph interpretation. Features identified were exclusively shallow features that consisted of debris flows,

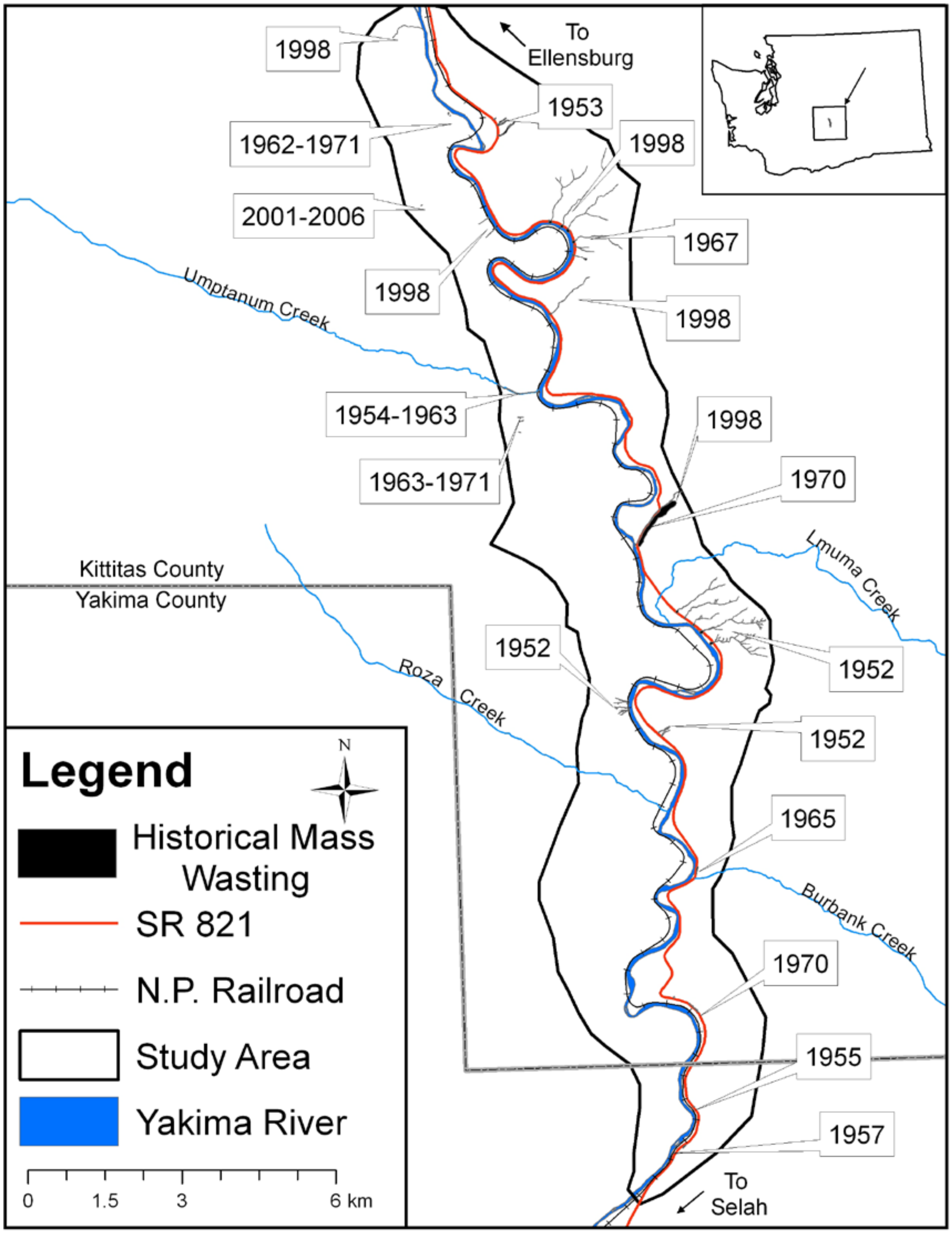


Figure 15. Mass wasting events occurring between 1942 and 2006 in the YRC as identified from aerial photographs and newspaper accounts. The labels showing a range (e.g., 154-1963) were identified from aerial photographs alone.

earth flows, shallow landslides, and rockfall. One deep-seated landslide identified in the canyon is suspected to be active due to a crack in the crown of the slide, but is likely in a dormant state or is a very slow-moving landslide because no movement could be detected with sequential images (Wieczoreck, 1984). With the scale of these images between 1:20,000 and 1:24,000, it would be difficult to detect a slow moving landslide at a rate of only a few centimeters per year (Wieczoreck, 1984).

State of Activity

Morphologic dating in the YRC shows 70% of mass wasting were active or inactive young, 18% were inactive mature, and 12% were inactive-old (Figure 16). The majority of active and inactive-young mass wasting features were shallow slides, debris flows, and rockfall, while the majority of inactive-mature and inactive-old features were deep-seated slides and complex slide-flows. The active features in the YRC were seemed to be spatially linked to cut banks of the Yakima River, with almost every sharp meander being adjacent to active features. Two deep-seated slides were classified as inactive-young. This can pose reconsideration for dating by morphology in semi-arid lands. These two features fit the inactive-young description perfectly, but have occurred before the oldest aerial photographic images and likely well over 100 years old, possibly hundredsof years old (McCalpin, 1984). The current semi-arid climate preserves these features keeping the scarps sharp and devoid of vegetation. All other deep-seated slides and complex slide-flows were classified as inactive-mature or inactive old and are likely late

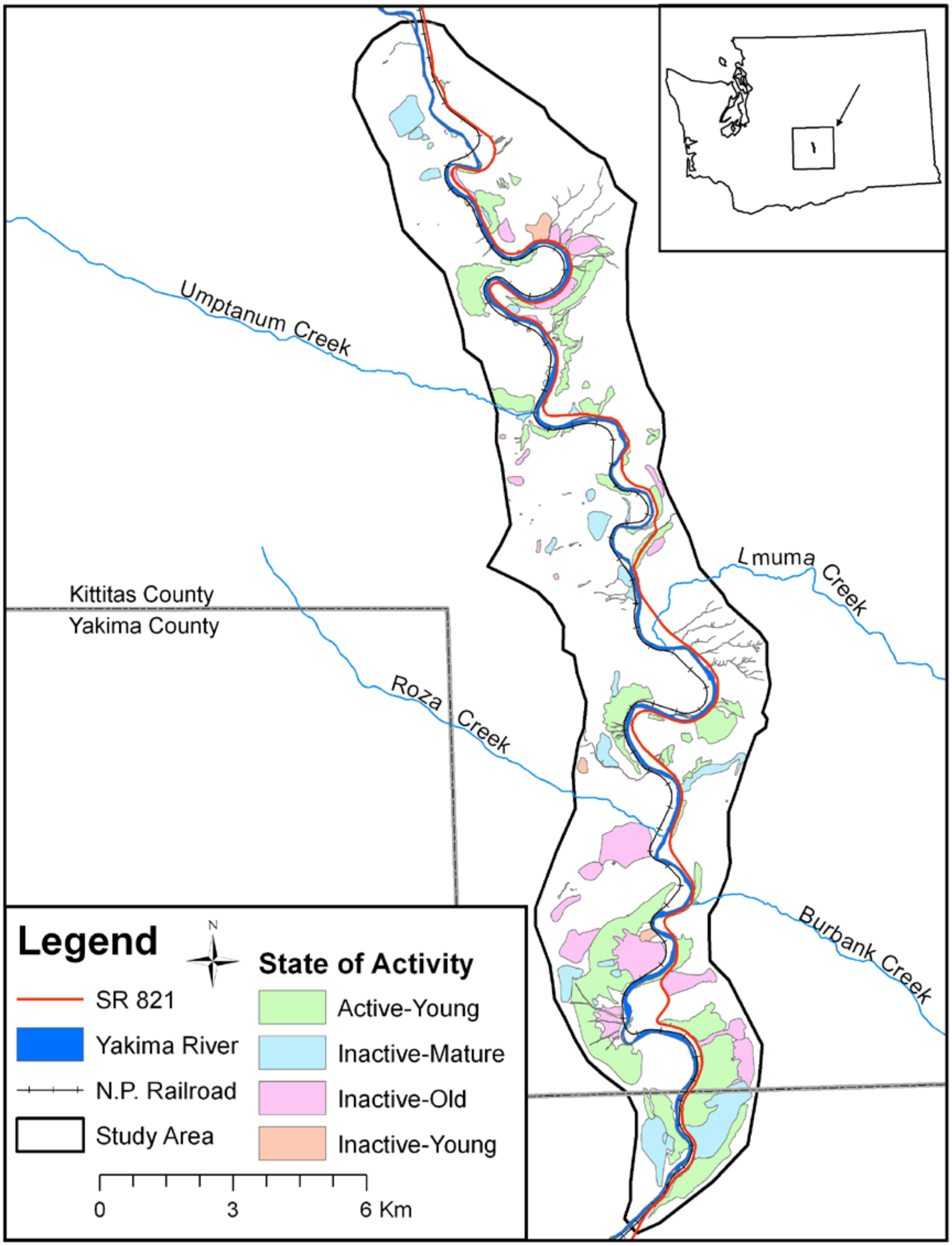


Figure 16. State of activity for mass wasting in the YRC. Based on Lillquist (2001) and McCalpin (1984).

Pleistocene to early Holocene age. This can be an indication of the current climate not being conducive for deep-seated landslide occurrence the YRC.

Mass Wasting Control Variables

Overview

Control variables for mass wasting in the YRC vary among different forms of mass wasting. This analysis separates deep-seated movements from shallow movements including shallow landslides, debris flows, and rockfall. This was done to provide the most accurate hazard maps for the canyon.

Debris Flow Control Variables

Debris flows in the Yakima River canyon were treated separately from other mass wasting events due to differences in formation, trigger mechanisims, and ultimately different control variables. GIS and statistical analyses indicate that debris flows are controlled by four major factors: slope angle, slope elevation, slope convexity, and watercourses (Table 9). Slope angles between 16 and 30 degrees were significant for debris flows, with 60% of debris flows initiating on these slopes. Slope elevations between 500 m and 700m were significant for debris flows initiation, with 63% of all flows starting between these elevations. Even though elevation is significant for landslide distribution, it should be considered an indirect factor (Jimenez-Peralvarez et al., 2009). Elevation is really about landscape position in the YRC with the elevations between 500-700m containing slope angles more prone to landsliding. Concave slopes and water courses are the most significant factors for debris flows with all of these features occurring in confined, concave drainages. This is likely because convex slopes have a

Table 9

Control Variables Analyzed for Debris Flows in the YRC

Factor	Class %	χ^2
Elevation		18.8*
<500m	26	
500-700m	**64**	
>700m	*10*	
Distance to Watercourses		83.1*
>50m	**100**	
<50m	0	
Lithology		4.8
Grande Ronde N2	65	
Grande Ronde R2	15	
Frenchman Springs	15	
Roza, Priest Rapids, Pomona	5	
Slope Angle		14.3*
0-15	10	
16-30	**60**	
> 30	*30*	
Slope Aspect		1.18
North	15	
East	30	
South	27.5	
West	27.5	
Slope Convextity		50.9*
Concave	**100**	
Convex	0	

Note. * indicates significant results. χ^2 = Chi Square Value, $P = 0.5$, df = Degrees of Freedom, $N = 41$, **High Hazard**, *Moderate Hazard*, Low Hazard higher ability to concentrate runoff (Baeza & Corominas, 2001). No significant relationship was found for lithology and debris flow occurrence. Because of this, debris flows were not tested for relationships between lithologic contacts and geologic structures since lithology was not a significant control variable. While some research has focused on lithology (Sterling & Slaymaker, 2007), many others have focused on parameters such as channel length, basin size, average basin slope, and availability of debris supply (Bovis & Jakob, 1999; Ikeya & Mizuyama, 1982; Kronfellner-Kraus, 1983).

Basin size and mean basin slope relate to debris flow occurrence (Kronfellner-Kraus, 1983). A Spearman rank test set at $p = 0.05$ showed a moderate inverse correlation ($r_s = -0.67$) between average slope of the basin and basin area for debris flow distribution in the YRC. This means the larger the basin area, the less the slope needs to be for debris flow occurrence. Smaller basins must have steeper slopes to be more susceptible to debris flows (Kronfellner-Kraus, 1983).

Historical records show that these events are mainly controlled by weather events. Even though the YRC is a winter wet precipitation regime there were over 10 significant debris flow events in the warm season months of the last 126 years. No cool season debris flows were recorded. This supports Kaatz’s (2001) conclusion that the YRC’s characteristic low intensity winter rain and snow events do not produce enough surface runoff to initiate debris flows. Spatially, the relationship for debris flow distribution seems to be controlled by the extent of the cloudburst and its relationship to drainages. Sources for debris flows seem to be abundant in the entire study area with recharge of sediment sources being very rapid. In 1967, debris flows covered the road in two spots at "Beavertail Bend" in the YRC just north of Umptanum Recreation Area ("Slides Block Highway" 1967). In 1998, these two same gullies, along with several other gullies, produced debris flows of greater magnitude. The abundance of rock-mantled slopes, old colluvium, and talus slopes are the likely sources for rapid recharge in the YRC.

Earth flows are likely the most unusual mass wasting features in the YRC. Earth flows are notably rare in semi-arid lands due to the shallowness of the regolith in these regions (Abraham & Parsons, 1994). These events occurred in an area of a thick loess deposit (Campbell, 1979), in which earth flows are common (Crozier, 1968). These events occurred on relatively shallow slopes, less than 15 degrees. The newspaper account attributed these events to near record rainfall that occurred during January of 1953 ("Canyon Road Cleared" 1953).

Rockfall Control Variables

Rockfall deposits are present in all areas containing very steep slopes and cliff faces. Two main types of rockfall were mapped in the canyon: 1) rockfall from cliff faces producing shallow, talus slopes; and 2) rockfall and dry ravel from anthropogenically destabilized slopes created from the construction of the railroad and State Route 821. In comparison to slides and flows, these events are small and frequent events, which are similar to current magnitude-frequency relationships (Hunger & Evans, 2007). Control factors seem to rely heavily on weather events. Rain and snow events are the most abundant factors that have led to rockfall in the YRC, but other factors have caused rockfall such as freeze/thaw and even wind. McCauly, Works, and Naramore (1985) attributes wind events for 12% of the rockfall that occurs along California highways. Bob Wolf, the road maintenance crew lead for the Washington State Department of transportation has also attributed small rockfall events to wildlife in the YRC, including mule deer and bighorn sheep (Personal Communication May 05, 2010).

Deep-Seated Slide Control Variables

Several control variables were tested for the YRC. Control variables tested include elevation, slope angle, slope aspect, slope convexity, lithology, lithologic contacts, distance to geologic structures, and distance to water courses. The control variables found significant to the YRC are elevation, slope angle, lithology, and lithologic contacts (Table 10).

Chi-square analysis revealed that elevation is a significant factor for landslide distribution in the YRC. Ten percent of the deep-seated landslides occurred in the canyon below 500m, 64% occurred between 500-700m, and 26% occurred above 700m. Even though elevation is significant for landslide distribution it should be considered an indirect factor (Jimenez-Peralvarez et al., 2009). Elevation is really about landscape position in the YRC with the elevations between 500-700m containing slope angles more prone to landsliding. Elevations above 700m were mostly shoulder slopes or ridge top summits with lower slope angles. Elevations below 500 were generally lower angle toe slopes and foot slopes, debris fans, and steep cliffs formed by fluvial erosion in the YRC which are generally less prone to deep-seated landsliding (Cruden & Varnes, 1996). Other factors with elevation include differences in precipitation, freeze/thaw cycles and vegetation development (Jimenez-Peralvarez et al., 2009).

Table 10

Control Variables Analyzed for Deep-Seated Slides in the YRC.

Factor	Class %	χ^2
Elevation		24.6*
<500m	5	
500-700m	**67**	
>700m	*28*	
Distance to Anticlines and Synclines		1.6
<1 km	54	
>1 km	44	
Distance to Faults		0.2
<1 km	54	
>1 km	46	
Distance to Watercourses		0.36
<200m	54	
>200m	46	
Lithology		26.2*
Grande Ronde N2	38	
Grande Ronde R2	*7*	
Frenchman Springs	**49**	
Roza, Priest Rapids, Pomona	*5*	
Lithologic Contacts		10.3*
<300m	**95**	
>300m	5	
Slope Angle		18.2*
0-15	8	

Table 10 (Continued)

Factor	Class %	χ^2
16-30	**69**	
>30	*23*	
Slope Aspect		0.9
North	15	
East	28	
South	28	
West	28	
Slope Curvature		0.36
Convex	51	
Concave	49	

Note. * indicates significance. χ^2 = Chi Square Value, *P* = 0.5, *df* = Degrees of Freedom, *N* = 39, **High Hazard**, *Moderate Hazard,* Low Hazard

Slope angle was also a significant control variable in the YRC with a Chi Square value of 18.2. Slope angle is generally considered to be one of the most common factors contributing to slope stability (Lee et al., 1997). Slope angles between 16 and 30 degrees encompassed 21% of the study area but contained 69% of the deep-seated landslides in the study area. Slopes of greater than 30 degrees were generally less prone to landsliding, but were more prone to rockfall.

Spatially, it appears that landslides in the YRC are clumped around geologic structures including anticlines, synclines, and faults. Landslide frequency-based statistics found these structures to be not significant. Safran and others (2011) found that local relief has a higher influence to landslide distribution than anticline axes in a geologically and climatically-similar area of Central Oregon. However, these factors can still create conditions for landsliding in the YRC. The combination of interbedded basalt layers of the CRBG and the uplift of the Yakima Fold Belt created dipping beds with that formed shear planes that are prone to landsliding. Fluvial and alluvial incision into these basalt layers can further decrease stability of slide planes by eroding material from the base creating room for the block to slide (Figure 17). This process also increases the shear stress on the slide block by removing the toe of the block.

Lithology and lithologic contacts are the most important factors for deep-seated landslide distribution in the YRC. The Frenchman Springs basalt had the highest rate of landslide occurrence and the highest significance in the analysis with a Chi Square valueof 21.2. The Frenchman Springs basalt made up 18% of the study area but was the source for almost half of the canyon's deep-seated landslides. This is likely due to the Vantage sandstone of the Ellensburg Formation, which is a soft, incompetent sediment layer underlying the Frenchman Springs basalt (Powell & Bentley, 1984). The Grande Ronde N2 basalt had the highest percentage of area making up 61% of the study area, but containing only 15 mass wasting features. The Grande Ronde R2 basalt consisted of 17% of the study and only contained 3 landslides. Since deep-seated landslide distribution seems to be largely dependent on sedimentary interbeds, the Grande Ronde R2 is likely lacking deep-seated landslides because the sedimentary contacts of the Grande Ronde R2 were not exposed by the uplift of Yakima Fold Belt. However, the Grande Ronde R2 produced smaller landslides on anti-dip slopes produced by the Baldy Mountain thrust fault (Bentley & Powell, 1984). Other lithology types present in the canyon include the

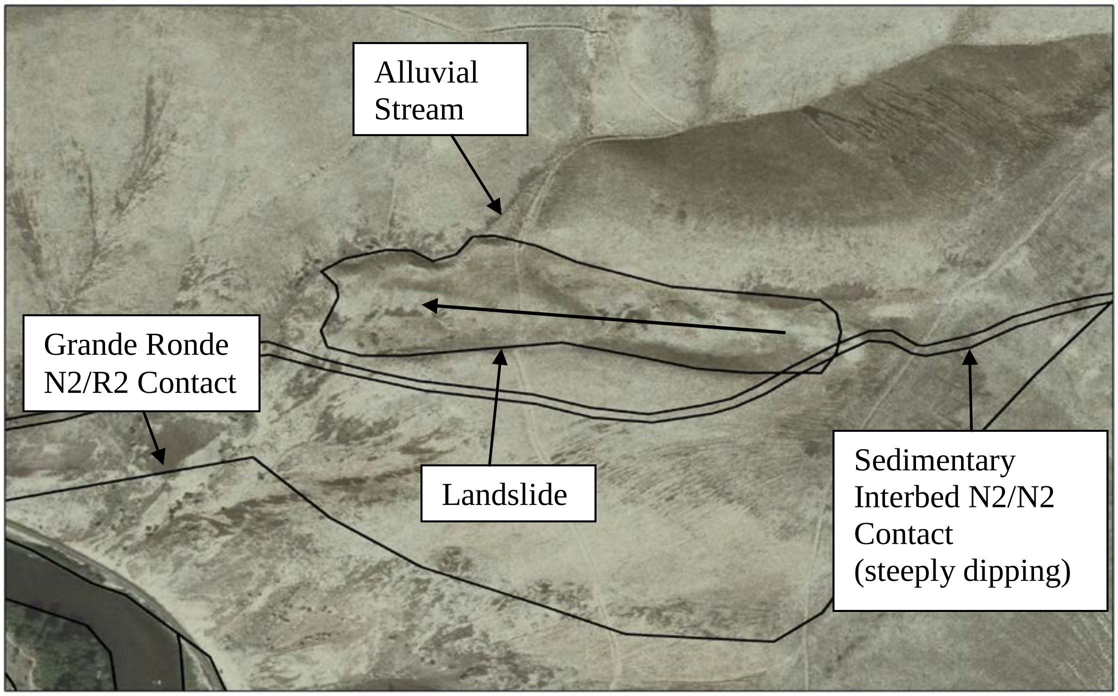


Figure 17. A landslide in the YRC with a relationship to lithology, lithological contacts, dipping bed plane, and alluvial down cutting.

Roza, Priest Rapids, and Pomona basalts. Due to the small overall area of these basalt types present in the canyon, these lithologies were clumped together for statistical analysis in order to meet assumptions for the Chi square test. Since they were overlying each other in one specific area this clumping did not seem to affect the results of the chi square test. This area of the canyon produced a different type of deep-seated landslide known as complex slide-flows. This is likely due to the fact that these basalt flows are much thinner in comparison to the Grande Ronde basalts and are interbedded between every layer of these thin basalts. These slides appear to have slid on the Vantage sandstone; however, the presence of multiple, invening, weak layers of the Ellensburg Formation caused these basalts to disintegrate and mobilize into a flow-like deposit.

Since these features have had more than one movement, they were labeled complex slide-flows (Cruden & Varnes, 1996). These slides are old. Like many of the deep-seated slides in the canyon the morphology of these features can make it difficult to distinguish features (Cruden & Varnes, 1996; McCalpin, 1984).

An important consideration for these old deep-seated landslides is the Yakima River. As an antecedent steam the Yakima River cut through this canyon and provided conditions for land sliding such as creating over-steepened slopes and outcroppings of weak interbeds that are prone to land sliding. Since the early 1900s many dams have been constructed in the Yakima River watershed, ultimately limiting and reducing the peak flows of the Yakima River. This reduction of peak flows could ultimately reduce mass wasting with the effects of fluvial undercutting being highest as peak flows.

Shallow Slide Control Variables

Shallow landsliding in the YRC should be considered independently from deep-seated landslides for several reasons. No significant relationship was found between lithology, lithologic contacts, and altitude which were the main control variables for deep-seated mass wasting features. Since lithology was not a significant control variable, the relationship between lithologic contacts and anticlines was not tested for shallow features. However, the distribution of anticlines can influence slope angle.

Shallow features were found to have four significant control variables including slope angle, slope convexity, slope aspect and relationship to water courses (Table 11). These results fit well with existing literature on shallow landsliding and their relationship

Table 11

Control Variables Analyzed for Shallow Translational Landsliding in the YRC

Factor	Class %	χ^2
Elevation		2.4
<500m	37	
500-700m	51	
>700m	12	
Distance to Watercourses		19.0*
<200m	**86**	
>200m	14	
Lithology		4.0
Grande Ronde N2	49	
Grande Ronde R2	28	
Frenchman Springs	20	
Roza, Priest Rapids, Pomona	3	
Slope Angle		18.9*
0-15	6	
16-30	**64**	
>30	*23*	
Slope Aspect		21.1*
North	*17*	
East	**63**	
South	14	
West	6	
Slope Curvature		31.9*
Convex	9	
Concave	91	

Note. * indicates significant results. χ^2 = Chi Square Value, *P* = 0.5, *df* = Degrees of Freedom, *N* = 35, **High Hazard**, *Moderate Hazard,* Low Hazard to colluvial hollows and inner gorges (Baeza & Corominas, 2001; Slaughter, 2009). Slopes between 16 and 30 degrees were most prone to landsliding as 71% of shallow landslides occurred in this class and concave slopes of colluvial bedrock hollows and inner gorges contained 91% of all shallow slides.

Descriptions of historical events link occurrences of shallow landslides to the wet season (including winter and spring). Historical records indicate that snowstorms and cool season rain events that produce moderate to heavy rainfall for a long duration are the primary trigger mechanisms for shallow landsliding in the YRC (Wieczoreck, 1996).

Hazard Mapping

Seven hazard maps were produced for the YRC consisting of debris flow initiation hazard areas, debris flow hazards, rockfall hazard areas along the transportation corridor, deep-seated landslide hazard areas (GMM), deep-seated landslide hazards (bivariate statistical analysis), and shallow landslide hazard (LiDAR-derived) and shallow landslide hazards (statistical approach) (Table 12).

Debris Flow Hazards

With 12 major events in the last 126 years, debris flows are the most likely type of mass wasting that could have a major effect on infrastructure in the YRC. Two debris flow hazard maps were created for the YRC: 1) a hazard map using all of the significant control variables tested (Figure 18); 2) a hazard map using all of the significant control variables except elevation (Figure 19). The first map was based on debris flow initiation, in which elevation was determined to be significant, illustrating more hazardous areas in

Table 12

Percentages of Each Hazard Class by Mass Wasting Type in the YRC.

Hazard Map	High %	Moderate %	Low %	Very Low %
Debris Flow Initiation	5	21	40	35
Debris Flow	10	24	44	23
Rockfall	40	9	28	23
Deep-seated (GMM)	12	16	20	52
Deep-seated (Statistical)	28	36	22	14
Shallow Slides (LiDAR)	8	7	16	69
Shallow Slides (Statistical)	8	27	38	27

the higher reaches of the canyon and lower hazards near the transportation corridor. This may be true for debris flow initiation, but it is not true for all debris flow hazards. Without the elevation parameter, the debris flow hazard map illustrates more precisely the potential hazards to the transportation area, essentially making a more useful map.

The debris flow initiation map indicates that 5% of the study area is classed as high hazard, where the debris flow hazard map doubles this percentage with 10% of the

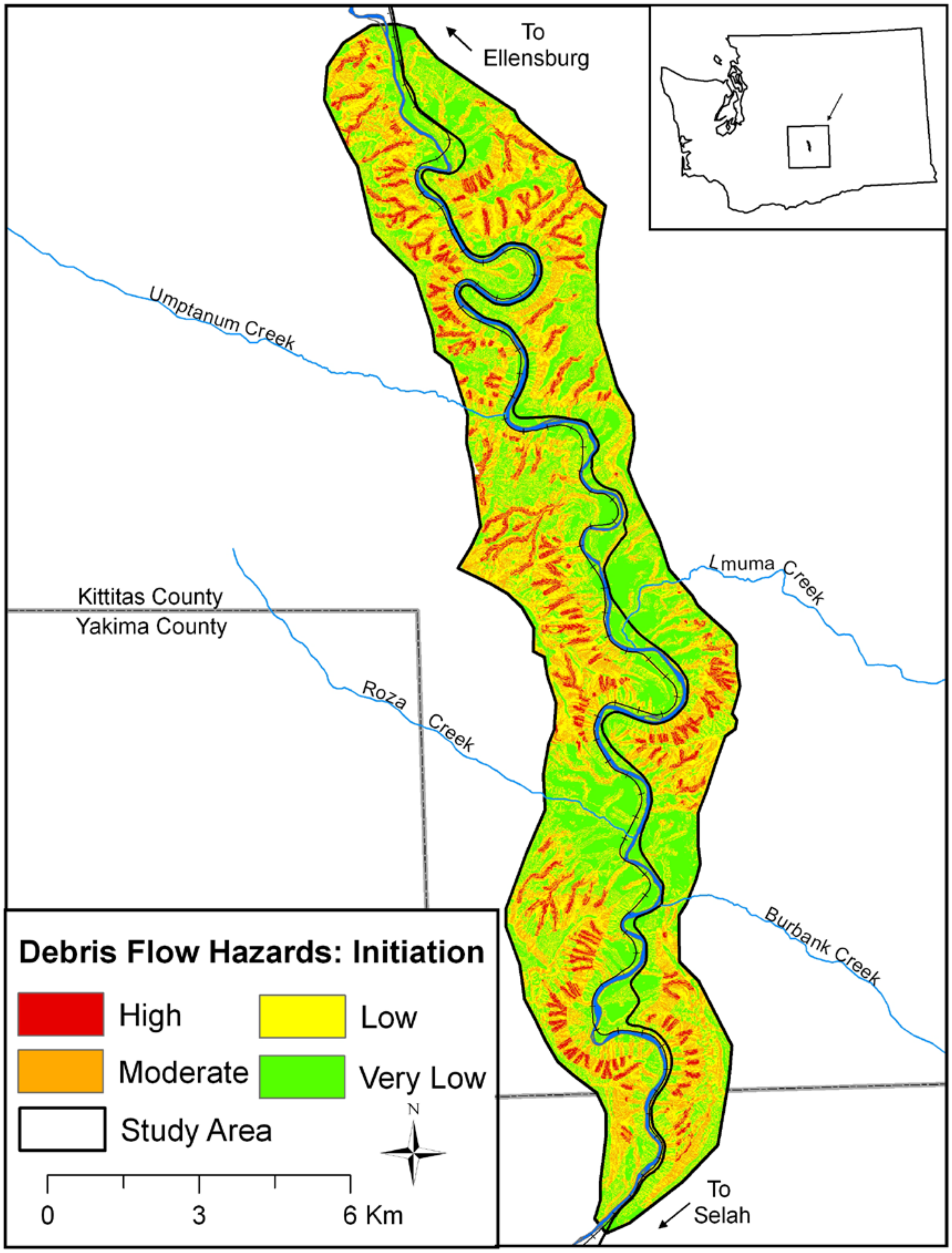


Figure 18. Hazard map for debris flow initiation in the YRC.

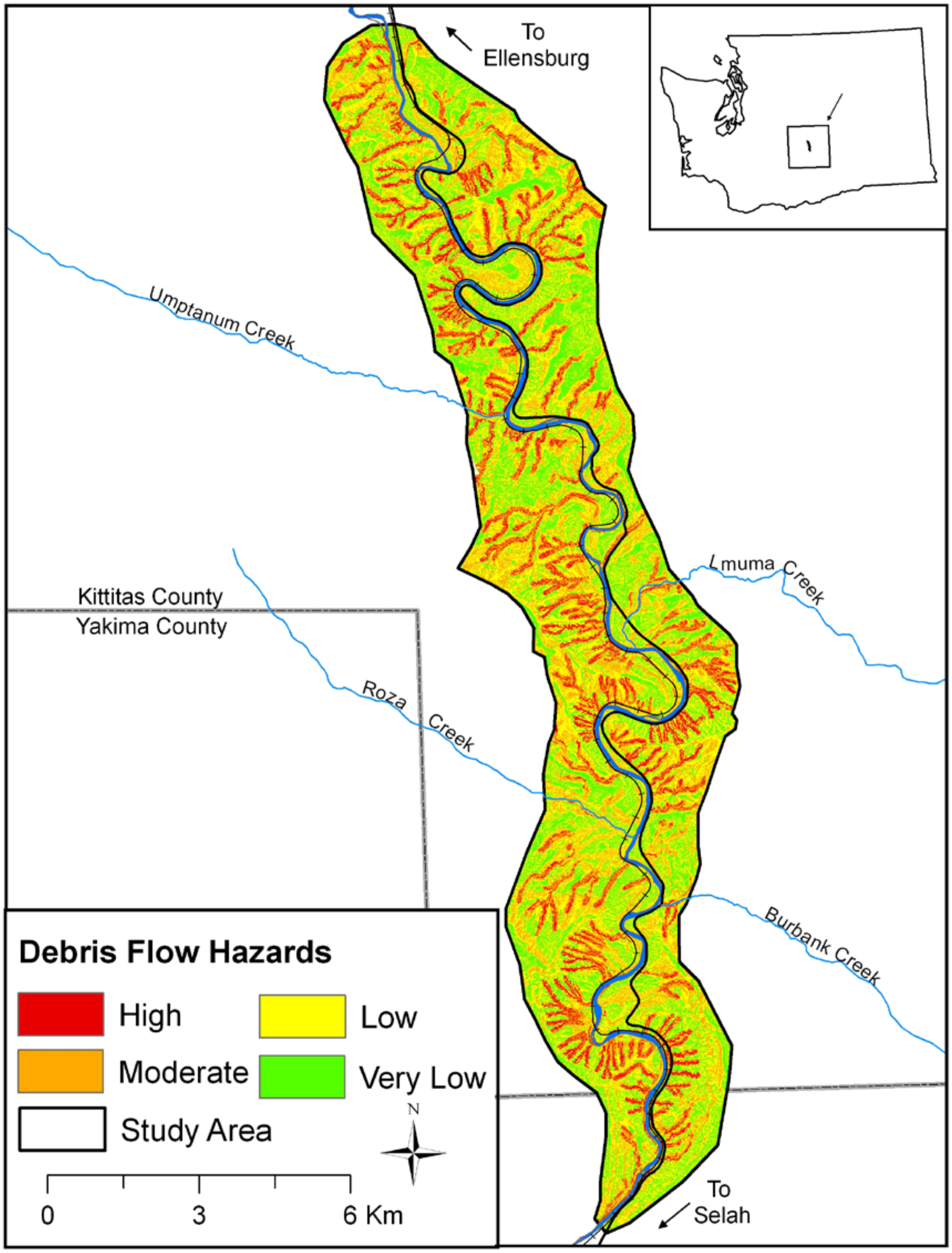


Figure 19. Hazard map for debris flows in the YRC.

study area consisting of high hazards. The areas of highest hazards were concave drainage basins or channels with steep slopes. Coe, Kinner, and Godt (2008) found that debris flow initiation occurred in rills and channels of 14 to 45 degrees in the semi-arid Chalk Cliffs of Colorado, which is climatically similar to the YRC.

Rockfall Hazards

Rockfall hazards along the transportation corridor are significant (Figure 20). Forty percent of the canyon is at a high risk for rockfall. Much of these high hazard areas are due to the construction of the highway and the railroad. Constructing these transportation corridors required under cutting out sections of the hillsides, which resulted in over-steepened slopes. These slopes produce rockfall, dry ravel, and shallow debris slides along the transportation corridor (Gabet, 2003; Wylie & Norrish, 1996). Other rockfall hazards exist below cliff faces along or near the highway and railroad. These cliffs were formed long ago by fluvial incision (Baker et al., 1987).

Deep-seated Slide Hazards

Two hazard maps were created for deep-seated landsliding in the YRC. This was done so that results could be compared to provide the most useful map. The hazard map produced for deep-seated landslides using the GMM in the YRC showed that 12% of the study area was highly prone to deep-seated landslides (Figure 21). Moderate hazard areas were found in 16% of the study area, while low hazard occurs in 20% and very low hazard is in 52%. The GMM used in this study has been compared to other methods in a mountainous area of Spain and produced similar, acceptable results, making it a suitable

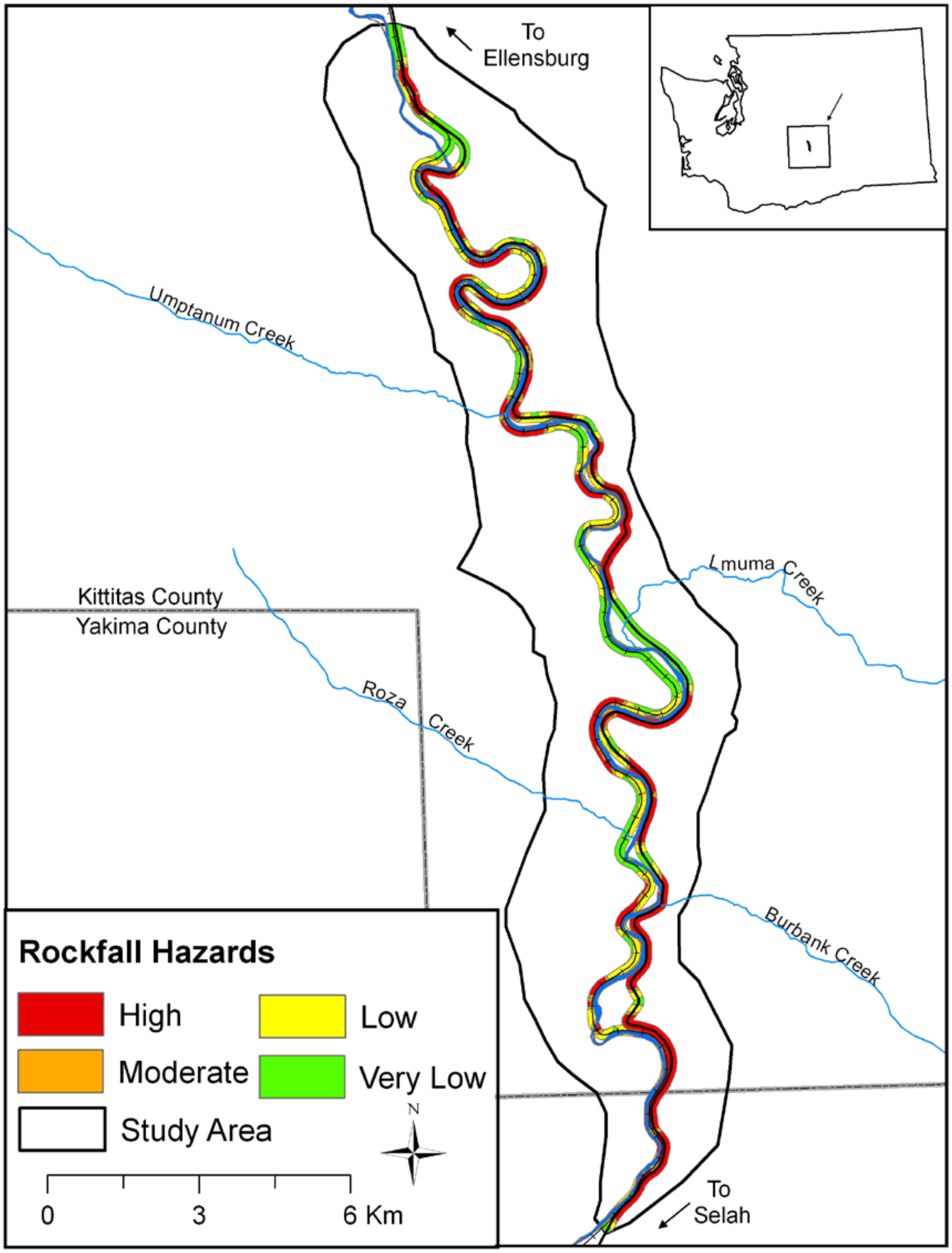


Figure 20. Rockfall hazards along the transportation corridor in the YRC.

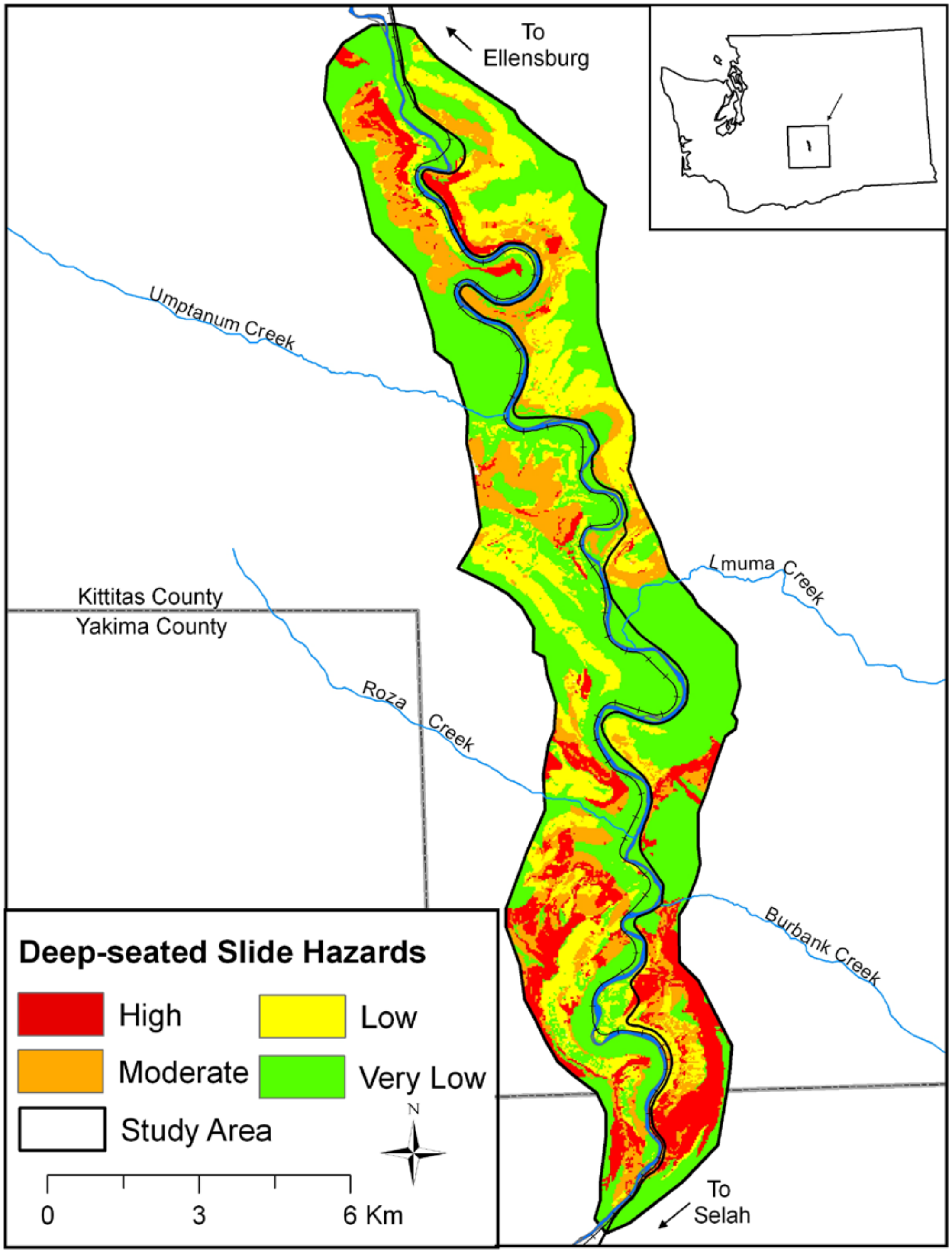


Figure 21. Deep-seated landslide hazard map using the GMM for the YRC.

method of landslide susceptibility mapping (Jimenenz-Peralvarez, Irigaray, & Hamdouni, 2009). The difference in the results is that GMM produced lower percentages for high and moderate susceptibility classes than the statistical approach. This could benefit the YRC since many of the landslides in the YRC are inactive and very old, indicating that Data from phytolith and pollen records also indicate a colder and wetter climate in the the current conditions and climate might not be well-suited for deep-seated landslides. late Pleistocene, with a transition to the warmer and drier climate into the Holocene leading to the present-day climate (Blinnikov, Busacca, & Whitlock, 2002). The GMM could, in turn, identify the most hazardous areas for future landslides to occur, while not over-exaggerating the potential for deep-seated landslides. This hazard map should be considered a screening tool and any proposed development should still require an onsite geomorphologic evaluation (Soeters & van Westen, 1996).

The hazard map produced for deep-seated landslides using the statistical approach produced higher percentages for high and moderate hazard classes (Figure 22). The statistical approach showed that 28% of the study area was highly prone to landsliding. Moderate hazards were found in 36% of the study area, while low hazards occurred in 22% and very low hazard is in 14%. This map is a better fit for landslide distribution with almost all of the deep-seated landslides being found in the high hazard areas, where the GMM placed many of the inventoried landslides into the moderate hazard class (Soeters & van Westen, 1996). Regardless of which hazard map may be used for land use planning, the key to control variables for deep-seated landslide distribution in the YRC are the sedimentary interbeds and lithologic contacts present in the canyon. This should

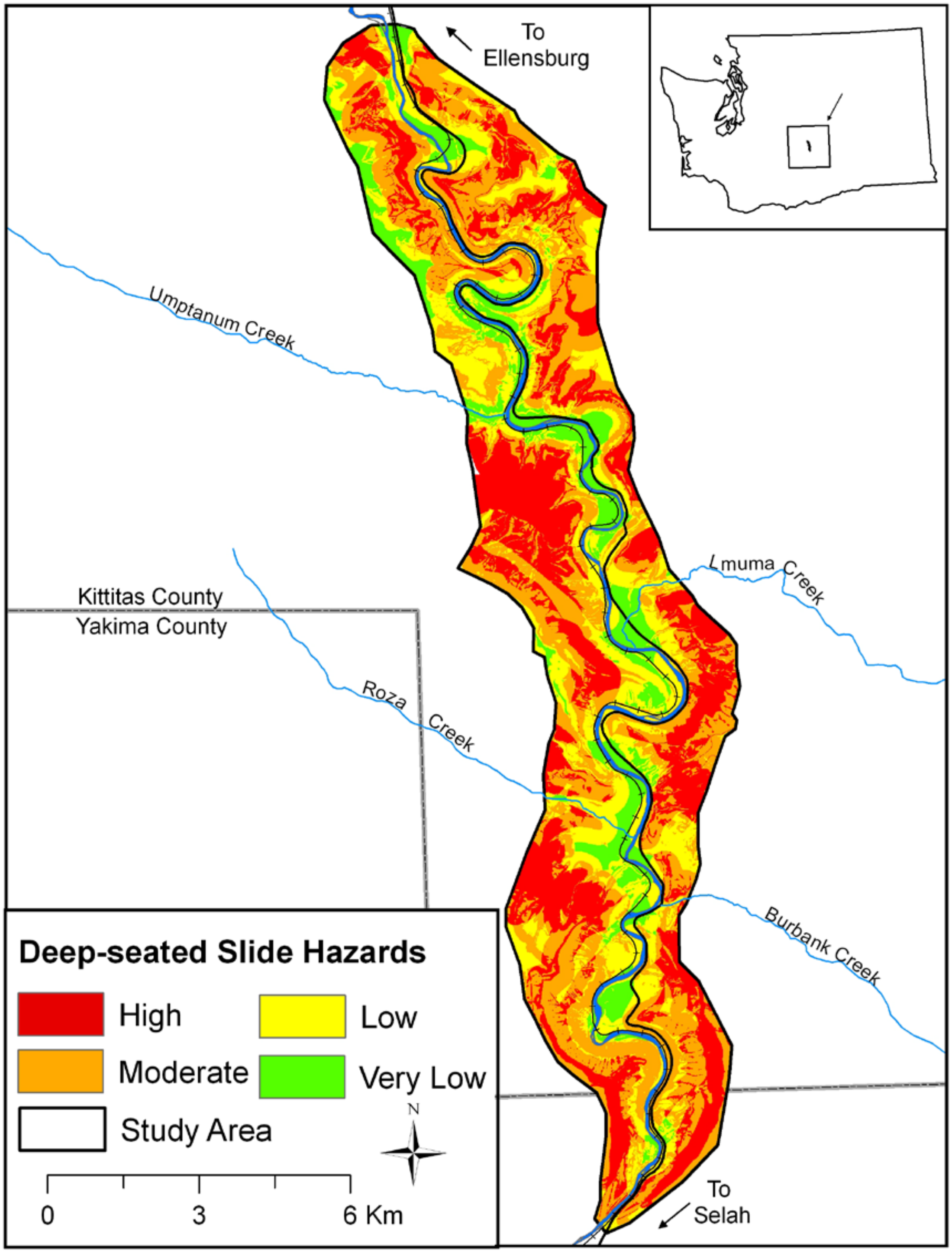


Figure 22. Deep-seated landslide hazard map using the statistical approach for the YRC.

indicate the statistical approach map should be the hazard map of choice for two reasons. It is a better match for landslide distribution in the YRC and it produced higher hazard scores to areas near sedimentary interbeds and lithologic contacts. These maps should be used as screening tools and any action leading to development should have an onsite evaluation by a certified engineering geologist (Soeters & van Westen, 1996).

Although the current climate is not conducive to deep-seated landslides, as evidenced by no deep-seated landslides occurring during historical times, the landslide inventory shows that they have happened in the past and they will likely happen in the future. Events that would most likely trigger deep-seated mass wasting in this semi-arid climate would be seismic activity. An earthquake comparable in magnitude to the quake of 1872 with an epicenter on the east side of the Cascades could prove to be a triggering event as it did in the hills near Wenatchee (“1872 North Cascades,” 1977). Other possibilities for deep-seated triggering events could include changes in groundwater quantity. Groundwater conditions could be altered with land uses such as irrigation and residential development.

Shallow Slide Hazards

The hazard map produced for shallow mass wasting using 2m LiDAR shows that 8% of the YRC is highly prone to future events (Figure 23). Moderate hazard areas totaled 7% of the study area, low hazards totaled 16%, and very low hazards totaled 69%. The hazard map using the statistical approach also shows that 8% of the YRC is highly prone to future events (Figure 24). However, moderate hazard areas totaled 27%, low

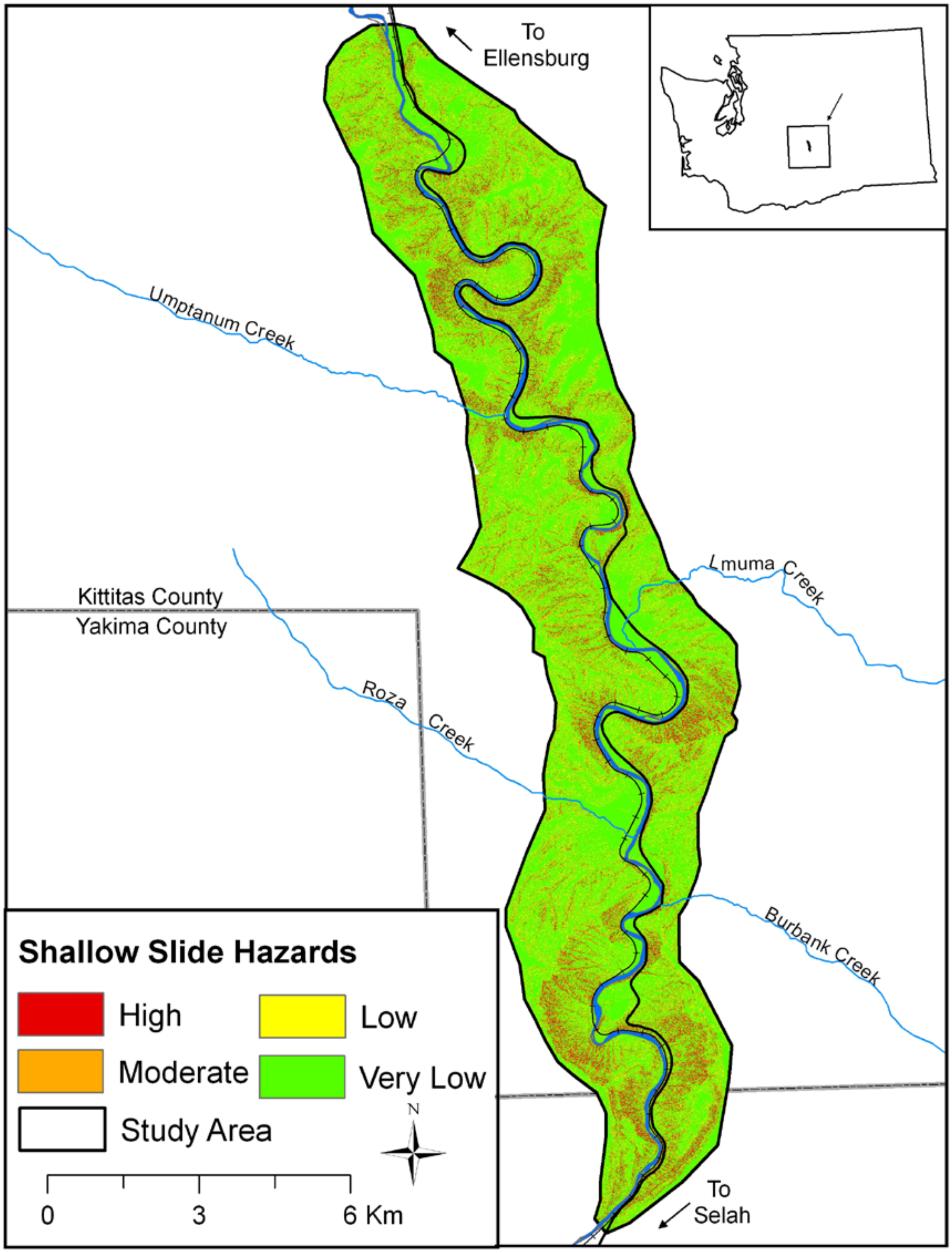


Figure 23. Shallow landslide hazard map for the YRC using 2m LiDAR.

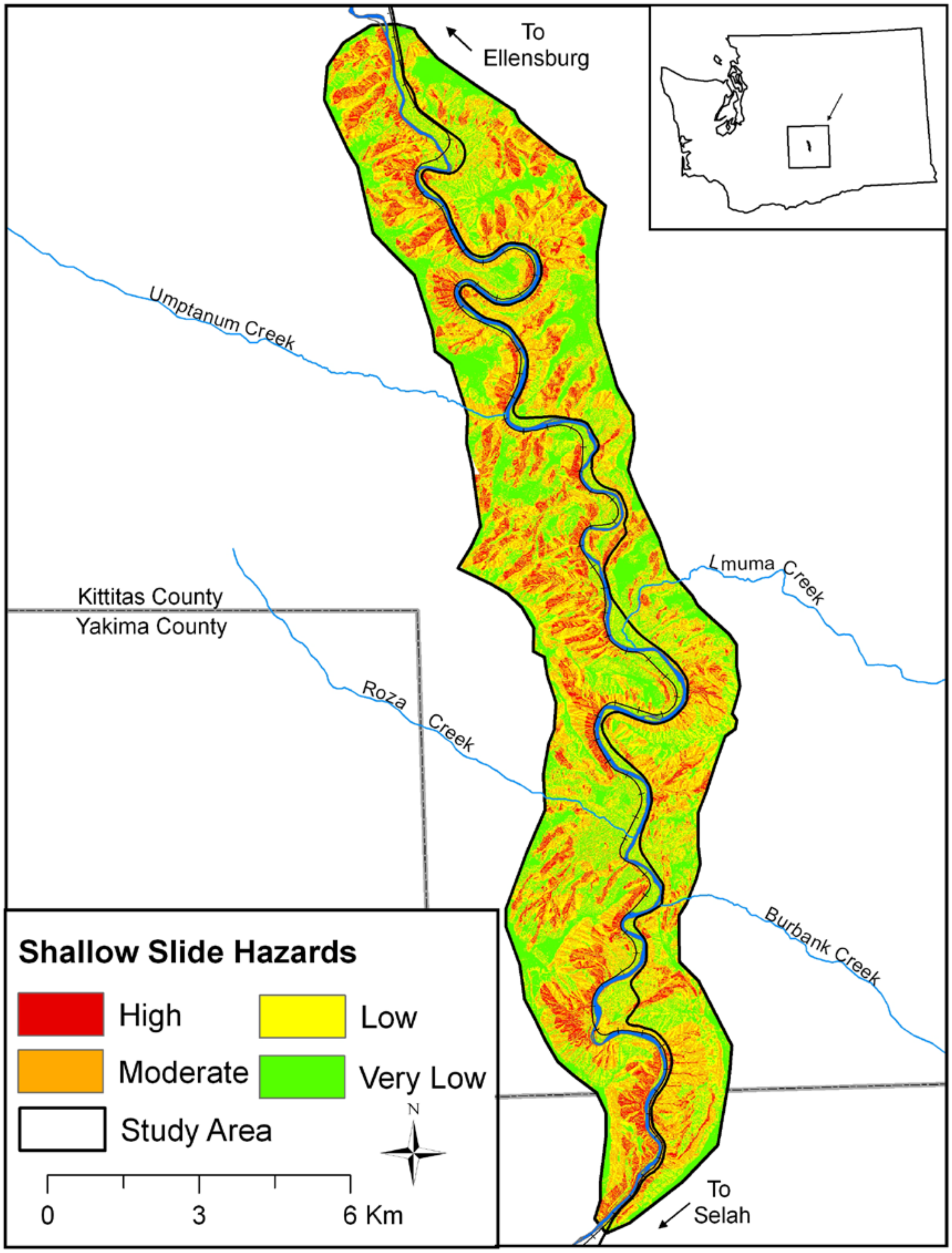


Figure 24. Shallow landslide hazard map for the YRC using the bivariate statistical approach.

totaled 37%, and very low totaled 27%. In both maps the hazard areas of high to moderate susceptibility were confined to steep converging slopes where water concentrates the most (Baeza & Corominas, 2001). These areas are gullies (i.e., inner gorges) and the heads (i.e., colluvial bedrock hollows). These areas in combination with east-facing slopes are the most likely locations for shallow slides to occur. These areas are capable of producing shallow landslides as well as debris flows ("Factors Affecting a Forested", 1999). Even though these maps used different parameters, they produced similar results, with the greatest differences in the moderate and very low hazard classes. The difference in results is likely due to the additional significant control variables used for shallow landsliding to create the bivariate statistical analysis map. Both maps should be considered as suitable screening tools for the YRC.

Management Recommendations

A comprehensive mass wasting management plan is essential for transportation corridors, areas of high recreational use, and residential areas, with the YRC containing all of those mentioned. This landslide inventory and accompanying hazard maps can be used as a comprehensive land management plan that suggests mitigation measures for the transportation corridor of the canyon and used by land use planners for assessing the potential for different land uses. Current techniques of mass wasting mitigation in the YRC include both passive and active mitigation strategies. Current passive mitigation in the YRC consists only of rockfall signs that are dispersed intermittently throughout the canyon. Active mitigation consists mainly of catchment ditches and cement barriers to catch rockfall. In the mid 1950s, a slope reduction project removed a bulging toe of a landslide on “Beavertail Bend” in the YRC (“Slide Hazard To”, 1956). No sliding in this area has occurred since the slope reduction. These measures provide a base for mass wasting mitigation but these measures do not adequately stop most occurrences of mass wasting.

Transportation Corridor

The YRC is a well-used transportation corridor year round. During the summer months, the canyon sees high volumes of tourist and recreationalist traffic. During winter months, the canyon sees increased trucking traffic, as it is legal for trucking between September 15 and May 15. This is significant because there is increased rockfall during these months due to higher amounts of precipitation and frequent freezing and thawing (Wylie & Norrish, 1996).

Results from the hazard map created from rockfall mapping and WSDOT data show that 40% of the transportation corridor is at high risk of rockfall. Some mitigation has occurred in the YRC mainly in the form of catchment ditches and some with accompanying cement barriers, which is effective in some locations. Other locations in the canyon do not control rockfall effectively with just catchment ditches as rocks bounce well over these ditches onto the road and railroad. Draped mesh and wire fence would be the most beneficial addition to the YRC (Figure 25). Draped mesh and wire fence are relatively inexpensive ways to mitigate rockfall. They are also very effective in limiting trajectories of rockfall and keeping these falls off the road and railroad (Wylie & Norrish, 1996). The idea of the YRC as scenic area should also be considered. Mitigation

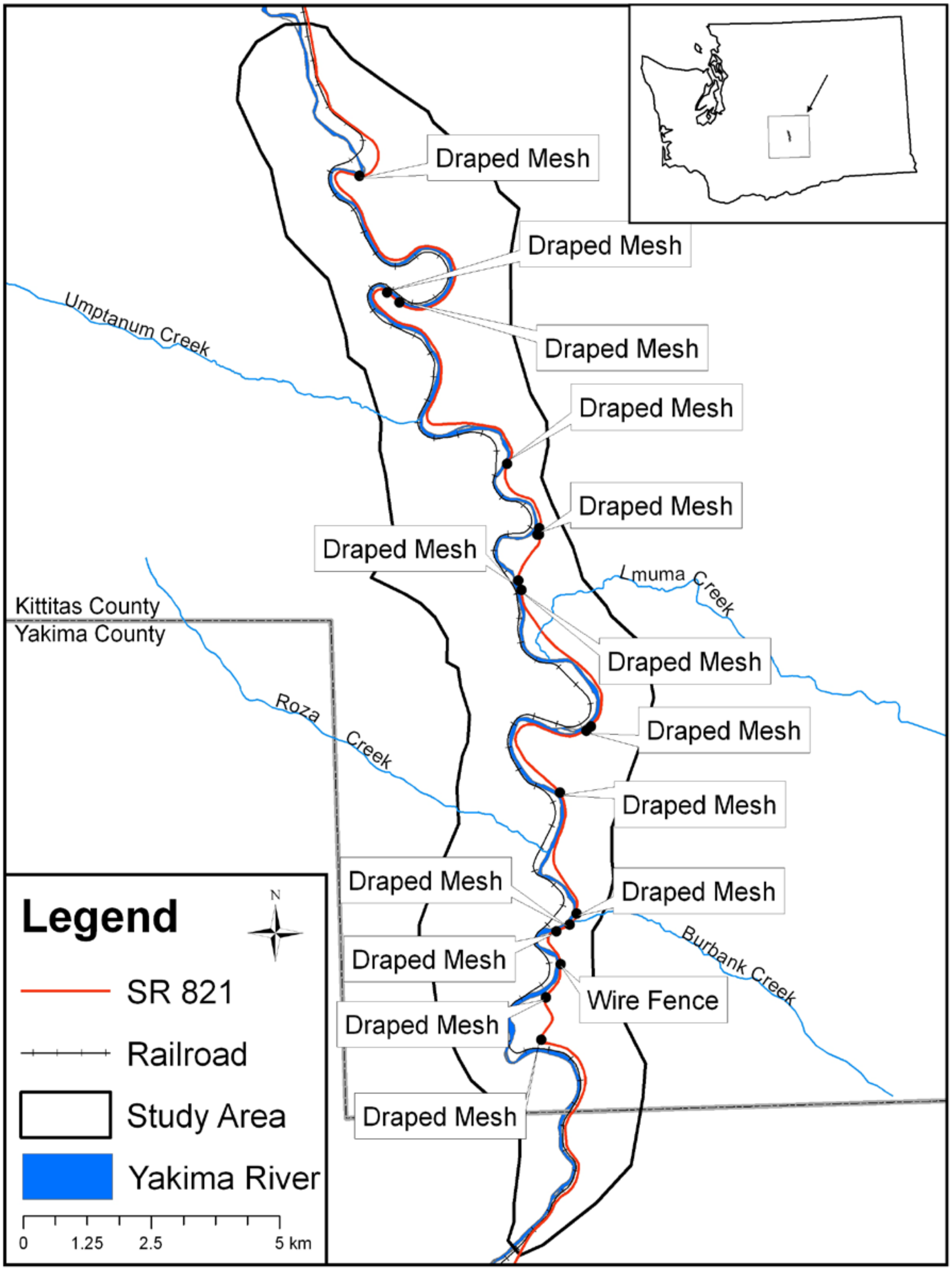


Figure 25. Mitigation measures recommended for the YRC.

techniques such as rock nets and fencing can be much less visually impacting than other techniques such as shortcrete to line unstable canyon walls.

In addition to these additional measures, rockfall in the canyon should be monitored and recorded. The WSDOT uses the rockfall rating system originally designed by Pierson (1991). However, this system does not actually record historical rockfall but rates a slope for hazards based on past rockfall occurrence. Recording simple data such as an estimate of size, date, place, and weather conditions would provide a wealth of knowledge for rockfall in the YRC. These data could provide rockfall rates for any specific slope, the triggering mechanisms, and insight into when falls occur most frequently. This analysis would provide the basis for the best management techniques.

Deep-Seated Hazard Mitigation

Deep-seated landslide hazards are notably difficult to mitigate, and development and developed should generally be avoided in these locations (Holtz & Schuster, 1996). This cannot always be the case in transportation corridors. When S. R. 821 was constructed in the early 1920s, a section of the road at the very southern end of the YRC dissected a large complex slide-flow near the toe of the slide, which can create further instabilities. There has been no sign of reactivation of the slide body; however, the cut itself is unstable and produces occasional rockfall. The best management strategy now is to avoid all further developments in areas of moderate to high deep-seated mass wasting susceptibility.

Shallow Hazard Mitigation

Shallow hazards are notably much easier to mitigate than deep-seated hazards. This can be done by simply removing these shallow materials by excavation (Holtz & Schuster, 1996). However, colluvial bedrock hollows, inner gorges, and slopes over 30 degrees should be avoided. If these geomorphic features cannot be avoided for certain land uses such as road construction, these areas must be carefully evaluated and planned by an engineering geologist.

Development in the YRC

Many areas of the YRC are not suitable for development. Much of the canyon contains steep slopes that are prone to many types of mass wasting. Areas that are suitable for development have mostly been developed with residential areas, ranches, or resorts. Other areas suitable for development are generally remote and access would likely require crossing marginal terrain. The YRC is far better suited as a scenic and recreational area and further development would increase the potential for socio-economic losses due to mass wasting.

CHAPTER VI

CONCLUSIONS AND FURTHER RESEARCH

Identifying, Mapping, and Classifying Mass Wasting

A total of 248 mass wasting features were identified, mapped, and classified in the YRC. Overall, mass wasting features totaled 22% of the study area. These were classified as slides, complex slide-flows, flows, and falls. Translational slides, rockfall, and debris flows were the most common in the YRC, totaling 204 features. The least common, but largest, mass wasting features were the 22 rotational slides and complex slide-flows present in the YRC. Deep-seated slides and complex slide-flows were the oldest features in the YRC and are likely from the late Pleistocene to early Holocene. The most common mass wasting events in historical time are debris flows, rockfall, shallow translational slides, and earth flows. Twelve major debris flow events have occurred in the last 126 years, and are likely the greatest major threat to the infrastructure in the YRC. These events occur frequently and are potentially quite large and destructive. Rockfall is common in the YRC with many falls occurring per year just in the transportation corridor. So much rockfall occurs in the YRC that catchment ditches need to be maintained annually (personal communication, May 05, 2010). Rockfalls are generally lower magnitude events, but remain a major concern for the YRC due to the very high frequency of these events. These events pose a high hazard to recreationalists, commuters, and residents that travel through the YRC.

Mass wasting control variables differ with each mass wasting type. Deep-seated slides and complex slide-flows seem to be mainly influenced by lithologic contacts and more specifically, sedimentary interbeds present between basalt flows. Other significant factors include slope angle and slope elevation. Shallow translational slides seem to be mainly influenced by slope angle, slope aspect, slope convexity, and proximity to watercourses (inner gorges and bedrock colluvial hollows). Debris flows seem to be mostly controlled by water courses, slope convexity, and slope angle. The extent and magnitude of debris flow events seem to rely heavily on severe thunderstorms. Rockfall occurs where cliffs have formed by fluvial erosion and where road cuts have over-steepened slopes and removed vegetation along S.R. 821 and the Northern Pacific Railroad. Rockfall triggering mechanisms are highly dependent on weather events including rain storms, snow storms, wind, and freeze/thaw conditions.

Hazard Mapping

Hazard maps were created for each type of mass wasting including debris flows, rockfall in the transportation corridor, deep-seated landslides and complex slide-flows, and shallow translational slides. These maps were statistically-based, created from the findings of significant control variables. The exception of these maps was the rockfall hazard map for the transportation corridor, which was based the combination of rockfall mapping and WSDOT data of known unstable slopes. The statistically-based hazard maps provide the best match for mass wasting distribution. A result from hazard mapping indicates that much of the YRC is not suitable for development and is much more suitable as a recreation area.

Management Recommendations

Management recommendations were based on the results of hazard mapping. These maps could provide a guide for land-use planning by identifying the most hazardous areas as well as areas of low hazard that are suitable for development. The transportation corridor is highly prone to future mass wasting events. Mitigation techniques including rock nets and wire fencing were recommended for the YRC due to their effectiveness in reducing rockfall trajectory and their relatively low cost for installation. Areas that are suitable for development occur in areas of low relief, mainly near the head of the canyon and in the center of the canyon near Wymer. Much of these areas have already been subjected to residential and commercial development.

Future Research

Identifying, Mapping, and Classifying Mass Wasting

Abundant opportunities exist for mass wasting research in the YRC. Further research can help provide a better understanding of mass wasting processes that can occur in the YRC and could even help reduce the impacts on infrastructure and humans.

Debris flows and shallow slides should be added to the inventory as they occur along with the same attribute information that was recorded for the inventory. This information should include type, material, size, and triggering mechanism.

Deep-seated landslides and complex slide-flows in the YRC were relatively dated by morphology; many of these features were classified as inactive-mature or inactive-old.

Only two were classified as inactive-young. These younger features fit the description of the decision rules perfectly during the analysis; however, these features are older than 1942, which was the earliest date of aerial photographs of the study area. Determining ages for all of the features including inactive-young, inactive-mature, and inactive-old by tephra dating or other techniques such as radiocarbon dating could provide a calibrated system for relatively dating landslides in Central Washington semi-arid lands. In addition, ages of these features could reveal triggering events such as earthquakes or climate change in the late Pleistocene of the Columbia Basin.

Stratigraphic profiles of alluvial and colluvial fans in the study area could be created to analyze prehistoric debris flows and their frequencies within alluvial fans. These stratigraphic profiles could potentially be dated using Optical Stimulated Luminescence to further analyze frequencies of debris flows in the YRC.

Keeping a record of rockfall in the YRC could provide valuable data for magnitude-frequency relationships in the YRC (Hungr, Evans, & Hazzard, 1999). I propose that WSDOT records each event in a maintenance log that describes the date of the event, place, size, type, material, and weather conditions. They could also use these data to improve their current inventory of unstable slopes in the YRC.

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