THE DISTRIBUTION AND IMPACT OF ROADS AND RAILROADS ON THE RIVER LANDSCAPES OF THE COTERMINOUS UNITED STATES

by

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Floodplain roads and railroads are common features in river landscapes, but their distribution and impacts have not been explicitly studied. This dissertation discusses the impacts of floodplain roads and railroads on channel and floodplain processes in river landscapes at the continental, regional, and local scales.

At the continental scale, I documented the spatial patterns of roads and railroads in the floodplains of the continental United States and the regional variability of their potential impacts. Based on these results, I developed a conceptual model based on topography and the interaction of transportation and stream networks that suggests that the area of lateral disconnection caused by transportation infrastructure should be most extensive in mid-sized alluvial valleys in relatively rugged settings, such as those located in the western United States.

I used pre-existing digital geologic, hydrologic, and transportation data with Geographic Information Systems software to map floodplain areas and lateral disconnection along the floodplains of two river systems in Washington State. I developed methods to quickly and inexpensively delineate potential or historic floodplain surfaces, to analyze lateral floodplain disconnection caused by different types of structure, and to rank floodplain reaches in terms of salmon habitat potential. Although all floodplains exhibited disconnection, the floodplain maps and habitat rankings helped identify opportunities for habitat preservation and restoration.

At the local scale, I mapped and measured the impacts of lateral disconnection, showing that channel and riparian habitat was degraded in locations with floodplain transportation infrastructure confining the channel compared with similar nearby sites lacking such confinement. Railroad grades and road beds function as confining structures in the riparian zone, disrupting flood pulses and the exchange of water, sediment, and biota between channels and their floodplains and within the floodplain. Over longer time periods, these structures can also impede the natural meandering and migration of channels across their floodplains, disrupting the erosional and depositional processes that drive the high habitat and biological diversity characteristic of floodplains. My results show that human-caused disconnections need to be further incorporated into river science and management.

This dissertation includes previously published and unpublished co-authored material.

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CHAPTER I

INTRODUCTION

Since the pioneering stream ecologist H.B.N Hynes (1975) made the famous statement that ‘the valley rules the stream,’ over three decades of research has resulted in a body of scientific understanding that emphasizes the ecologically important linkages between rivers and their adjoining terrestrial landscapes. In addition, the understanding has emerged that study of river landscapes requires contributions from many disciplines, including biology and ecology, hydrology, and geomorphology (Stanford et al. 1996). The concept of connectivity is a unifying theme in contemporary river science, most broadly defined as the exchange of water, sediment, and biotic material between components of the river landscape (Blanton and Marcus, 2009). These components include the river channel, its adjoining riparian zone and floodplain, upland features such as terraces and hillslopes, and sub-surface zones. The linkages that define connectivity may be between upstream and downstream reaches of a river (longitudinal), between channel and floodplain (lateral), and between surface and groundwater (vertical). These three types of linkages act together over time to drive ecological function in the river landscape (Ward, 1989).

Likewise, the significance of the many impacts that human activities have had on river landscapes is also a central component of contemporary river science. Researchers in both Europe and the U. S. have enumerated and analyzed the impacts of these activities on hydrologic, geomorphic, and biotic processes. Dams have resulted in fragmentation of river systems; disrupting longitudinal connectivity with a host of ecological impacts, including an altered flow regime, entrapment of sediment and wood, altered thermal regime, downstream channel erosion, drowning of floodplains by reservoirs, impeding or blocking fish migration, and degradation of riparian forests (Graf 2006, Magilligan and Nislow 2005). Dikes, levees, and other channel modifications such as channelization have resulted in disconnection of channels from their floodplains resulting in habitat and species loss and impairment in both channel and floodplain (Bravard et al. 1986, Decamps 1988, Marston et al. 1995). Floodplain land uses such as deforestation and urbanization have lead to increased sedimentation, altered runoff, and impaired water quality.

Human impacts on river systems have resulted in major environmental issues for river science to contend with. In the Pacific Northwest, the combined effects of human activities have resulted in salmon populations dwindling to a fraction of their historic abundance. The federal listing of salmon species as endangered or threatened under the Endangered Species Act brought the issue of human impacts on rivers to the forefront in both river science and policy. Habitat loss is one of the major factors driving the endangered status of salmon and other aquatic species, and habitat preservation and restoration has become a critical issue in river science. The linkages that define connectivity in the river landscape act together to create habitat form and function, and their disruption by human activities is a primary limitation to preservation and restoration efforts. Understanding the natural processes of connectivity and how they are impacted by human activities is crucial to river restoration, and this understanding is enhanced greatly by the adoption of a landscape-based perspective (Ward et al., 2001).

Dams are the most studied human impact on connectivity. The distribution of dams and their impacts are described for the U.S. by Graf (1999, 2006) and globally by Dynesius and Nilsson (1994). The ecological impacts of dams on connectivity are articulated in the Serial Discontinuity Concept (SDC, Ward and Stanford 1983). The SDC was later expanded to include downstream impacts on floodplains (Ward and Stanford 1995). Many dams were built with the purpose of flood protection; however with the recognition of the importance of naturally variable flow regime including periodic flooding (Poff et al. 1997), modification of dam operation or outright dam removal is now a central issue in river management (Richter et al., 2003).

Lateral connectivity is understood as important for fish and other aquatic species. Side channels and ponds are important for Coho salmon at different life stages, offering cover from predators and low-velocity refugia habitat (Brown and Hartman, 1988). During high flows, pulses of water, sediment, and nutrients revitalize the riparian zone (Junk et al. 1989). In turn, a healthy riparian forest provides shade for the channel, ameliorating temperature, and provides cover, nutrient inputs, and inputs of large woody debris into the channel—all important for fish and other species (Gregory et al., 1991). Over longer time periods, the channel migrates across its floodplain, eroding and depositing sediment, creating a ‘shifting habitat mosaic’ pattern that explains the high productivity and biodiversity of floodplain systems (Hauer et al. 2003). Where lateral connectivity is impaired, the result is degraded habitat and lower species abundance and diversity (Ward et al. 2002).

Floodplain roads and railroads are near ubiquitous features in river landscapes, yet they have not been systematically studied. This dissertation examines the geographic patterns and impacts of roads and railroads on lateral connectivity at multiple scales. In Chapter II, I document the distribution of floodplain roads and railroads across the coterminous U.S., and develop a simple conceptual model that relates topography and network density to potential impact type. Material in Chapter II is co-authored with W. Andrew Marcus, and was published in the journal *Geomorphology* (Blanton and Marcus, 2009)

In Chapter III, I address the issue of how to map floodplain disconnection along a river corridor. I evaluate different methods and data sets for mapping the extent of the floodplain prior to human disturbance, and mapping the extent of disconnection caused by different transportation structures. I show how GIS and freely available digital data may be used to readily map floodplain disconnection, and how this information may be used to help guide river restoration and preservation efforts. Material in Chapter III is co-authored with W. Andrew Marcus.

In Chapter IV, I map and measure the impacts of disconnection caused by floodplain roads and railroads on channel and floodplain habitat along seven pairs of river reaches on the Yakima and Chehalis rivers in Washington State. I used a ‘paired reach’ approach to control for factors impairing habitat other than disconnection, such as dams or floodplain development. Material in Chapter IV is co-authored with W. Andrew

Marcus. Chapter V briefly summarizes the overall findings and significance of this dissertation research.

CHAPTER II

RAILROADS, ROADS AND LATERAL DISCONNECTION IN THE RIVER LANDSCAPES OF THE CONTINENTAL UNITED STATES

This chapter has been published as a co-authored manuscript in the journal *Geomorphology* (Blanton and Marcus, 2009).

1. Introduction

Humans profoundly transform river landscapes by altering watersheds, climate, and channels, which in turn modify the hydrologic, biotic, and sediment fluxes through river systems (James and Marcus, 2006). Human impacts to rivers result from a vast array of activities ranging from local bank stabilization to watershed-wide effects of large dams to global alterations of rainfall by greenhouse gas emissions. Regardless of the specific driver or the scale of focus, impacts often alter connectivity within the fluvial system, where connectivity is the exchange of water, sediment, and biota between components of the river landscape. Components include the channel, riparian zone, floodplain, terraces, and hill slopes. Alterations to connectivity may well be the most common characteristic of human impacts in river systems (Wohl, 2001, 2004).

Connectivity controls the evolution of channel and floodplain environments, habitat formation and destruction, and the potential for restoration policies and projects to succeed or fail (Hauer et al., 2003; Montgomery et al., 2003; Kondolf et al., 2006).

Despite the ubiquity of human impacts to fluvial connectivity, however, most studies have focused on local scales of analysis (e.g., Bravard et al., 1986; Snyder et al., 2002) with fewer studies that have examined large-extent impacts on connectivity (e.g., Graf, 1999). The local focus has been necessary as researchers work to understand process-response relations within the limitations of existing data sets and field logistics. Nonetheless, the local focus has constrained our understanding of the magnitude and distribution of human impacts on river connectivity. In turn, this limited understanding hinders our ability to develop national and state policies that effectively address geographic variations in the potential for impact mitigation, stream restoration, and associated resource allocation.

Recent advances in digital data availability enable broader scale examinations of human impacts on river connectivity. At the national scale, research on dams is an example of how a continental-scale focus can help inform understanding of human impacts on river connectivity (Graf, 1999, 2006), which in turn can inform policy development (Heinz Center, 2002, 2003). The ubiquity of dams and their dramatic effects on water and sediment fluxes have made them an obvious target of fluvial research. Surprisingly, however, roads and railroads, which are even more ubiquitous features in American rivers and floodplains than dams, have received relatively little research attention in terms of their impacts on connectivity, particularly at regional to national scales.

This study documents the geographic distribution of roads and railroads with respect to the river landscapes of the continental United States, and the regional variability of their potential impacts on lateral connectivity and resultant channel and floodplain structure and function. Specifically, this study examines the following questions: (i) how useful are available national-scale data and different metrics for characterizing potential impacts of roads and railroads on floodplains across different water resource regions of the continental United States; (ii) how do patterns of floodplain and road or railroad interaction vary within and between regions; and (iii) what regional-scale variables explain these variations in patterns across the United States? The study concludes with process-based hypotheses concerning the impacts of roads and railroads on floodplain connectivity and a discussion of the implications of this study for policy and management. While transportation infrastructure is not the only cause of lateral disconnection in river landscapes (dikes, levees, and other engineered structures also impair lateral connectivity), roads and railroad data exist at the national scale. Analysis of the impacts of roads and railroads on floodplains thus is a useful first step towards understanding floodplain disconnection across the coterminous United States.

2. Background

2.1. The Importance of Connectivity

Connectivity varies in three spatial dimensions (Amoros et al., 1987; Ward, 1989). Longitudinal connectivity refers to linkages between upstream and downstream sections of a river, vertical linkages are between the surface and ground water, and lateral linkages are between a river, its floodplain, and surrounding slopes. Major theoretical advances in the understanding of ecological function in river landscapes have resulted from studying connectivity. The River Continuum Concept (Vannote et al., 1980) and

Serial Discontinuity Concept (Ward and Stanford, 1983), for example, address longitudinal connectivity. The importance of vertical connectivity is captured in studies of the hyporheic zone (Stanford and Ward, 1993), and lateral connectivity is addressed by the Flood Pulse Concept (Junk et al., 1989).

The significance of connectivity and human disruptions of connectivity is reflected in the growing literature devoted to these topics over the past 30 years. Many researchers have documented the importance of longitudinal connectivity and human disruptions to it, particularly in the context of dams and regulated flows (e.g., Ward and Stanford, 1983; Nilsson et al., 2005; Graf, 2006). Likewise, human impacts on vertical connectivity, particularly on the hyporheic zone, are also well-documented (e.g., Amoros and Bornette, 2002; Hancock, 2002). Lateral disconnection, the focus of this study, is recognized as a significant impact on ecological function in the river landscape, negatively affecting the development of side-channel habitats, floodplain evolution, riparian ecosystem processes, and biodiversity in the fluvial landscape (e.g., Bravard et al., 1986; Ward and Stanford, 1995).

Lateral connectivity results when geomorphic processes operate over time to create channel and floodplain habitat structure and function (Poff and Ward, 1990; Montgomery and Buffington, 1998). Over the long term, river power and cut-and-fill alluviation produce what Hauer and Lorang (2004) referred to as the "shifting habitat mosaic"—a dynamic floodplain landscape with high physical and ecological habitat diversity. In particular, fluvial erosion and channel migration at the floodplain scale over decades to centuries create and maintain habitat units such as side channels, backwaters, cut-off channels, and floodplain lakes, ponds, and wetlands (Gregory et al., 1991; Amoros and Bornette, 2002; Ward et al., 2002). These habitat units are often areas of particularly high biodiversity (van den Brink et al., 1996; Robinson et al., 2002) and are also critical habitat components for fish at various life stages (Brown and Hartman, 1988; Sedell et al., 1990; Meehan and Bjornn, 1991). Deposition of floodplain sediments also drives long-term patterns of floodplain forest succession (Nanson and Beach, 1977) and biodiversity (Ward et al., 2002).

At shorter time spans and finer spatial scales, fluvial disturbances create patches of habitat such as freshly deposited bars and areas cleared of vegetation, thus driving patterns of floodplain vegetation in diverse river environments (Hupp and Osterkamp, 1996; Hughes, 1997). Moreover, the ecological significance of disturbance is not limited to vegetation. The importance of periodic fluvial disturbance for ecological function across the fluvial landscape was articulated by Junk et al. (1989) for large river systems as the "flood pulse" concept, later expanded to smaller systems (Tockner et al., 2000) and higher frequency, lower magnitude "flow pulses" (Hohensinner et al., 2004). The flood/flow pulse concept states that flow variability creates a "shifting littoral" at the terrestrial-aquatic interface that facilitates exchanges of water, sediment, and biota between channel and floodplain (Junk et al., 1989; Tockner et al., 2000). These exchanges further enhance the biodiversity of floodplain systems for both aquatic and terrestrial species.

2.2. Road and Railroad Impacts on Lateral Connectivity

Railways and roads are often built along the banks of rivers, especially in hilly or mountainous terrain where rivers provide low gradient corridors (Forman et al., 2003). Even in low relief settings, proximity to water transportation networks and settlement location patterns prompted location of transportation networks along rivers (Schwantes, 1993; Forman et al., 2003). Many transportation networks have been located along river courses for over a century, with the earliest rail lines dating to the 1830s in the eastern U.S. (Dunbar, 1915) and the mid-to late-nineteenth century in the western U.S. (Schwantes, 1993). Road construction, particularly paved roads, generally came later, with paved roads accounting for only 4% of the U.S. road network in 1900 (National Research Council, 2005).

Most studies on road impacts in river landscapes have focused on how culverts, bridges, and other in-stream structures affect longitudinal connectivity (e.g., Harper and Quigley, 2005); on how roads alter water, sediment and contaminant delivery to channels (e.g., Jones et al., 2000); on road effects on hillslope stability and mass wasting (e.g., Montgomery, 1994); or on road density as an indirect proxy for land use impact on habitat (e.g., Baxter et al., 1999). In contrast, relatively few studies have examined the role of roads and railroads in valley bottoms. Eitemiller et al. (2000) noted that railroad grades and highway beds often act as levees, causing disconnection in the fluvial landscape. Snyder et al. (2002) found that the construction of roads, railroads, and levees resulted in the lateral disconnection of 44 to 69% of the Holocene floodplain on four different reaches of the Yakima River in Washington State. This disconnection disrupted the natural flood regime and decreased side- and off-channel habitat, channel complexity, and riparian forest cover.

Although not identical, impacts of levees on floodplain connectivity can serve as a proxy for how transportation ways affect rivers. Studies along the upper Rhone (Bravard et al., 1986) , Garonne (Décamps et al., 1988), upper Rhine (Deiller et al., 2001), Wisconsin (Gergel et al., 2002), Danube (Hohensinner et al., 2004), Elbe (Leyer, 2004), Ain (Marston et al., 1995), and Meuse (Van Looy et al., 2003) all demonstrated that disconnections resulting from levees caused significant ecological damage, including loss of riparian forest, channel and floodplain habitat loss and/or simplification, and loss of richness and diversity for both terrestrial and aquatic species.

The studies of road, railroad, and levee impacts cited above generally focused on local scale impacts. Transportation networks, however, extend for long distances along rivers. At this broad spatial extent, the impacts of transportation infrastructure along river landscapes may be divided into two general categories: crossing impacts, including bridges and culverts, and lateral disconnection impacts, such as levees, roads, and railroad grades alongside stream channels (Forman et al., 2003). The road network alone in the U.S. has over 500,000 bridges >6 m long and over 12.5 million smaller structures, mostly culverts and pipes (Forman et al., 2003). Bridges and culverts cause small-scale impacts by changing local channel form and hydraulics. Although the local and aggregate importance of such point impacts is not questioned here, in this study our emphasis is on the systemic landscape-scale impacts of lateral floodplain disconnection.

The ubiquity of roads and railroads in fluvial landscapes and previous reach-scale studies suggest that these features often should act as lateral "dams" along the length of rivers (Fig. 2.1). Over short timescales, these transportation networks interrupt flood and flow pulses and the exchange of water, biota, and sediment between stream channels and their floodplains. Over longer time periods (decades to centuries), these structures affect floodplain dynamics by impeding the natural meandering and migration of channels across their floodplain, limiting the shifting habitat mosaic crucial for ecosystem function. Unpacking the relationships between landscape properties (such as topography and transportation networks) requires examining the relations at broader spatial perspectives in order to know the nature of potential impacts, their magnitude, and their locations. This study uses preexisting GIS data sets to explore spatial relationships between roads, railroads, and rivers in the continental U.S. to assess the magnitude and distribution of potential floodplain disconnection relative to more localized point impacts such as bridges.

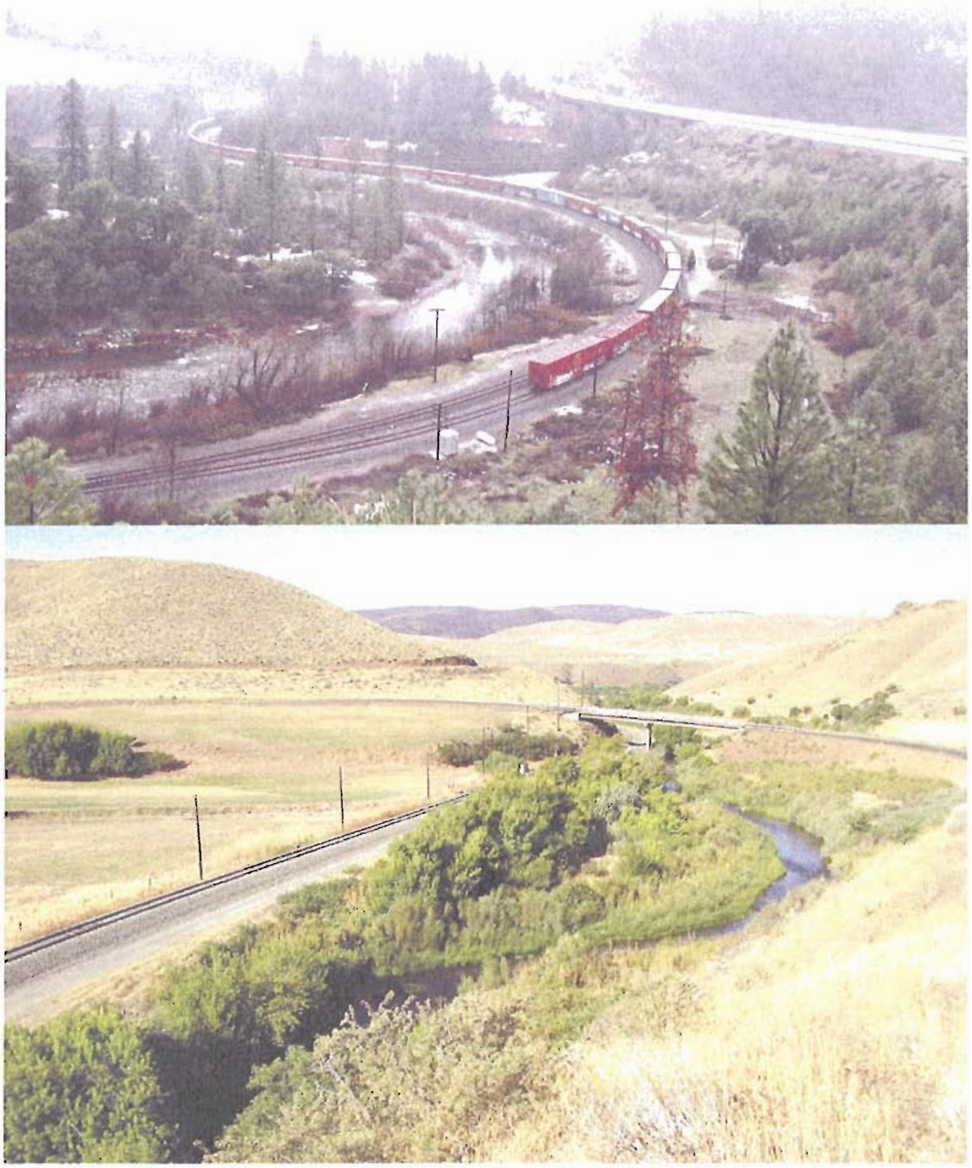


Fig. 2.1. Floodplain transportation lines. Top: Sacramento River, CA (photo courtesy of Kim Graves). Bottom: Umatilla River, OR. These features effectively act as lateral dams, disrupting lateral connectivity in the river landscape.

3. Data and Methods

Our approach in assessing the potential impacts of transportation infrastructure on fluvial systems is based on Forman et al.'s (2003) suggested framework that combines theory from landscape ecology and network analysis to analyze the ecological impacts of roads. Such analysis begins with the measurement of road, rail, and stream density as (i) many ecological patterns are strongly linked to density patterns and (ii) density is the simplest spatial measure of potential ecological impact. However, dissimilar network forms may have the same density value but very different ecological conditions. Hence, we also focus on the interaction between the transportation and stream networks (the point and diffuse impacts above) and their relation to topography.

To compare the potential for floodplain disconnection across the continental U.S., we inventoried, assessed, and compiled GIS layers relevant to roads, railways, rivers, and floodplains at the national scale. We used existing GIS vector data of roads, railroad, and river networks (Fig. 2.2) to generate point layers of road and railroad river crossings, create buffers to evaluate road and railroad interactions with rivers, perform nearest-distance analysis between transportation and stream networks, and analyze the geometric patterns of transportation networks. Finally, we created maps showing these values in quartiles for the 18 water resource regions for the continental U.S. We performed all GIS analysis using ARC-GIS 9.2. These data sources, metrics, and their limitations are discussed below.

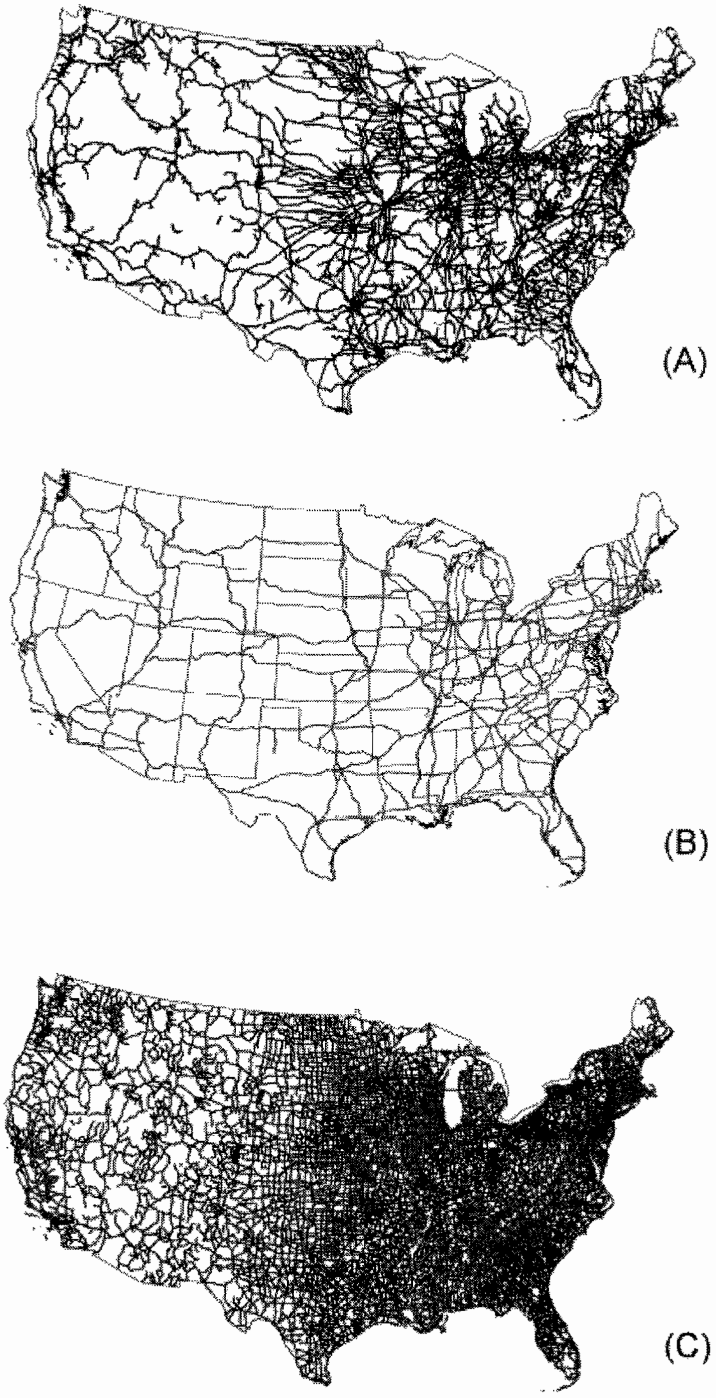


Fig. 2.2. GIS data sources used in analysis. (A) Railroads. (B) Interstate Highways. (C) U.S./state Highways. Source: National Atlas of the United States.

3.1. Regional Data

To compare continental-extent metrics indicative of the potential for floodplain disconnection among regions, we used the highest order region in the four-level hierarchical subdivision developed by the USGS (Seaber et al., 1987) and used by Graf (1999) for his national census of dams (Fig. 2.3). The highest level consists of 18 continental U.S. water resource regions (Table 2.1), the most common watershed-based, large-scale regions used in hydrologic analysis (Graf, 1999).

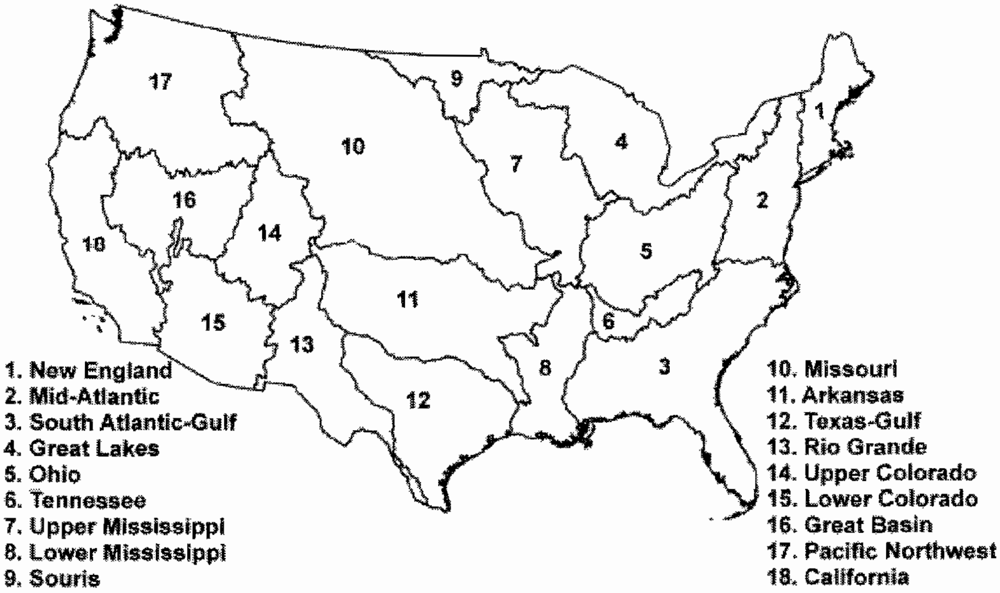


Fig. 2.3. Water resource regions of the continental United States.

Table 2.1: Water resource region area and length of railroads, interstate highways, and U.S./state highways for the 18 water resource regions of the continental United States

	Water resource region	Area (km^2)	Length streams (km)	Length railroads (km)	Length interstate (km)	Length U.S./state (km)
1	New England	158,385	13,898	6,016	2,869	14,882
2	Mid-Atlantic	287,515	30,431	15,365	5,944	37,351
3	South Atlantic-Gulf	697,932	62,606	29,097	9,325	78,269
4	Great Lakes	461,341	28,426	15,569	4,814	30,691
5	Ohio	422,094	41,895	23,812	6,823	46905
6	Tennessee	106,038	10,500	4,160	1,445	10,870
7	Upper Mississippi	491,756	48,231	25,561	6,176	50,813
8	Lower Mississippi	262,301	30,781	8,613	2,444	22,351
9	Souris	153,763	10,848	5,826	615	9,459
10	Missouri	1,323,996	118,386	27,886	8,548	68,693
11	Arkansas	641,599	52,473	18,797	3,953	44,156
12	Texas-Gulf	464,434	35,262	12,835	3,727	32,296
13	Rio Grande	343,991	21,178	4,507	1,980	12,549
14	Upper Colorado	293,472	28,293	1,945	924	8,535
15	Lower Colorado	362,758	20,654	4,166	2,544	9,641
16	Great Basin	367,602	17,807	3,959	2,039	11,015
17	Pacific Northwest	710,011	50,899	12,125	3,772	27,756
18	California	417,417	23,548	9,464	3,808	20,440

Water resource regions are geographic areas based on surface topography and contain either the drainage area of a major river (e.g., the Missouri) or the drainage area of a series of rivers (e.g., the Texas-Gulf region, which includes a group of rivers that drain into the Gulf of Mexico).

From a GIS analysis perspective, the USGS regional classification system is preferable to ecoregion systems (such as Bailey, 1983) because the USGS water resource regions are aggregates of watersheds, which allows for seamless transition to finer scales of analysis. The explicit hierarchical nature of the USGS system is in line with the growing recognition of the importance of multiscale, hierarchical frameworks for the analysis of river systems (Montgomery et al., 1995).

3.2. Road, Railroad and Water Data

We obtained GIS vector data for railroads, major roads, and streams and water bodies of the continental United States from the National Atlas of the United States website (http://nationalatlas.gov/). The National Atlas data are standardized geospatial data sets created specifically for continental-scale spatial analysis. The railroad and road data and the streams and water bodies data are all created at 1:2 million scale. Fig. 2.4 shows an example of the stream and transportation data at the scale of the Pacific Northwest water resource region.

The "Major roads" National Atlas data include interstate and state highways only; the implications of the absence of smaller roads in the analysis are discussed later. Based purely on structure size, a multiple lane interstate freeway is likely to have a larger local impact on floodplain function than a two-lane highway or smaller road (Forman et al. 2003). We subdivided the roads data into interstate highways versus U.S. and state (generally two-lane) highways. Further subdivision was impossible because of the lack of road attributes in the data set.

The "Streams and water bodies" data include major water features captured at the National Atlas scale of 1:2 million. Coastlines, lakes, and reservoirs were excluded from the streams and water bodies data set, creating a subset of streams and rivers. Ideally rivers should be differentiated by size, as impacts logically would be different on

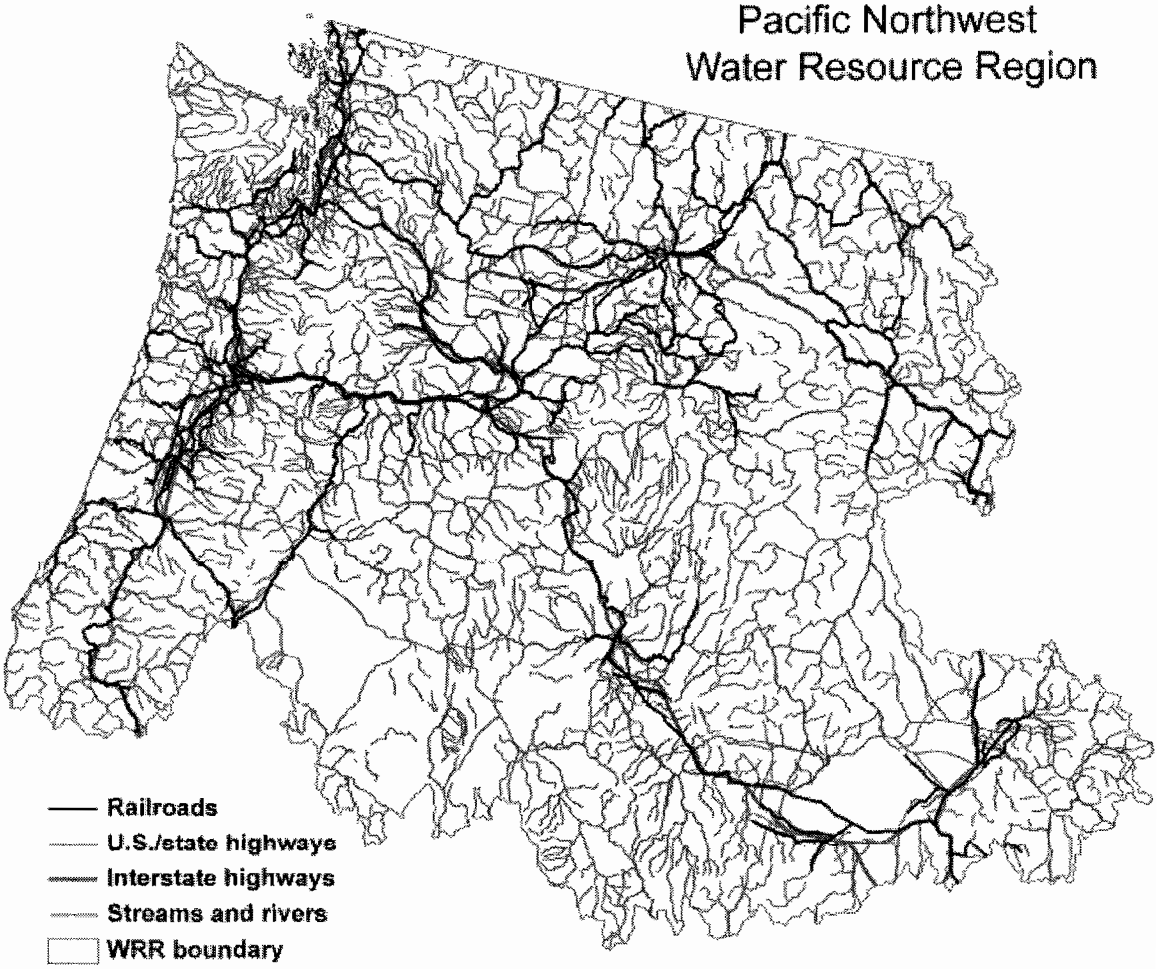


Fig. 2.4. Example of transportation and stream data at the water resource region scale.

different-sized floodplains. Again, the lack of attribute data in this data set precluded sorting the water bodies by size, stream order, or other metrics of stream magnitude. We also initially subdivided streams into "river" and "stream" layers based on the feature name, but this split did not prove useful. Patterns of designation as a "stream" or "river" are likely an artifact of local naming conventions and fail to consistently portray actual differences in stream size.

3.3. Floodplain and Topographic Data

Ideally, one would be able to measure intersection between transportation lines and floodplain area. Unfortunately, no national-scale floodplain data set that captures all rivers and streams is currently available. The most comprehensive floodplain data set is the FEMA Q3 100-year floodplain data, but no water resource region has full coverage (see map at http://msc.fema.gov) and comparison of all regions is impossible with these data. To characterize regional topography, we obtained digital elevation data for the continental U.S. with a 500-m cell size from the Berkeley/Penn Urban and Environmental Modeler's Toolkit website (available at: http://dcrp.ced.berkeley.edu/research/footprint/). This DEM was created for large-scale GIS analysis, and required little modification or assembly.

3.2. GIS Analysis

Our analysis used five metrics to indicate potential interactions between transportation and stream networks: (i) stream and transportation network density, (ii) nearest distance between transportation and stream networks, (iii) intersections of stream and transportation layers, (iv) buffer/clip analysis of transportation layers, and (v) transportation network pattern. We characterized potential control of topography on frequency and type of impact using the Topographic Ruggedness Index (TRI) that Riley et al. (1999) developed as a measure of topographic heterogeneity. This index is derived from a DEM by calculating the difference in elevation between a grid cell and the surrounding eight cells (squaring the differences to ensure only positive values) and by averaging the squared values. The square root of the average value is the TRI, which represents average elevation change between any cell in the elevation grid and the surrounding area. We calculated TRI values for the 500-m resolution DEM and isolated cells with TRI values > 116 m, which is the breakpoint between "nearly level" and "slightly rugged" landscapes, creating a binary classification of "rugged" versus "flat" landscape (categories from Riley et al., 1999). We then calculated the percentage of the total area of each water resource region that was classified as "rugged" to obtain a regional metric.

Stream drainage, road network, and railroad network density for each water resource region were calculated as the total length for each variable divided by water region area. Regional variations were plotted as graphs showing stream density plotted with rail, interstate highway, and U.S./state highway network density by water resource region.

In order to characterize regional patterns of crossing impacts, we intersected the stream layers with the railroad layer and the two road layers (interstates and state highways) to create three layers for rail and road stream crossings. To compare regions, we divided the number of crossings in each water resource region by region area; the resulting metric is an indication of the relative density of crossings in each region. Following Graf's (1999) census of U.S. dams, we created quartile maps to facilitate visual comparison of this metric across the U.S. This metric does not capture locations where rail lines or roads are located in floodplains, proximal to streams or rivers without crossing them.

To identify floodplain locations where roads and railroads approach but do not necessarily cross channels, we performed a buffer/clip analysis to provide a rough approximation of potential interaction between transport networks and floodplains. We created a buffer polygon around the rail and two highway layers and clipped the stream line layers with this buffer to create a subset of the river and stream layers that approached the transportation layers. Essentially, this process is similar to the intersection analysis above, with a thicker transportation line providing a larger "target" to intersect the stream layer. The output of this buffer/clip process was stream segment length inside the railroad buffer, expressed as length and percent of total stream length for each water resource region. We created a similar metric for the two roads layers and created quartile maps. The intersection and buffer/clip analysis together represent the potential for crossing impacts of transportation infrastructure on floodplains, with the intersection analysis reflecting stream crossings, and the buffer/clip analysis reflecting floodplain (but not stream) crossings.

We analyzed how sensitive the buffer/clip metric results were to different buffer widths values in order to identify the optimal buffer width. We used values of 10, 30, 100, 300, and 1000 m (the range of values for effect-distances of roads for streams as reported by Forman et al., 2003, p. 308). We tested these values for the two sample regions of the Ohio River and the Pacific Northwest. These two regions have different densities of transportation infrastructure as well as significantly different topography and therefore represent a range of potential interaction possibilities between fluvial and transportation networks.

We chose to use a 30-m buffer width in both regions because the count and total length of river or stream segments did not change noticeably until the buffer was expanded from 30 to 100 m (Fig. 2.5). We then buffered the rail and road layers by 30 m, and this buffer layer was used to calculate the number of stream segments and total length of streams and rivers within 30 m of a rail line or road.

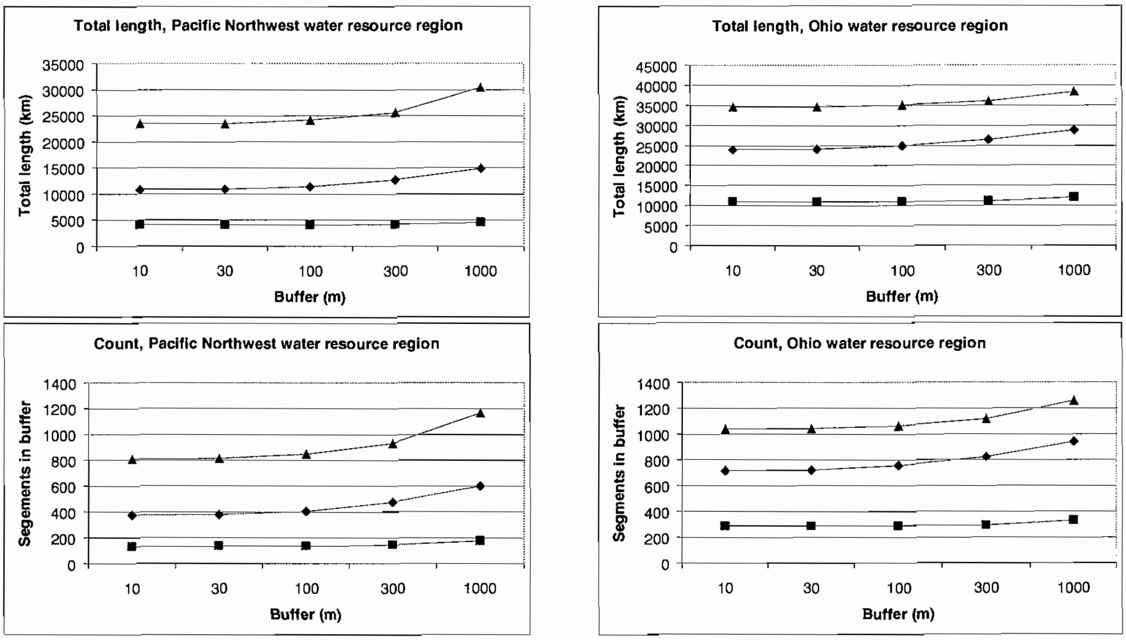


Fig. 2.5. Buffer width sensitivity analysis. Left: Sensitivity analysis of transportation line buffer width. Top: Sensitivity of total length of stream segments within buffer to buffer width, Pacific Northwest region. Bottom: Sensitivity of count of stream segments within buffer to buffer width, Pacific Northwest region. Right: Sensitivity analysis of transportation line buffer width. Top: Sensitivity of total length of stream segments within buffer to buffer width, Ohio region. Bottom: Sensitivity of count of stream segments within buffer to buffer width, Ohio region. Diamonds: railroads. Squares: Interstate highways. Triangles: U.S./state highways.

Nearest-distance analysis is commonly used to quantify the extent of road development in an area, and, by extension, the relative magnitude of potential ecological impact (e.g., Watts et al., 2007). We created a systematic sample of points every 1 km along streams, then calculated the nearest distances between these points and railways, interstate highways, and U.S./state highways. We created quartile maps to visualize the geographic pattern of median nearest distance across the regions.

The pattern of transportation networks is often a function of topography (Forman et al., 2003), with route location being a tradeoff between minimizing distance between transportation nodes and minimizing effort (Lowe and Moryadas, 1975). Minimizing effort is accomplished by building transportation lines (particularly railroads) in as straight a line as possible, while also trying to build at the lowest grade possible, thus minimizing construction and energy costs once the line is functional (Lowe and Moryadas, 1975). In mountainous landscapes, transportation lines are often preferentially sited in low gradient stream valleys, where the lines tend to follow the valley and stream sinuosity to avoid costly crossings and to take advantage of flat floodplains and terraces. In flatter topography, transportation lines tend to be more linear (Forman et al., 2003). Therefore, one would anticipate that railways and roads in alluvial valleys will have a different pattern relative to streams than those built in open plains.

Haggett (1967) suggested isomorphism (similarity in pattern) between transportation networks and stream networks, using the well-known stream network concepts of Horton (1945) and Strahler (1952) to analyze transport patterns. To differentiate relatively straight transportation lines from those with more curvature, we created the Rail Road Curvature Index (RRCI), analogous to the sinuosity metric for streams as

$$RRCI = L_s/L_{sf} \qquad (1)$$

where L_s is the curvilinear length of a section of rail line, and L_{sf} is the linear distance between the start and finish points for each line segment. We also calculated similar metrics for interstate highway (ICI) and U.S./state highway (USCI) curvature.

In order to determine the optimal curvature value that separated transportation networks that are relatively independent of topography (i.e. relatively straight) from valley hugging transportation networks (i.e. curved), we tested different curvature values in the Ohio region. Visual analysis indicated that curvature values of 1.1 or more represented locations where transportation lines were following the pattern of stream valleys (such as the West Virginia-Kentucky border), while values lower than 1.1 were associated with radial patterns in low relief areas (such as Northern Indiana) (Fig. 2.6). We isolated transportation lines with curvature $\geq$ 1.1 as portions of the transportation network with a high potential for linear disconnection along their lengths. To determine spatial patterns of these metrics at the continental scale, we calculated percent of the total rail and road length with rail or road curvature $\geq$ 1.1 in the 18 water resource regions and, again, created quartile maps.

To describe the frequency of crossing relative to lateral disconnection impacts at the regional scale, we divided the total length of rail and highway lines with a curvature index of $\geq$ 1.1 (a proxy for potential lateral disconnection impacts) by the total number of intersections (a proxy for potential crossing impacts) and plotted this ratio against the

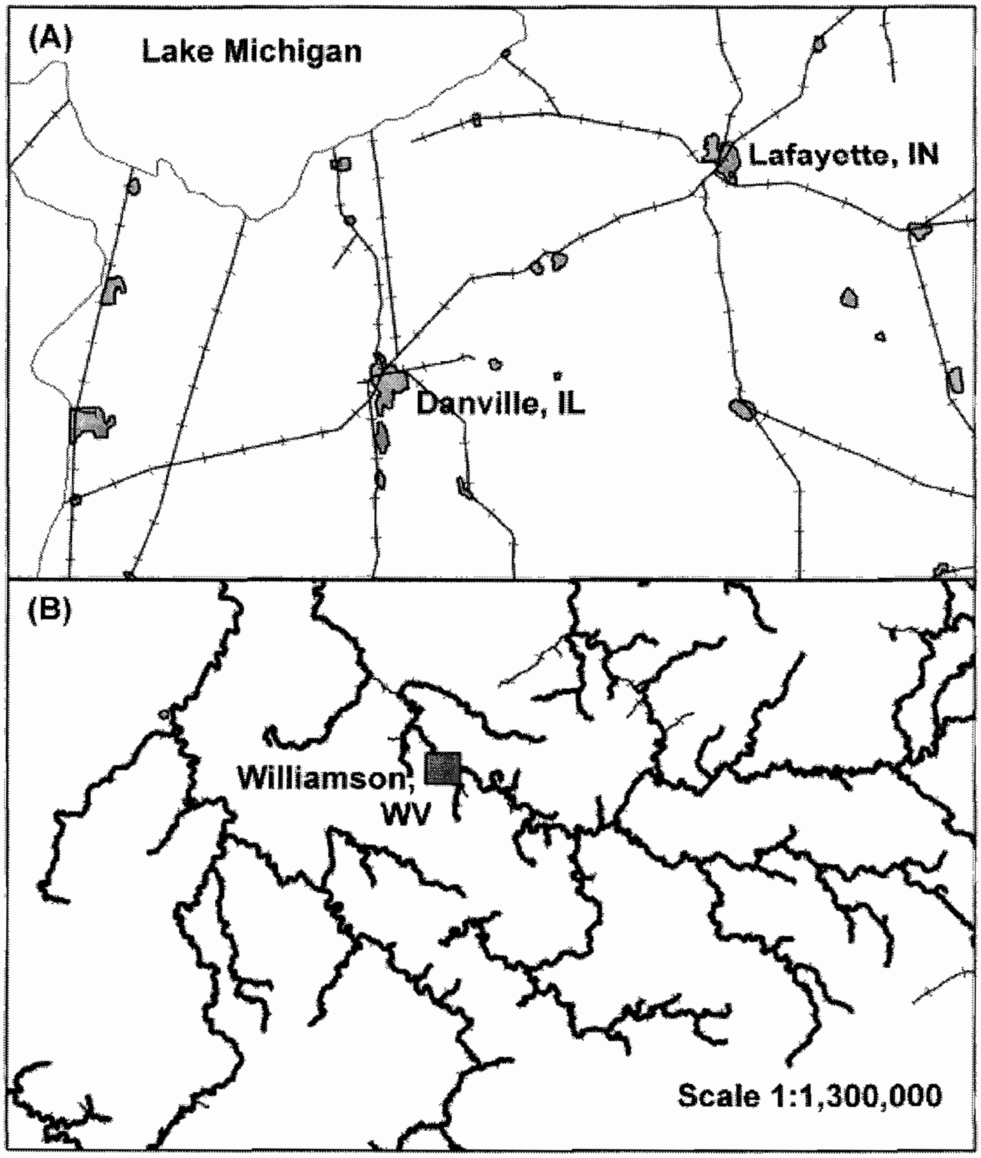


Fig. 2.6. Railroad lines in two different landscapes. All lines with curvature value > 1.1 are bolded. A curvature index value of 1.1 effectively distinguishes linear radial transportation network patterns (top, Northern Indiana and Illinois) where no curvature values are > 1.1 from sinuous, dendritic patterns where almost all lines have curvature values > 1.1 (bottom, West Virginia-Kentucky border).

percent of area classified as rugged for each water resource region. These plots show the relationship between topography and relative frequency of potential crossing versus lateral disconnection impacts.

4. Results

4.1. Stream and Transportation Network Density

Water resource regions located in the Eastern U.S. and Upper Midwest have the highest rail densities and the largest difference between stream and rail densities (Table 2.2; Fig. 2.7). In contrast, regions in the West, Southwest, and south central U.S. have lower rail densities and the largest difference between stream and rail densities. The difference between rail and stream densities is most evident in the American Southwest. This general east-west gradient holds true for interstate highway density, although the California region is higher (9th) and the Souris region is much lower (17th) in density than railroad values. Interstate density values are generally much lower than the values for rail lines and smaller highways (Table 2.2; Fig. 2.8). U.S./state highway density values are higher than stream density values for several regions (Table 2.2; Fig. 2.9), and again the general east-west pattern persists.

Table 2.2: Density values and ranks for streams, railroads, interstate highways, and U.S./state highways for the 18 water resource regions of the continental United States

	Water resource region	Stream density (km/km^2)	Rank	RR density (km/km^2)	Rank	Interstate density (km/km^2)	Rank	U.S./state density (km/km^2)	Rank
1	New England	0.0877	9	0.0380	6	0.0181	2	0.0940	6
2	Mid-Atlantic	0.1058	2	0.0534	2	0.0207	1	0.1299	1
3	South Atlantic-Gulf	0.0897	7	0.0417	4	0.0134	5	0.1121	2
4	Great Lakes	0.0616	14	0.0337	8	0.0104	7	0.0665	10
5	Ohio	0.0993	3	0.0564	1	0.0162	3	0.1111	3
6	Tennessee	0.0990	4	0.0392	5	0.0136	4	0.1025	5
7	Upper Mississippi	0.0981	5	0.0520	3	0.0126	6	0.1033	4
8	Lower Mississippi	0.1173	1	0.0328	9	0.0093	8	0.0852	7
9	Souris	0.0705	13	0.0379	7	0.0040	17	0.0615	11
10	Missouri	0.0894	8	0.0211	13	0.0065	12	0.0519	12
11	Arkansas	0.0818	10	0.0293	10	0.0062	13	0.0688	9
12	Texas-Gulf	0.0759	11	0.0276	11	0.0080	10	0.0695	8
13	Rio Grande	0.0616	15	0.0131	15	0.0058	14	0.0365	15
14	Upper Colorado	0.0964	6	0.0066	18	0.0031	18	0.0291	17
15	Lower Colorado	0.0569	16	0.0115	16	0.0070	11	0.0266	18
16	Great Basin	0.0484	18	0.0108	17	0.0055	15	0.0300	16
17	Pacific Northwest	0.0717	12	0.0171	14	0.0053	16	0.0391	14
18	California	0.0564	17	0.0227	12	0.0091	9	0.0490	13

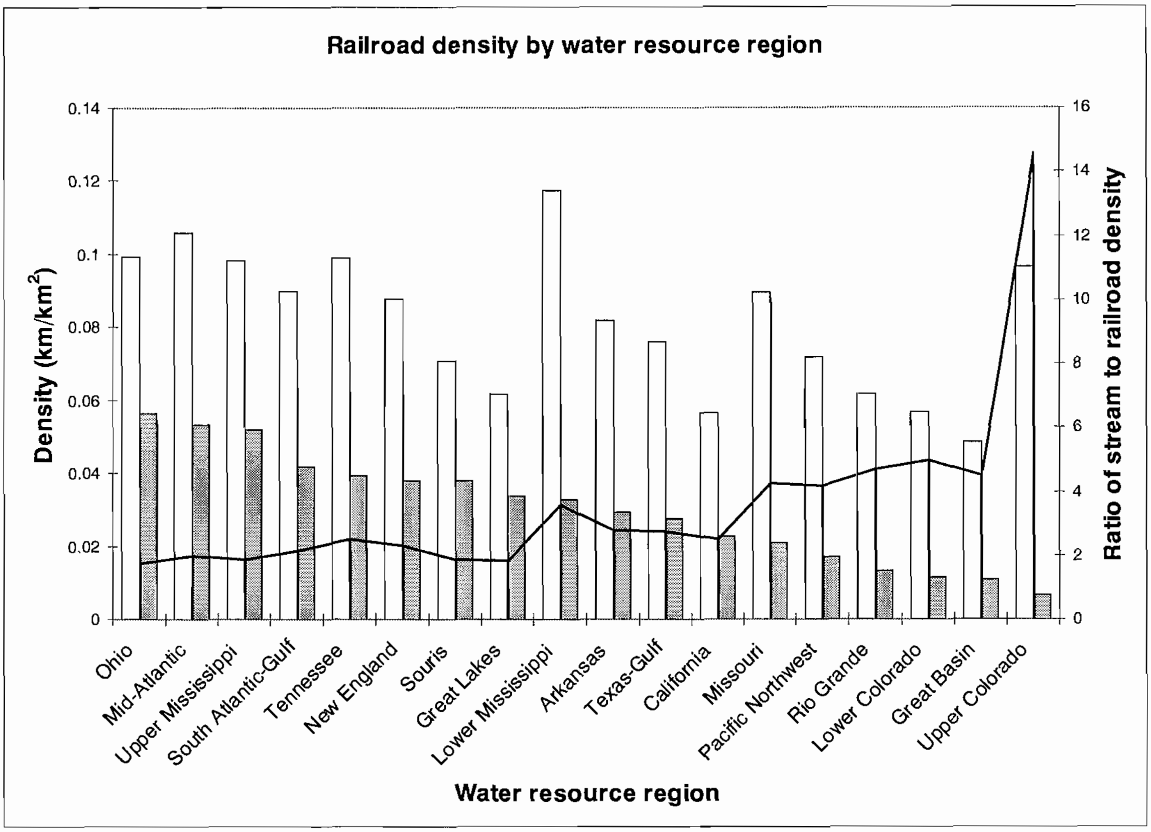


Fig. 2.7. Stream and railroad network density by water resource region. Density = total length of lines in network/region area. Ratio of stream to railroad density is also plotted to facilitate interregional comparison. White columns = stream density. Grey columns = railroad density. Line = ratio of stream to railroad density.

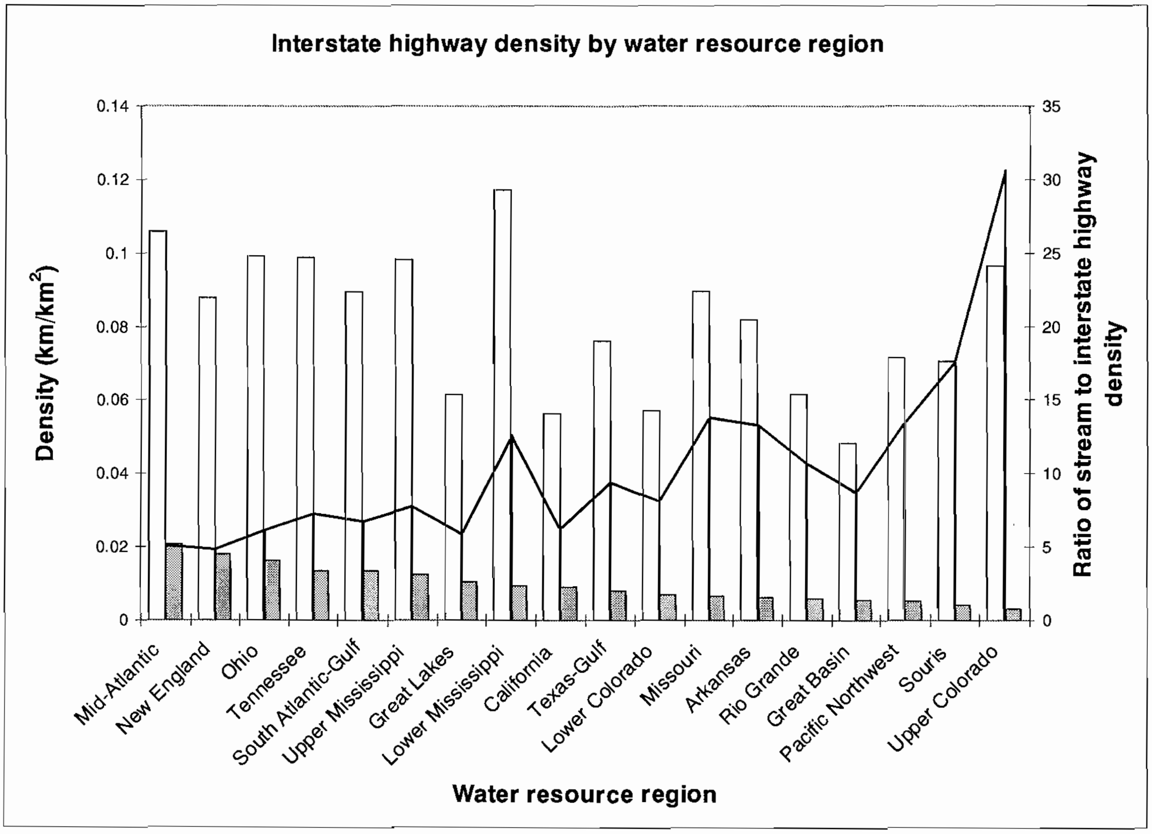


Fig. 2.8. Stream and interstate highway network density by water resource region. Density = total length of lines in network/region area. Ratio of stream to interstate highway density is also plotted to facilitate interregional comparison. White columns = stream density. Grey columns = interstate highway. Line = ratio of stream to interstate highway density.

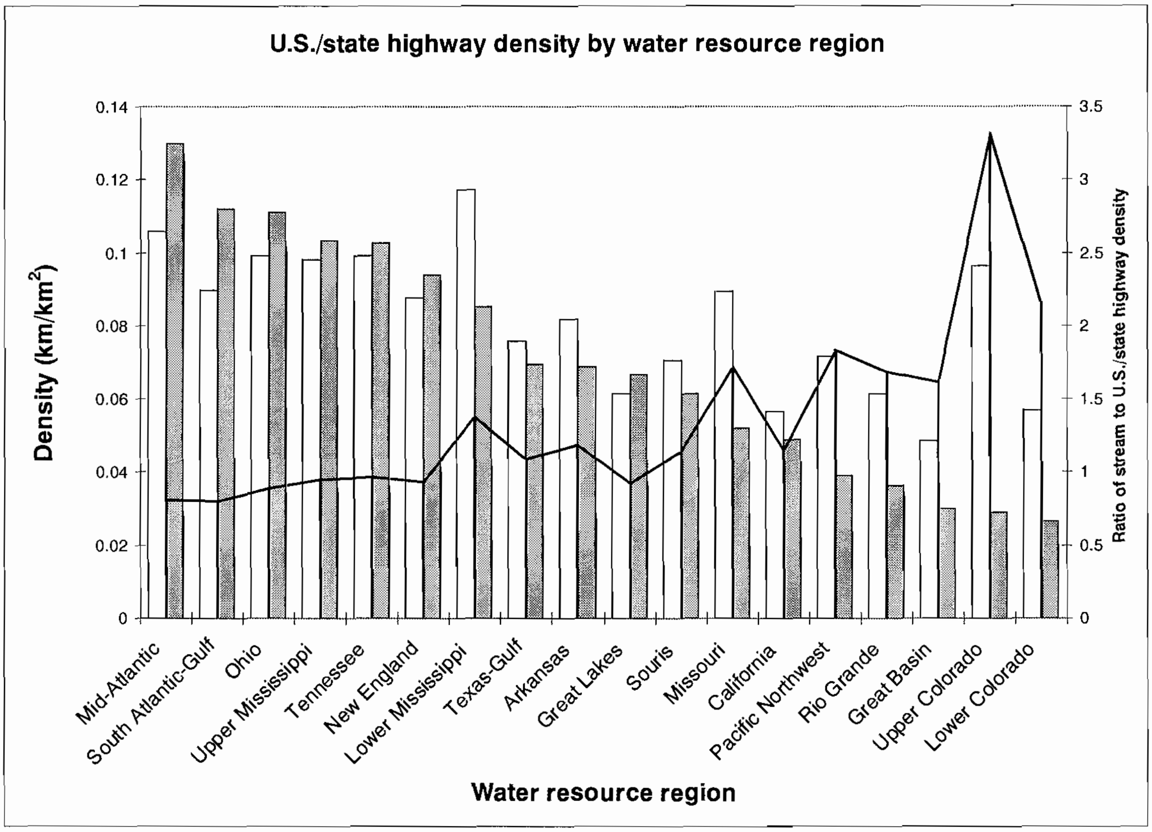


Fig. 2.9. Stream and U.S./state highway network density by water resource region. Density = total length of lines in network/region area. Ratio of stream to U.S./state highway density is also plotted to facilitate interregional comparison. White columns = stream density. Grey columns = U.S./state highway. Line = ratio of stream to U.S./state highway density .

4.2. Intersections of Stream and Transportation Layers

The geographic distribution of the density of railroad, interstate, and U.S./state highway stream crossings exhibits a strong east-west gradient, with the highest values in the Upper Midwest and Northeastern continental United States (Table 2.3; Fig. 2.10). Lowest values occur in the Southwest.

4.3. Buffer Analysis of Transportation Layers

The highest values of total stream length within 30-m of transportation lines are generally found in the same regions that have the highest number of intersections. The Rio Grande and Upper Colorado likewise have the lowest values. The rest of the regions display less of a geographic pattern, although the Pacific Northwest region is higher for all three transportation line types (Table 2.4; Fig. 2.10).

4.4. Near-distance Analysis

Table 5 shows the distribution of near-distance values across the 18 water resource regions. Railroads, interstates, and U.S./state highways display similar patterns for nearest distance by water resource region. Median distance between streams and rivers and transportation lines follows the same geographic trends as network density, with the exception of the Pacific Northwest and Upper Colorado regions, which had some of the lowest median distance values for all transportation route types.

4.5. Transportation Network Curvature

The geographic distribution of percent rail and roads with curvature indexes > 1.1 (representing transportation lines that often follow valley bottoms) exhibits a very different pattern than the crossings and buffer analysis (Fig. 2.10), but is somewhat

Table 2.3: Intersections/area for railroads, interstate highways, and U.S./state highways for the 18 water resource regions of the continental United States.

Intersections/area (number of intersections per 10,000 square kilometers)				
	Water Resource Region	Railroads	Interstate highways	U.S./state highways
1	New England	21.72	10.80	47.92
2	Mid-Atlantic	29.01	11.30	60.76
3	South Atlantic-Gulf	15.37	6.00	41.22
4	Great Lakes	17.47	5.44	31.45
5	Ohio	27.58	8.15	48.31
6	Tennessee	17.54	5.94	44.32
7	Upper Mississippi	25.60	6.08	48.15
8	Lower Mississippi	13.72	4.69	36.56
9	Souris	13.79	1.95	23.41
10	Missouri	9.64	3.19	24.43
11	Arkansas	10.54	2.63	25.50
12	Texas-Gulf	10.51	3.94	25.02
13	Rio Grande	3.49	1.77	11.16
14	Upper Colorado	4.16	1.60	14.18
15	Lower Colorado	3.45	1.98	7.14
16	Great Basin	3.02	1.66	8.51
17	Pacific Northwest	7.44	2.56	16.10
18	California	6.61	2.92	13.39

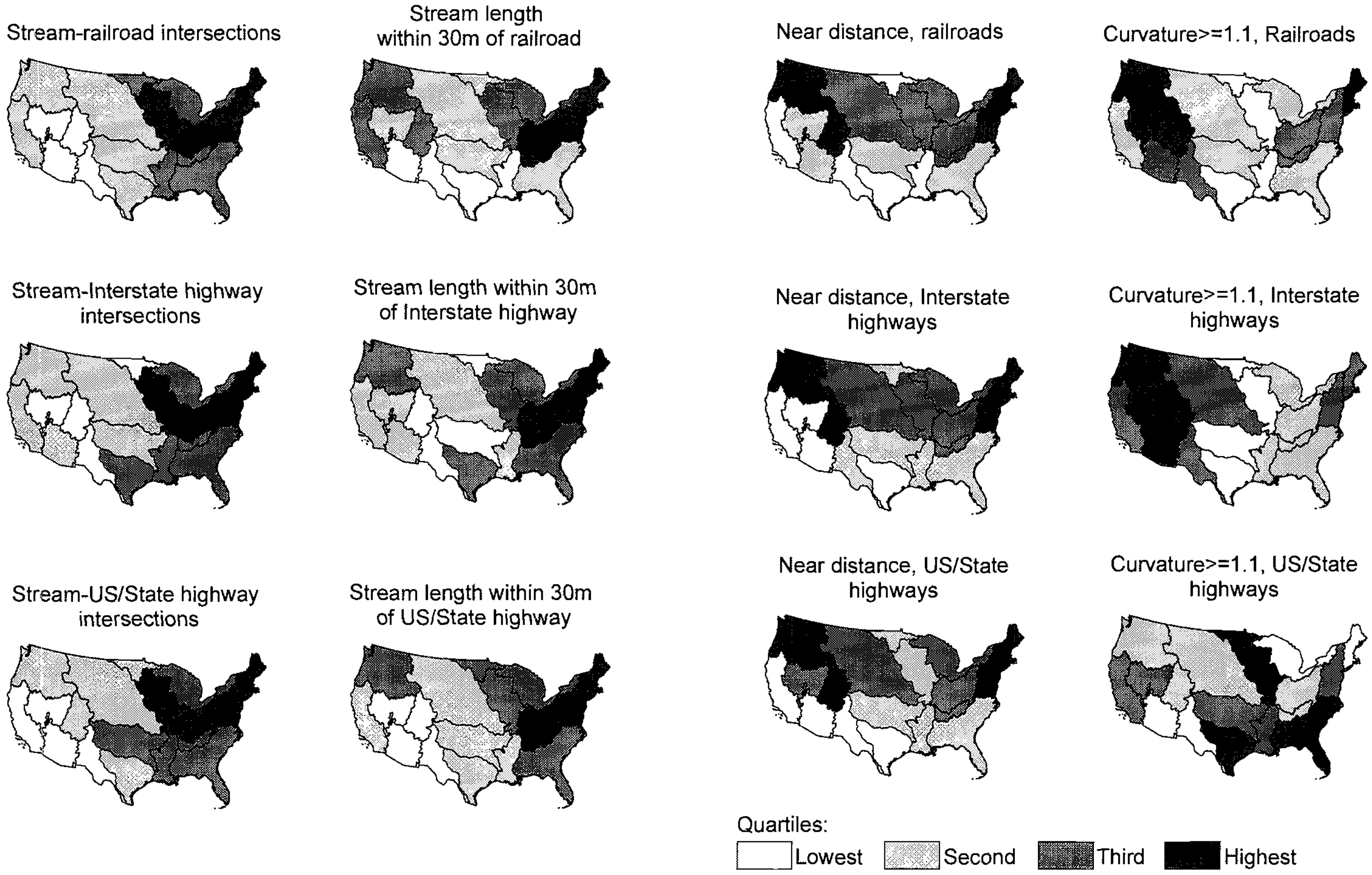
Table 2.4: Stream length within 30m buffer of transportation line for railroads, interstate highways, and U.S./state highways for the 18 water resource regions of the continental United States.

Stream length within 30m buffer of transportation line per total stream length (m/km)

	Water Resource Region	Railroads	Interstate highways	U.S./state highways
1	New England	8.81	5.44	1.62
2	Mid-Atlantic	11.20	5.42	2.07
3	South Atlantic-Gulf	1.83	22.51	0.08
4	Great Lakes	3.57	8.80	0.41
5	Ohio	10.94	4.42	2.48
6	Tennessee	6.44	6.89	0.93
7	Upper Mississippi	4.46	10.79	0.41
8	Lower Mississippi	1.30	28.15	0.05
9	Souris	2.02	11.60	0.17
10	Missouri	1.93	12.65	0.15
11	Arkansas	1.64	15.56	0.11
12	Texas-Gulf	1.35	18.55	0.07
13	Rio Grande	1.32	8.46	0.16
14	Upper Colorado	2.04	6.96	0.29
15	Lower Colorado	1.51	4.74	0.32
16	Great Basin	1.79	4.77	0.37
17	Pacific Northwest	4.18	3.85	1.08
18	California	2.16	6.20	0.35

Table 2.5: Median nearest distance for railroads, interstate highways, and U.S./state highways for the 18 water resource regions of the continental United States.

Median nearest distance, transportation line to stream				
	Water Resource Region	Railroads	Interstate highways	U.S./state highways
1	New England	1072.59	2133.27	1805.12
2	Mid-Atlantic	1206.98	2160.14	2179.10
3	South Atlantic-Gulf	3077.13	3480.34	3665.15
4	Great Lakes	2279.33	2462.45	2602.37
5	Ohio	1566.88	2900.19	2497.76
6	Tennessee	1942.99	2182.25	2411.58
7	Upper Mississippi	2346.84	2795.91	2640.23
8	Lower Mississippi	2496.44	3105.54	2687.74
9	Souris	3502.64	3063.04	3300.96
10	Missouri	1718.69	2262.21	2449.32
11	Arkansas	2976.60	3136.03	3416.35
12	Texas-Gulf	3449.94	3522.40	3679.88
13	Rio Grande	3615.51	3913.85	3664.93
14	Upper Colorado	510.99	1319.41	1525.60
15	Lower Colorado	3070.61	4138.20	3780.53
16	Great Basin	2595.16	3012.32	3863.89
17	Pacific Northwest	1160.13	1904.69	1799.03
18	California	3949.45	5004.87	3943.93



Stream-railroad intersections

Stream length within 30m of railroad

Near distance, railroads

Curvature>=1.1, Railroads

Stream-Interstate highway intersections

Stream length within 30m of Interstate highway

Near distance, Interstate highways

Curvature>=1.1, Interstate highways

Stream-US/State highway intersections

Stream length within 30m of US/State highway

Near distance, US/State highways

Curvature>=1.1, US/State highways

Fig. 2.10. Quartile maps of stream-transportation network interaction metrics.

similar to the nearest distance analysis, especially for railroads and interstates. High curvature values for railroads and interstates are concentrated in the Western continental United States, and the Northeast region also has high curvature values for interstates and rail lines. However, curvature values for U.S./state highways do not display the same geographic trend, with highest values in the north central regions, the Southeast, and Texas.

4.6 General Patterns of Interaction Metrics

We tested for correlation between metrics for each transportation line type to determine if the rank order of metrics varied in similar ways across the U.S. (e.g., to determine if there was a correlation between median nearest distance and number of intersections for railroads in each region). The degree of correlation between the ranked values of two metrics for each transportation type suggests whether the types of interactions captured by these metrics were more or less likely to be associated at the regional scale. Intersection and buffer metrics were strongly correlated for all transportation line types (Table 2.6). No other pairs of metrics correlated strongly for roads, although median nearest distance correlated with buffer and curvature metrics for rail lines.

Table 2.6: Correlation of interaction metrics for each transportation line type. Values given are Spearman's Rho (r_S) where 0 indicates no correlation and 1 or -1 indicates perfect correlation.

	Railroads	Interstate highways	U.S./state Highways
Number of crossings X median nearest distance	-0.37	-0.24	-0.47
Number of crossings X length inside buffer	0.68*	0.90*	0.89*
Number of crossings X % curvature > 1.1	-0.22	-0.36	0.25
median nearest distance X length inside buffer	-0.63*	-0.31	-0.46
median nearest distance X % curvature > 1.1	-0.57*	-0.26	0.34
length inside buffer X % curvature > 1.1	0.39	-0.10	0.11

* denotes significance at p=0.05

Likewise, we tested for correlation between transportation types for each metric (e.g., to test if there was a correlation between rail and interstate crossing for each region). Degree of correlation here is indicative of whether the regional patterns of rail, interstate, and U.S./state highways follow the same general pattern across the U.S. We found a high degree of correlation for all transportation types by metric (Table 2.7).

Table 2.7: Correlation of transportation line type for each interaction metric . Values given are Spearman's Rho (r_s) where 0 indicates no correlation and 1 or -1 indicates perfect correlation.

	Number of crossings	Length inside buffer	Median nearest distance	% curvature > 1.1
Railroad X Interstate highways	0.90*	0.68*	0.93*	0.81*
Railroad X U.S./state highways	0.97*	0.76*	0.90*	-0.51*
Interstate highways U.S./state highways	0.92*	0.86*	0.93*	-0.55*

* denotes significance at *p*=0.05

4.7. Topography and Transportation Network—Stream Network Interaction Metrics

The regions with the highest percentage of topography classified as "rugged" are the Pacific Northwest, Upper Colorado, Great Basin, and California (Fig. 2.11), followed by the American Southwest and Appalachian regions. The mid-continent regions have the lowest values. For the water resource regions, rank order of ruggedness does not correlate significantly with the rank ordered metrics calculated above, with the exception of curvature index (Table 2.8).

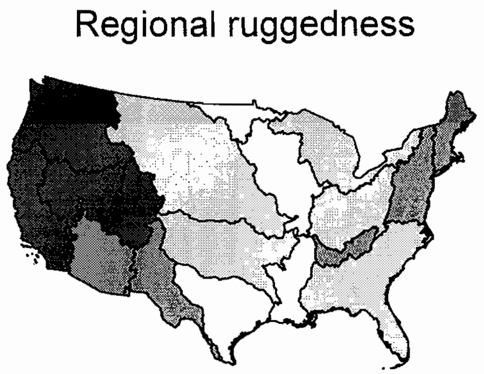


Fig. 2.11. Quartile map of regional ruggedness by water resource region. Regional ruggedness based on TRI of Riley et al. (1999). See text for explanation. Symbology identical to Fig. 10.

Table 2.8: Correlation of topographic ruggedness and transportation impact metrics. Values given are Spearman's Rho (r_s) where 0 indicates no correlation and 1 or -1 indicates perfect correlation

% WRR area classified as rugged' for:	Nearest Distance	Intersections	∑ length within buffer	Curvature
Railroads	-0.34	-0.39	0.31	0.88*
U.S./state Highways	-0.20	-0.27	0.00	-0.90*
Interstate highways	-0.28	-0.36	-0.28	0.83*

* denotes significance at p=0.05

5. Discussion

5.1. Crossing Impacts, Lateral Disconnection Impacts, and Topography: A Conceptual Model

In keeping with Forman et al. (2003), our data indicate that there are two different categories of floodplain impacts caused by transportation networks: crossing impacts such as bridges, and lateral disconnection impacts similar to those caused by levees. Crossing impacts are captured by the intersection and buffer metrics, which correlate strongly (Table 2.6) for all transportation types, probably because the buffer analysis is basically an intersection analysis with a thicker target line for the streams to intersect. Lateral disconnection impacts are captured by the nearest neighbor metric and network curvature. The quartile maps indicate two patterns (i) a very general NE-SW, high-to-low gradient of metrics indicative of crossing impacts that are products of transportation network density; and (ii) a topographic gradient where more rugged areas have higher curvature and, for some rugged areas, lower nearest distance between streams and transportation networks.

The ratio of total length of transportation line with a curvature value $\geq$ 1.1 to the total number of intersections provides an index for the proportion of potential lateral disconnection to crossing impacts. This index correlates strongly with the percent of water resource region area classified as "rugged" for railroads (Spearman's ρ $r_s = 0.83$; Fig. 2.12), interstates ($r_s = 0.90$; Fig. 2.13) and U.S./state highways ($r_s = 0.83$; Fig. 2.14).

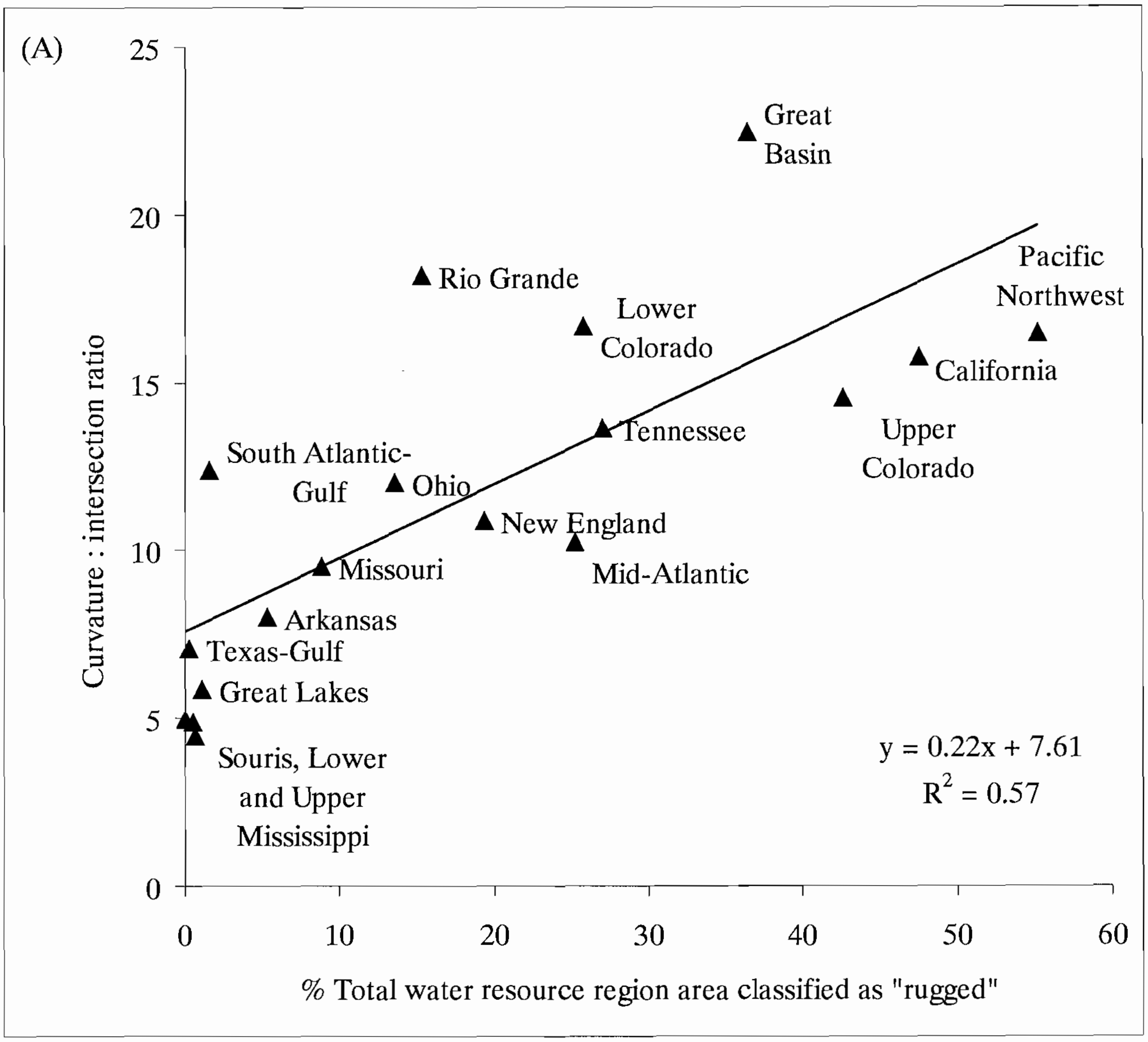


Fig. 2.12. Relationship of regional ruggedness to disconnection type, railroads.

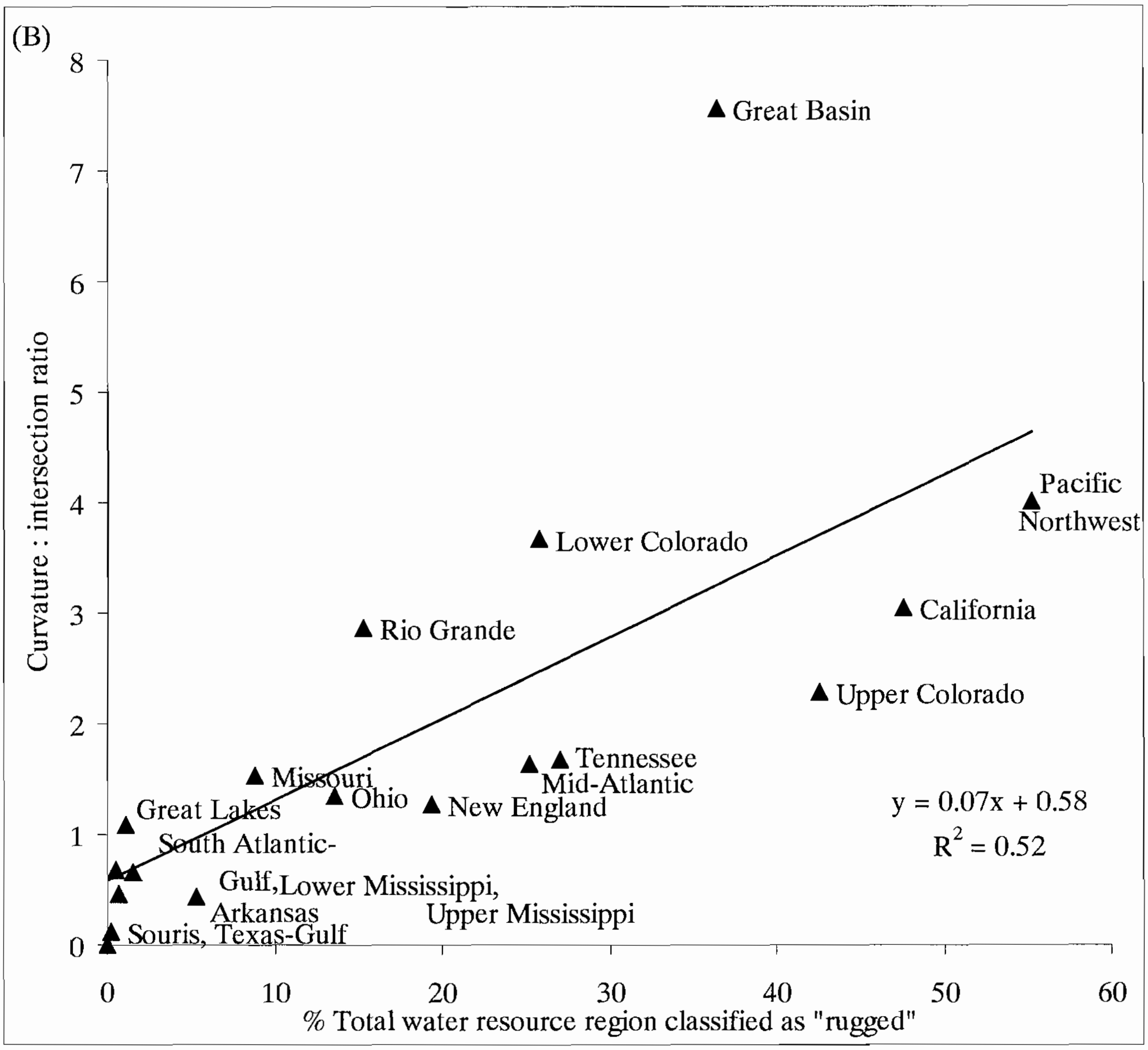


Fig. 2.13. Relationship of regional ruggedness to disconnection type, interstate highways.

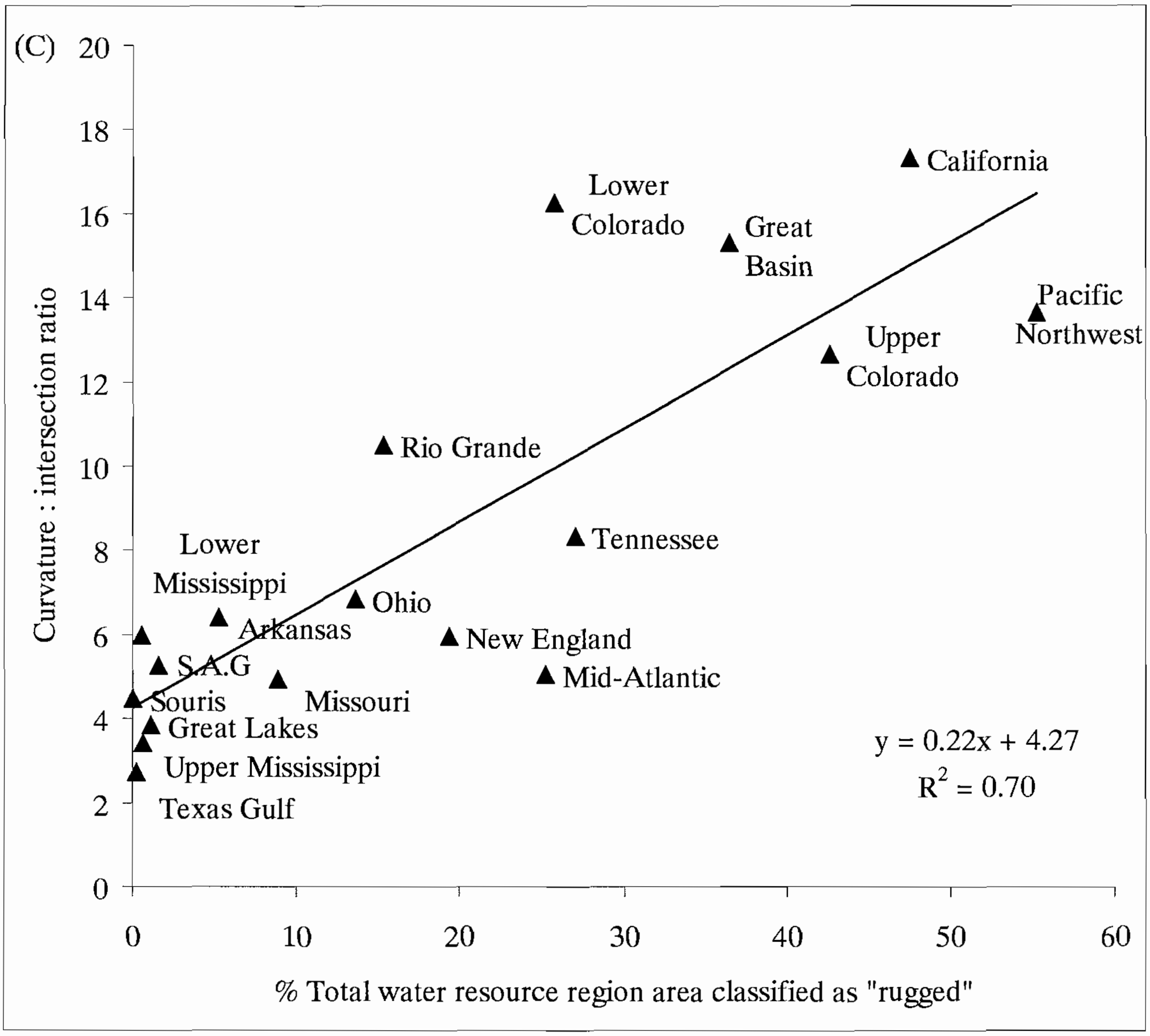


Fig. 2.14. Relationship of regional ruggedness disconnection type, U.S./state highways.

The slope of these relationships differs significantly from zero for all transportation line types ($p < 0.0001$). This indicates intersections (such as bridge crossings) will be the predominant impact in flat settings and that lateral disconnection will become more prevalent as topography becomes increasingly rugged. The points in Figures 2.12-2.14 generally resolve into three geographic domains: the rugged West and Appalachians (upper right), low relief landscapes of the Mississippi drainage, Great Plain and South (lower left), and a transition regions of intermediate topography like the Tennessee and Rio Grande Valleys. Moreover, the ratio of point to diffuse impacts varies as an approximately linear function of ruggedness (Figs. 2.12-2.14).

At the landscape scale, the potential for river floodplain disconnection is thus primarily a function of topographic relief (Fig. 2.15). We distinguish four landscapes in terms of relative potential for lateral disconnection: (i) plains, (ii) wide alluvial valleys, (iii) intermediate alluvial valleys, and (iv) narrow alluvial valleys. Alluvial valleys are distinguished here by valley width and confinement. Wide alluvial valleys are typically > 5 km across and their trunk streams are generally unconfined (i.e., valley width is greater than four times channel width; Bisson and Montgomery, 1996). Intermediate alluvial valleys are between 1 and 5 km across and are moderately confined (valley width is between two and four times channel width; Bisson and Montgomery, 1996). Narrow alluvial valleys are < 1 km across, and channels are often confined (valley width less than two times channel width; Bisson and Montgomery, 1996).

In areas of low relief, such as the glaciated area of the Midwest (e.g., the vicinity of Indianapolis, IN; Fig. 2.15A) the geographic pattern of transportation infrastructure is

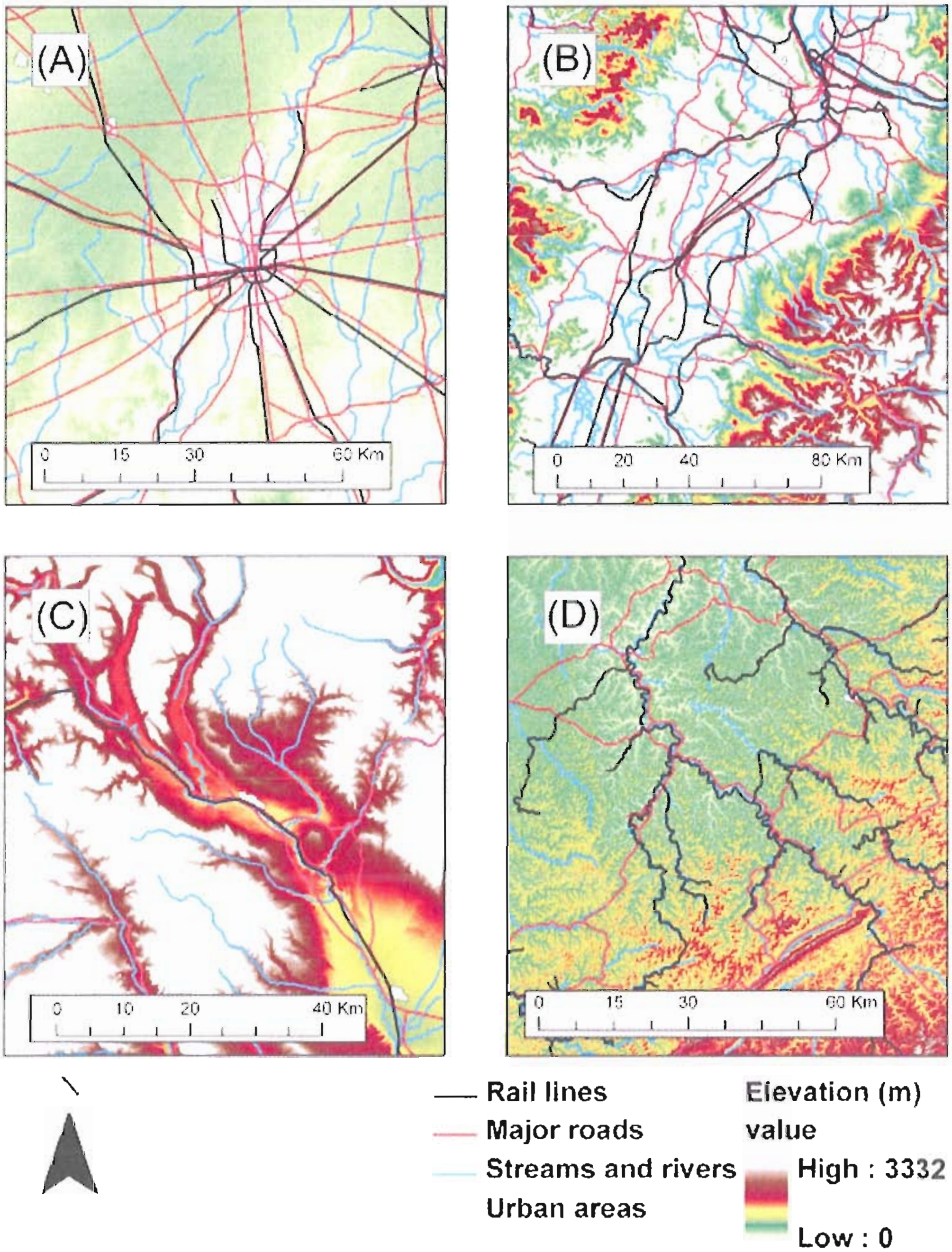


Fig. 2.15. Four landscapes distinguished in terms of relative potential for disconnection: (A) plains, (B) wide alluvial valleys, (C) intermediate alluvial valleys, and (D) narrow alluvial valleys. See text for explanation.

largely independent of stream pattern. The radial pattern of rail lines and roads radiating outward from urban centers is more likely to interact with the stream network in crossings (i.e., bridges). In large alluvial valleys, such as the Willamette Valley, OR (Fig. 2.15B), interaction between stream and transportation networks is more complex, with the roads and railroads paralleling the streams in some locations but not in others. The valley is wide enough, however, that roads and railroads need not always be immediately adjacent to the river. In smaller valleys such as the Kittitas Valley, WA (Fig. 2.15C), the transportation network follows the trunk stream more closely as the valley confines the transportation routes. In both of these alluvial valley settings, bridge impacts and diffuse linear impacts are likely to occur. In confined valleys, particularly in areas of greater topographic relief such as the West Virginia-Kentucky border (Fig. 2.15D), the rail lines in particular follow stream courses and lateral disconnection is highly likely. These patterns are summarized graphically in Fig. 2.16.

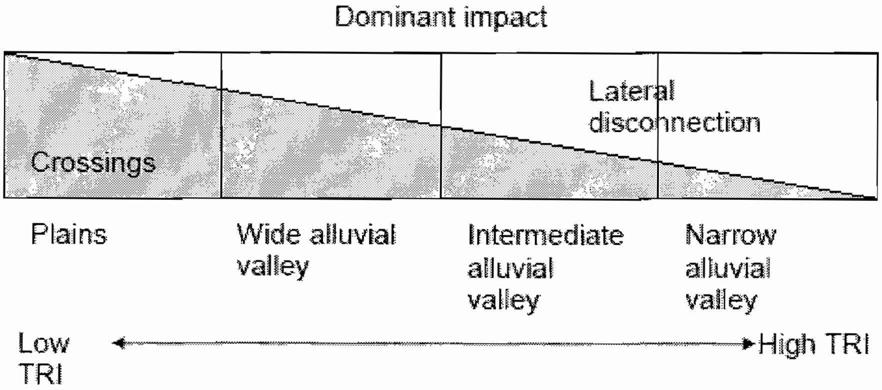


Fig. 2.16. Conceptual model of topography and potential for disconnection.

The high degree of correlation for all transportation types by metric (Table 2.7) suggests that regions with a high incidence of one type of interaction (i.e., crossing or lateral disconnection) will have that interaction for both roads and railroads. River landscapes with lateral disconnection caused by railroads will likely also have similar impacts from roads, as these sites are often well-developed transportation corridors.

5.2. Magnitude of Ecological Impacts

While our results and the conceptual model (Figs. 2.15 and 2.16) indicate that lateral disconnection of floodplains is more prevalent in areas of rugged topography such as the Cascades, Rockies, and Appalachians, we suggest the magnitude of ecological impacts (i.e., the total area of disconnected stream habitat) from lateral disconnections *within* these regions will be greatest in mid-sized alluvial valleys. In plains (Fig 2.15A), and to a lesser degree in wide alluvial valleys (Fig. 2.15B), transportation corridors need not be sited adjacent to rivers, thus minimizing total impact. At the opposite end of the topographic spectrum, valley bottoms in small, high gradient settings may be too small for transportation corridors and (even if roads do exist) will have small to nonexistent floodplains, thus minimizing potential lateral disconnections.

In contrast, the mid-sized alluvial floodplains (Fig. 2.15C) of major trunk streams of the West and the Appalachians have a long history as transportation corridors, a relatively large area of floodplain, and therefore a high potential for disconnection. Not only are these transportation corridors likely locales for large structures (i.e., rail grades and interstates), but also are more likely to have multiple rail or road structures affecting lateral connectivity. These alluvial valleys are “hot spots” of high local native biodiversity, with extensive longitudinal, lateral, and vertical structural and functional linkages (Stanford et al., 1996). Moreover, visual analysis of our GIS layers indicates that rail lines in these settings often have a high degree of curvature, suggesting they are in near proximity to stream channels. As these rail lines have been in place since the nineteenth century, lateral disconnection in these floodplains is not a new phenomenon and has been exacerbated by road construction over the course of the twentieth century.

5.3. Implications for Policy and Future Research

Transportation infrastructure is ubiquitous to river landscapes across the United States. Especially in areas of greater topographic relief, the potential large-scale cumulative impact of miles upon miles of roads and railroads on habitat structure and function is great. The research structure of this study intentionally parallels that of Graf's (1999) national scale census of dams and their hydrologic impacts, generating maps and descriptive statistics of regional metrics that can be used to generate hypotheses concerning the location, extent, and nature of disconnections at finer scales of analysis. Establishing how much alluvial floodplain landscape has been lost to transportation disconnections across the U.S. is a large task. Understanding the specific nature of the impacts, their magnitudes, the potential for mitigating or reversing the impacts, and the limitations these findings impose on river management are key issues for further study.

Setting realistic goals for river management and/or restoration requires better understanding of the anthropogenic floodplain. Major rail lines and roads are highly unlikely to be removed wholesale from river landscapes, so understanding these structures as limiting factors in the floodplain environment is crucial. Major dams are also unlikely to be removed wholesale from the river landscape, and a more plausible management option is to alter dam operation—for example, releasing strategically timed flow pulses for geomorphic and ecological purposes. The built environment of the downstream floodplain must be factored into such attempts because failure, either in the form of failing to meet ecological goals or in the destruction of property, will be problematic from both a scientific and social perspective.

Doyle et al. (2008) also argued that selective decommissioning of infrastructure (including roads and levees) opens up opportunities for environmental restoration. Removal of infrastructure with degraded functionality or utility is specifically a rehabilitation option under the National Infrastructure Improvement Act of 2007. Just as federal relicensing of dams provides an opportunity for removal, modification, or the release of strategically timed flow pulses for geomorphic and ecological purposes, infrastructure decommissioning may provide opportunities for the restoration of river landscapes. Although some research has been conducted on the effects of road removal on chronic erosion and landslides, a need exists for more research on road removal and habitat recovery (Switalski et al., 2004). Our analysis of the overall region-wide impacts, the nature of valley-scale impacts, and the likely locations of crossing versus lateral disconnection impacts of floodplain roads and railroads offers a geographic perspective of where and how these structures are a major impediment to successful river restoration.

5.4. Scale Effects and Data Set Evaluation

While the National Atlas railroad data set is comprehensive, the roads data set only includes state or U.S. highways and interstate highways—roughly 30% of the U.S.

road network (Forman et al., 2003). These larger roads are significantly more damaging to the environment because (i) their construction requires far more ecological disturbance than smaller roads, (ii) they have larger rights-of-way and are more likely to have barriers and other large structures associated with them, and (iii) major roads are more likely to be placed in transportation corridors with a long history of use and associated disconnection going back to the time of rail line construction (Forman et al., 2003). In addition, smaller floodplain roads are often overtopped in floods, reducing their ecological impact on short-term connectivity. In many if not most floodplains, local roads (excluding those constructed on levees) are on top of the 100-year floodplain and do not constitute major obstacles to flood waters (although they do constrain sediment movement and habitat formation), while highways and railroad grades often constitute the boundary of the 100-year floodplain. Although we do not dismiss the potentially significant ecological damage of smaller roads on river floodplains, cataloging potential impacts of railroads and major roads is a useful first step in understanding the magnitude and distribution of transportation-driven lateral disconnection across the United States.

Larger rivers will likely respond differently to the presence of transportation infrastructure in their floodplains than smaller streams. The size of river or floodplain that is documented by the data sets raises questions regarding scales of ecologically significant impacts at landscape scales. For example, is it more ecologically important to document 50% disconnection of a large alluvial floodplain rather than 90% loss of a small bedrock-confined floodplain? Such questions are better addressed at the river corridor to reach scale of analysis and answers are likely to vary with the social and management goals.

6. Summary and Conclusions

We collected continental-scale data of railroads, interstate highways, U.S./state highways, and rivers. These data were analyzed in GIS to produce metrics of potential impacts of transportation infrastructure on river landscapes across the continental U.S. These metrics included (i) density of stream and transportation networks, (ii) intersections of stream and transportation lines, (iii) length of streams within a 30-m buffer of transportation lines, (iv) nearest distance between streams and transportation lines, and (v) curvature of transportation networks. We compared these metrics across the water resource regions of the continental U.S., relating them to regional topography as characterized by national-scale elevation data.

The impacts of transportation infrastructure can be divided into two broad categories: crossing impacts (bridges, culverts, etc.) and lateral disconnection impacts (similar to that caused by levees). The distribution of these impacts is a function of topography and transportation density. In more rugged topography, local relief and valley configuration are the primary driving factors, and lateral disconnection dominates; while in areas of gentle topography, the density of transportation networks is the driving factor and crossing impacts dominate (Fig. 2.15). In the continental U.S., the highest values of the point impact metrics are located in the lower-relief areas of the East, which have relatively high density transportation networks (Fig. 2.10). The highest values of the linear diffuse impact metrics are found in more rugged terrain, particularly in the West

(Fig. 2.10). The intermediate size alluvial valleys in these settings have a high degree of natural connectivity and a history of use as transportation corridors, making them likely hot spots in terms of the severity and significance of transportation line-caused lateral floodplain disconnection.

Proximity of stream channels and transportation lines is a necessary but not sufficient condition for lateral floodplain disconnection by transport networks. Transportation line elevation, height, and composition determine the extent of local disconnection. Where disconnection occurs, loss of aquatic and floodplain habitat richness and diversity and degraded riparian ecosystem function is likely. This study likely underestimates the aggregate impact of transportation infrastructure on floodplains. Detailed floodplain mapping and modeling will enhance understanding of the nature and extent of transportation-driven disconnections in individual river corridor landscapes. Understanding the cumulative historic impact of transportation structures on river landscapes, how they alter floodplain dynamics and associated river management restoration efforts, and what opportunities exist for the removal or modification of floodplain structures are all important questions deserving of further inquiry.

The results of this study indicate that role of transportation infrastructure on floodplain form and function should receive more systematic attention in the large yet informal research agenda of researchers examining floodplains as landscapes altered by humans. Here, roads and railroads should accounted for along with dams, dikes, levees, floodplain land uses, and other modifications already widely accepted as radically altering river corridors.

The pioneering stream ecologist H.B. Hynes famously said that, in every aspect, the valley rules the stream (Hynes, 1975). Valley morphology and width clearly influences geomorphic, hydrological, and ecological processes in the river landscape and provides a template for potential floodplain disconnection. Valley confinement is a key metric in geomorphic stream classification systems (Rosgen 1994; Montgomery and Buffington 1998; Brierly and Fryris, 2005), most of which treat valleys as unconfined save for bedrock-confined channels and gorges. However, the extent of transportation infrastructure in the alluvial valleys of the U.S. shows that in many areas the degree of natural confinement is greatly increased by transportation networks. These transportation networks are so ubiquitous and so long-standing in valley bottoms as to be invisible to the modern eye; they are hidden in plain sight. To paraphrase Hynes, in modern landscapes in the U.S., the valley rules the transportation network — and the transportation network rules the stream.

Research presented in this chapter documents the widespread potential impact of roads and railroads on river landscapes. In the next chapter, I investigate the impacts of floodplain roads and roads at the basin scale. A key component of this investigation is the development of techniques for mapping floodplain disconnection.

CHAPTER III

MAPPING THE IMPACTS OF ROADS AND RAILROADS ON FLOODPLAIN CONNECTIVITY AT LANDSCAPE SCALES

This chapter is to be submitted to the Annals of the Association of American Geographers. This paper was co-authored with W. Andrew Marcus, who provided editorial assistance.

Introduction

River floodplains sustain aquatic and terrestrial ecosystems. Floodplains also have long histories of human alteration due to resource extraction, settlement, and use as avenues for transportation. The large majority of these human activities disrupt flows of water, sediment, and biota between the channel and floodplain, disconnecting the river from its floodplain and degrading habitat structure and function. Roads and railroads in floodplains are primary drivers of these disconnections (Foreman, 2003; Blanton and Marcus 2009). Delineating and mapping these transportation-driven lateral disconnections within floodplains therefore is key to understanding the extent of human impacts on river systems and identifying opportunities for stream preservation and restoration. Yet despite the widespread extent of roads and railroads in floodplains, there is little literature on mapping and assessing their impacts of on river landscapes.

This study develops methodologies for documenting floodplain disconnections caused by roads and railroads at landscape scales and discusses potential applications and implications of these techniques for management, planning, and policy. Specifically we use GIS and pre-existing, publicly available digital data sets for soils, geology, topography, floodplain extent, land cover, and transportation networks to: 1) compare methods for mapping potentially functional and disconnected floodplain areas, 2) compare floodplain disconnections caused by transportation infrastructure across a variety of valley settings in the State of Washington, and 3) investigate the potential of the mapping methods and findings as guides for mitigation and restoration planning.

Background

Mapping Floodplains

Mapping floodplain disconnections requires mapping the functional floodplain prior to and after human intervention. ‘Functional floodplain’ here is defined as the unobstructed areas of the floodplain that are geomorphically and hydrologically connected to the channel.

The National Flood Insurance Act (1968) and the Flood Disaster Protection Act (1973) initiated the systematic mapping of flood-prone areas across the United States. However, these acts and the flood maps associated with them defined areas of potential inundation, which often do not correspond to the functional floodplain. Inundation may be confined by human structures in the floodplain or be limited by river regulation (Ward and Stanford, 1995). In addition, inundation maps may not capture important geomorphic processes such as channel migration (Rapp and Abbe, 2003).

Wolman (1971) reviewed the variety of techniques for mapping modern floodplains. He grouped methods into categories based on the type of evidence they used, which were: 1) valley and channel physiography, 2) local soil maps, 3) local vegetation maps, 4) local data on historic floods, 5) flood frequency curves developed using regional flood frequency data from other sites, and 6) flood profiles and backwater curves. Wolman noted that there is inherent uncertainty in all of these techniques. Dingman and Platt (1977) quantified this error, focusing on error in the measurement of discharge data, the derivation of flood frequency analysis, and the construction of topographic maps.

In the decades following these studies, available data sources and tools used for floodplain mapping changed greatly. For example, sub-meter accuracy LiDAR elevation data are now available in many settings (Jones et al., 2007). Likewise, a variety of digital data are now freely available that may be manipulated and analyzed in GIS for many applications. In addition, computer models such as HEC-RAS (U.S. Army Corps of Engineers, 2010) and MIKE (DHI Software, 2010) are widely used for inundation estimates and other river modeling.

The technical issues of precision and accuracy with data sources, models, and predicative ability noted by Wolman (1971) and Dingman and Pratt (1977) still remain, but increasingly, researchers are examining fundamental questions related to how to define floodplains for different user groups and their needs (including non-human users).

Ecological function, habitat quality, water quality, erosion hazard, resource extraction, and land use all speak to broader sets of issues than inundation modeling.

More complex dynamic approaches that delineate historical and potential future floodplain changes and incorporate the effects of human modifications provide alternatives to modeling only the extent of inundation. Geomorphologists took an early lead on this topic, producing change-over-time maps and future predictions of floodplain changes (Graf 1983, 1987). Since then, several groups have incorporated these mapping approaches into regulatory frameworks. For example, the Channel Migration Zone (CMZ) approach developed for the Washington State Department of Ecology (Rapp and Abbe, 2003) delineates the floodplain area susceptible to erosion and other active fluvial processes. It does this by overlapping the historical zone of channel migration and avulsion with a user-defined erosion hazard zone, and removing the disconnected floodplain that is protected by structures. The “erodible corridor concept,” developed in Europe, is a similar multi-scale, historical, process-based approach (Piégay et al., 2005). Such process-based approaches provide a robust picture of floodplain extent and function; however they are relatively time consuming, data-extensive, expensive, and require extensive local and professional expertise.

A simpler option to such multifaceted floodplain reconstruction is to define the likely extent of the floodplain prior to human alteration using more limited geomorphic criteria. Snyder et al. (2002), for example, defined the ‘Holocene floodplain’ of the Yakima River in Washington State as surfaces associated with fluvial activity in the last 10,000 years. They were able to delineate the boundary of this zone based on airphoto and field geomorphic mapping. Digital elevation, geologic and/or soils data are now available to help quickly define such surfaces.

Given the array of available methods it can be difficult to know which technique(s) to use, and no ‘gold standard’ fits all needs. The appropriate method for floodplain definition varies with (1) the application at hand (e.g. flood hazard, ecology, gravel mining, etc.); (2) the time scale in question (e.g. Quaternary, 100-yr, or seasonal delineations); and (3) available data sets and logistical constraints (Wolman, 1971). Wolman asserted that the appropriateness of a particular approach should be judged by the utility of information it generates relative to the objectives of the user. While some locations and objectives may require more expensive, precise and time-consuming methods, other locations and objectives may be adequately addressed by simpler, less expensive approaches.

Few approaches exist that are specifically designed for mapping lateral disconnection. Field and air photo approaches rely on local mapping of structures using aerial photographs and subsequent field surveys (e.g. Stanford et al., 2002). GIS overlay approaches rely on simple indicators of proximity for roads and railroad grades (Blanton and Marcus, 2009). The recent availability of landscape scale digital data, however, opens up new opportunities for mapping disconnections at multiple spatial scales, classifying them by causal mechanisms and size, and exploring their ecological impacts and implications.

Lateral Disconnections

Connectivity is the exchange of water, sediment, and biota in and between the channel, the riparian zone, the floodplain, terraces, and hill slopes. These exchanges combine to create habitat complexity and biodiversity across the floodplain (Ward et al., 1999). Connectivity varies in three spatial dimensions over time: longitudinally along the length of the stream system, vertically, and laterally across valleys and slopes (Amoros et al., 1987; Ward, 1989).

The impacts of transportation infrastructure on river systems may be divided into two broad categories (Forman et al., 2003). 'Crossing impacts,' such as bridges and culverts, can have significant impacts on longitudinal connectivity in the up and downstream direction. Such impacts tend to dominate in low relief areas such as the East and Midwest of the United States (Blanton and Marcus, 2009).

'Lateral disconnection impacts' occur where structures act as dams along the length of a stream, blocking movements of materials between the active channel and surrounding floodplain and slope environments. These lateral disconnections interrupt flood and flow pulses, disrupt channel migration, and hinder the cut-and-fill alluviation important for floodplain and in-channel habitat creation and maintenance (Figure 3.1). These natural processes are ecologically significant, creating and maintaining off-channel habitat important for macroinvertebrates and fish community structure and diversity, (Arscott et al., 2005; Barko et al., 2006). In a national-scale analysis of potential impacts of transportation lines on connectivity in the floodplains of the contiguous United States, Blanton and Marcus (2009) showed that lateral disconnection impacts are dominant in areas of more rugged relief such as the Pacific Northwest.

Figure 3.1: Yakima River, Kittitas Valley, Washington. Channel is laterally confined by railroad grade, creating both long-term and short-term disconnection.

Floodplain Management and Restoration Prioritization

River management and restoration are increasingly focusing on maintaining or restoring connectivity within the floodplain and between the floodplain and active channel. Floodplain connectivity is a particularly important control on biodiversity in the river landscape (Ward et al. 1999, Amoros and Bournette 2002). Isaak et al. (2007) showed that connectivity of habitat patches was more important than patch size, and far more important than habitat patch quality in predicting Chinook salmon nest occurrence, a key species of concern in our study area. This is because organisms require multiple habitat types and must be able to access them all. There thus may be excellent feeding habitat and resting habitat in nearby areas, but if these habitats are not connected, the organism cannot access them and will be in peril.

Because connectivity is often impaired by human activities, connectivity metrics are needed that are indicative of river response to human impacts and management (Lasne et al., 2007). Le Pichon et al. (2009) used landscape ecology metrics based on spatial analyses to identify opportunities and obstacles to habitat preservation and restoration. They found these metrics were useful, but must be tailored to the particular nature and issues of the river in question. For example, metrics used to characterize critical salmon habitat may differ from those used for amphibians. In this study, we focus on habitat function in the context of endangered salmonids, which do best in laterally migrating channels and floodplains (Hall et al., 2007).

In summary, assessing human impacts on lateral connectivity and developing rationale restoration approaches along river corridors requires: 1) establishing the functional and disconnected floodplain extent prior to development, 2) assessing anthropogenically-driven floodplain disconnection at local to regional extents, and 3) developing approaches to apply these maps to guide management and policy. In this article, we provide potential solutions to meeting each of these needs using GIS and readily available digital data, comparing floodplain mapping results using different data sources to each other, as well as to floodplain mapping results for a limited number of reaches in the study area mapped in more detail by Snyder et al. (2002).

Study Area

We applied and evaluated digital data-based techniques for mapping floodplains and lateral disconnections in the Yakima and Chehalis Rivers of Washington (Figure 3.2). These river corridors span a range of river morphology types, valley confinement, urbanization, land cover, and proximity of roads and railroads to the channel. The study areas include alluvial valleys in areas of rugged relief, which are the type of area expected to be 'hotspots' of lateral disconnection (Blanton and Marcus, 2009). In addition, previous researchers have extensively examined human impacts on floodplain connectivity and fish habitat in the Yakima basin (Eitemiller et al. 2000, Snyder et al 2002, Stanford et al., 2002), providing a basis for comparison with our results.

Both the mainstem Yakima and Chehalis Rivers alternate between short confined valleys and open alluvial floodplain reaches, with generally low to moderate gradients exhibiting pool-riffle to plane-bed reach types (Montgomery and Buffington, 1997). The Yakima's substrate is primarily comprised of large gravel to small cobbles, while the Chehalis also includes finer material. The Chehalis floodplain is a complex mix of unconsolidated sand and gravel glacial deposits mixed with modern alluvial deposits that, in places, abut older marine sedimentary terraces (Stanford et al. 2002, Chehalis Basin Partnership Habitat Work Group, 2008). The Yakima's hydrologic regime is snowmelt

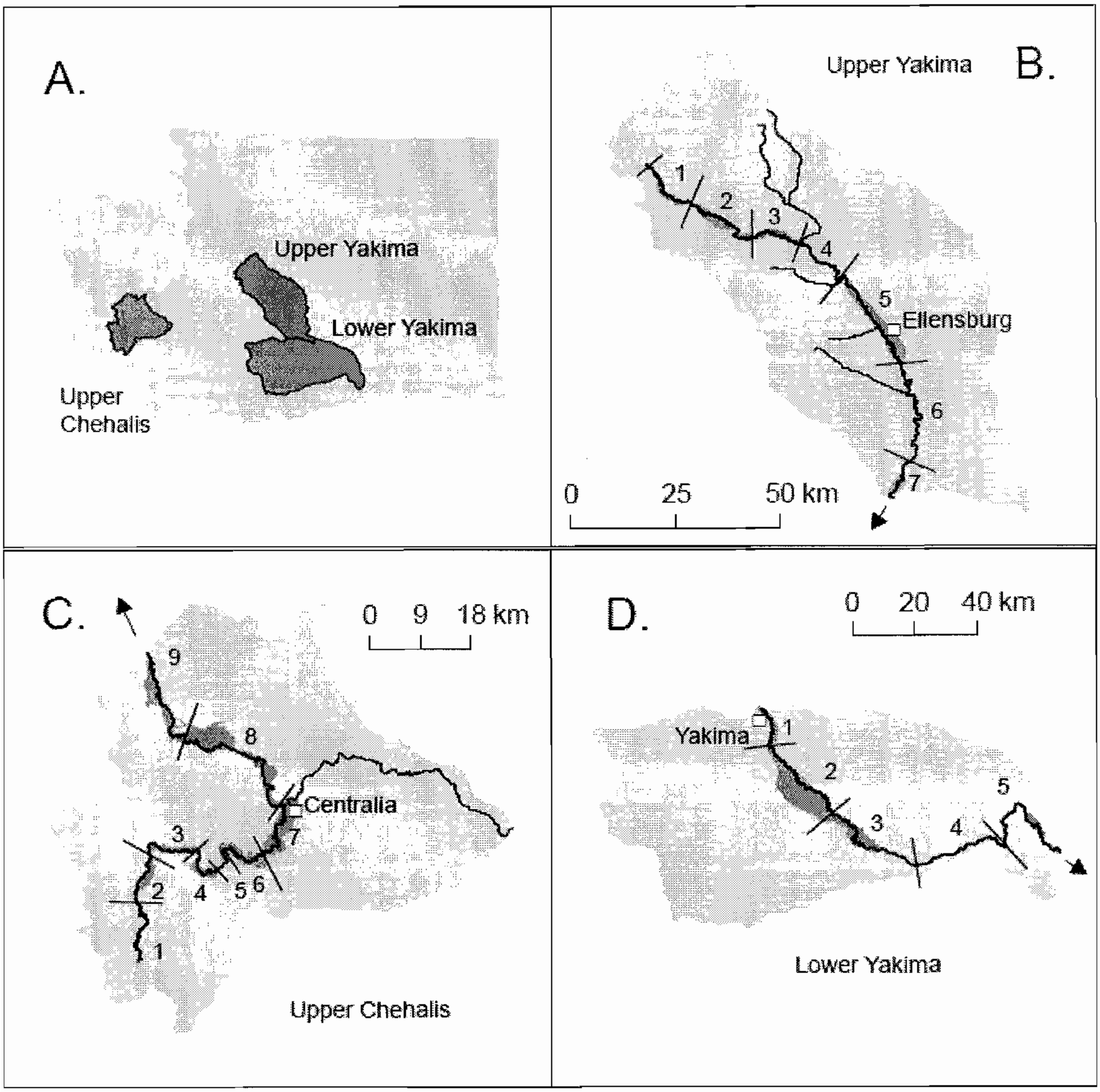


Figure 3.2: Study area locations. A. Location of watersheds within State of Washington. B. Upper Yakima reaches: 1. Keechelus, 2. Easton, 3. Cle Elum, 4. Upper Canyon, 5. Kittitas Valley, 6. Lower Canyon, 7. Selah. C. Upper Chehalis reaches: 1. Headwaters, 2. P Ell, 3. Doty, 4. Ceres Hill, 5. Mill, 6. Bunker, 7. Centralia, 8. Chehalis Village, 9. Oakville. D. Lower Yakima reaches: 1. Yakima, 2. Wapato, 3. Sunnyside, 4. Prosser, 5. Richland. Direction of flow indicated by arrows.

dominated, but is a regulated system so that the highest flows tend to be in the summer months when irrigation demands are high. The Chehalis' hydrologic regime is dominated by winter rain and rain on snow events and has low flows during the summer due to its altered runoff regime (Table 3.1).

Table 3.1: Geomorphic and hydrologic characteristics of the study areas with location of the recording station.

	Upper Yakima	**Lower Yakima**	**Upper Chehalis**
Drainage area (km2)	5,423	7,603	3,358
Maximum elevation (m)	2,429	2,127	1,138
Minimum elevation (m)	330	191	8
Mean annual ppt. (mm/yr)	225 (Ellensburg)	206 (Yakima)	1,170 (Centralia)
Discharge (cms)	Umptanum gage	Kiona gage	Porter gage
Mean annual flood	69	99	115
100-year flood	950	1,682	2,260

Alluvial floodplain reaches in both systems once supported large riparian gallery forests, with particularly extensive black cottonwood forest along the Yakima (Braatne et al., 2007). These forests are still present where not impacted by human modification of the floodplain.

In the past, the Chehalis and Yakima Rivers supported large populations of salmon and both rivers currently are the focus of active salmon restoration efforts. In the Yakima basin, the disconnection of off-channel habitat by roads and railroads is a major threat to endangered and threatened salmonids (Stanford et al. 2002). Likewise, in the

Chehalis watershed, floodplain infrastructure has disconnected off-channel habitat, wetlands, and sloughs to the detriment of fish populations, and culverts have disconnected tributaries (Chehalis Basin Partnership Habitat Work Group, 2008).

To evaluate the different data sets and approaches for mapping floodplains and floodplain disconnections in different geomorphic valley settings, we subdivided the river corridors into reaches that ranged from 10 to 50 km in length (Figure 3.2). Divisions between segments were located at major changes in valley confinement and major tributaries. Valley confinement was defined using the metric of valley width index (VWI), which is the ratio of flood prone width to active channel width (Hauer and Lamberti, 1996).

Methods

All metrics for the functional floodplain and later disconnections were calculated in ARC-GIS 9.3 for the individual reaches, as well as for the entire corridor. In the Yakima River, we compared our results with those of Snyder et al. (2002), who mapped the extent of the Holocene floodplain and lateral disconnections along the Cle Elum and Kittitas reaches in the Upper Yakima watershed (reaches 3 and 5, Figure 3.2b) and the Yakima reach in the lower Yakima watershed (reach 1, Figure 3.2d).

All data sources utilized in this study (Table 3.2) are publically available free of charge from U.S. or state government on-line sources. The data sets generally require little modification to be used in GIS analysis, except where noted otherwise.

Mapping the Functional Floodplain

We evaluated methods for calculating the functional and disconnected floodplain area by comparing results derived from readily available digital data for each of the valley reaches (Table 3.2). Data sources were: (1) soil survey data, which identifies soils associated with floodplains, (2) geologic maps of alluvial deposits, which identify

Table 3.2: Pre-existing digital data sets used in floodplain analysis

Application	Data Layer	Source
Floodplain delineation	Soils (SSURGO)	U.S. National Resources Conservation Service
	Surficial Geology (Quaternary alluvium)	Washington State Dept. of Geology
	FEMA 100-year floodplain	U.S. Federal Emergency Management Agency
Mapping lateral disconnection	Highways and rail lines	Washington State Dept. of Transportation
	Local Roads	U.S. Bureau of Transportation Statistics
Management prioritization	National land Cover data, Impervious Surface (2001)	USGS National Map
	National Hydraulic Data (NHD)	USGS
	Salmonid Status of Stock (SASI) data	Washington State Salmonscape data download site
Evaluating relationship between land development and disconnection	National land Cover data, Land Use/land Cover (2001)	USGS National Map

materials worked by the rivers within the last ~10,000 years and may be used to delineate the maximum extent of the floodplain (Snyder et al., 2002), and (3) FEMA maps of the 100-year floodplain. All three of these data sources are freely available in GIS format. To evaluate the relative merits of the different data sets for identifying the functional floodplain, we mapped and calculated the overlap between floodplains extents defined by each data type.

Soil Survey Data

Soil Survey Geographic (SSURGO) data are the highest-resolution soils data that are widely available in digital format. Mapped at scales as fine as 1:10,000, these data are available for the entire United States and are available on-line from the Natural Resources Conservation Service website. While the soils data contain great detail, they may be difficult to interpret for the non-soil specialist and require polygon-by-polygon analysis by the user to isolate true floodplain units.

To identify the functional floodplain with the SSURGO soil data, we clipped the data to the watershed boundary and then used the soil survey characteristics of landform (floodplain), parent material (alluvium), and an upper limit of slope of 5% to create a map layer of floodplain soils. Some soil units were associated with upland surfaces as well as floodplains. In these situations we used DEMs, topographic maps and air photos to visually identify and manually remove soils on terraces, alluvial fans, landslide deposits or other non-alluvial surfaces. We also removed the polygons associated with tributary streams, thus isolating the soil layers associated with the floodplains of the Yakima and Chehalis rivers.

Surficial Geology Data

Digital geologic data are not available for the entire U.S., but where available, the Quaternary alluvium (Qa) map units from geologic maps provide a potential mechanism for mapping the modern floodplain. Surficial geology is typically mapped onto 1:24,000 topographic maps and aggregated to 1:100,000 or 1:250,000 geologic maps.

We obtained 1:100,000 scale digital geologic data from the Washington Division of Geology and Earth Resources, and clipped these data to the watershed boundary. As with the soils, care must be taken to isolate alluvium from other non-riverine Quaternary units such as terraces, landslide deposits, alluvial fans, and tributaries. However, these data are much simpler to manipulate in GIS than the soils data as there is only one layer (Qa) to manipulate.

FEMA Floodplain Data

FEMA offers a variety of on-line flood mapping products, but the most widely available data are still the Q3 flood maps derived from the older Flood Insurance Rate (FIRM) paper maps. These data are intended to be used for general hazard awareness, education, and flood plain management rather than for engineering or legal purposes (FEMA, 1996). Typically these maps are used to identify the 100-year floodplain. More detailed digital flood hazard data also are available for much more limited spatial extents, chiefly around urban areas.

We isolated the portion of the FEMA-defined 100-year floodplain that was associated with the main stem river corridors by clipping the portions of the floodplain layer associated with tributaries. In addition to comparing the FEMA data with the functional floodplain measures, preliminary analysis led us to also compare the extent of the FEMA floodplain with the ‘connected floodplain’ metrics, as is discussed below.

Mapping Lateral Disconnections

We defined the boundary of disconnection due to transportation infrastructure as the distance from the active channel edge to the closest transportation line on the same side of the channel. The ‘connected floodplain’ (in terms of transportation infrastructure) is the portion of the floodplain inside the transportation line, while the ‘disconnected floodplain’ is the remainder of the floodplain. The metric of lateral river disconnection is the ratio of the area of the disconnected floodplain to the total area of the functional floodplain.

Not all structures have equal potential for disconnection. We classified the disconnected floodplain into two categories based on the type of structure causing disconnection, which in turns controls its potential to be overtopped by major floods and smaller flow pulses and to be removed or modified for restoration purposes. We classified highways and rail lines as Class I disconnections, which have the greatest impact on connectivity among the various transportation lines (Forman et al. 2003, Blanton and Marcus 2009). Class I disconnections completely disconnect the floodplain structurally and functionally. These structures are not overtopped even by large floods (they are often the extent of the FEMA 100-year floodplain) and are major impediments to channel migration. Except in rare circumstances, these structures will not be removed from the floodplain and are unlikely to be modified for ecological purposes.

Local roads create Class II disconnections, which typically do not block water movement to the same degree as Class I disconnections, but do limit meandering, channel migration, and development of side channel habitat. Moreover, if they are constructed on top of levees or other structures, they may have an effect on connectivity disproportionate to their size. Local roads are also more amenable to modification or removal than larger structures. We mapped lateral floodplain disconnection for all alluvial valley reaches, excluding confined (VWI < 2) canyon reaches, as these settings have minimal floodplain area, and lateral connectivity as a fish management issue is relatively unimportant.

Assessing Restoration Potential

We developed a simple ranking system for the study reaches in terms of potential value as salmon habitat. These rankings were then combined with our characterization of disconnection to qualitatively assess the potential for altering transportation infrastructure to preserve or enhance salmon habitat. Based on previous studies (Snyder et al. 2002, Stanford et al 2002, Chehalis Basin Partnership Habitat Work Group, 2008), we ranked the study reaches in terms of habitat potential based on: (1) the number of salmon-bearing tributaries per floodplain area and (2) the floodplain channel complexity, which is the length of secondary channels divided by the main channel length.

In order to evaluate the potential for and limitations to floodplain restoration, we mapped the loss of otherwise functional floodplain surface area due to development. To map the percent impervious surface, we used the 30-m resolution 2001 National Land Use/Land Cover (NLCD) data set (Table 3.2). The NLCD is derived from LANDSAT imagery (Homer et al., 2007) and includes a data set showing percent (from 0 to 100%) impervious surface for each 30m raster cell. Ecological function is impaired at relatively low levels of impervious surface (Brabec et al., 2002). Starting with the assumption that impervious areas represent a land cover that will not return to natural conditions without human intervention, we defined *impaired connected floodplain* (ICF) as those 30m cells that were otherwise connected, and thus may have habitat potential, but had >10% impervious cover. We created a raster layer of this impaired floodplain area, and ranked the reaches in terms of disconnection by type and by the amount of impaired floodplain.

To identify key locations for restoration and preservation, we also examined the reaches classified as having high restoration potential for within-reach variability. We identified areas likely to be of local significance in terms of potential fish habitat restoration and preservation by looking for: (1) downstream portions of alluvial valleys where local geomorphic controls drive upwelling and channel complexity (Stanford et al. 2002); (2) areas where a high percentage of the Holocene floodplain may be disconnected, but a significant riparian zone is still intact; and (3) areas that are developed or have low channel complexity but are connected to major tributaries in the reach.

Results

Mapping the Functional Floodplain

At the scale of the entire sub-basins, the Holocene floodplain defined by the geologic data was always within several percent of the modern floodplain as defined by soil maps (Table 3.3). In general, the reach-by-reach correspondence between the soils and geology-defined floodplains was within 10% of one another, with the exception of the confined reaches that have low VWI values (Figure 3.3, Table 3.3).

If the two floodplain definitions are in close agreement in terms of spatial extent, we would expect high values for both proportions of overlap, although the percent overlap varies with polygon size and shape (Figure 3.4). All reaches with less than 75% overlap between soils-based and Qa-based floodplain extents were in confined valley reaches with relatively small floodplain areas.

In contrast the 100-year FEMA floodplain consistently corresponded poorly to the soils and geology-based floodplains. The FEMA-based floodplain extents were generally much smaller in extent (Table 3.3, Figures 3.5 and 3.6).

Table 3.3: Floodplains as defined using soils, Quaternary alluvium, and FEMA floodplain data

	Entire Sub-basin	Easton	Cle Elum	Upp. Canyon	Kittitas Valley	Low. Canyon	Selah
Length (km)	155.8	43.7	17.4	12.3	33.7	37.1	11.6
Valley Width Index		37.5	16.6	1.3	18.7	1.5	6.4
Soils-based (km2)	129.9	36.2	17.0	2.3	56.6	4.9	11.8
Qa-based (km2)	129.6	40.2	17.5	2.7	56.7	2.2	10.6
FEMA-based	65.2	14.1	8.3	2.2	24.9	5.5	10.1

	Entire Sub-basin	Yakima	Wapato	Sunnyside	Prosser	Richland
Length (km)	192.0	15.2	41.7	53.4	34.7	47.2
Valley Width Index		22.9	102.7	40.3	1.6	13.4
Soils-based (km2)	300.1	24.2	150.3	71.1	20.5	34.0
Qa-based (km2)	314.7	21.6	182.5	66.0	13.9	30.7
FEMA-based	186.8	21.2	83.4	46.5	6.7	29.0

	Sub-basin	Headwaters	Pe Ell	Doty	Ceres Hill	Mill Conf	Bunker	Centralia	Che Vill	Oakville
Length (km)	147.3	20.0	11.4	12.5	9.2	2.5	14.7	19.0	32.2	25.6
Valley Width Index		1.4	5.7	10.7	14.3	1.3	16.7	19.6	21.9	11.7
Soils-based (km2)	170.7	0.4	12.7	11.6	9.5	0.5	22.8	28.3	56.0	28.9
Qa-based (km2)	155.0	0.0	9.9	8.6	7.0	0.3	20.0	30.3	51.4	27.4
FEMA-based	122.6	1.2	3.6	1.0	4.7	0.2	7.5	26.9	47.2	30.4

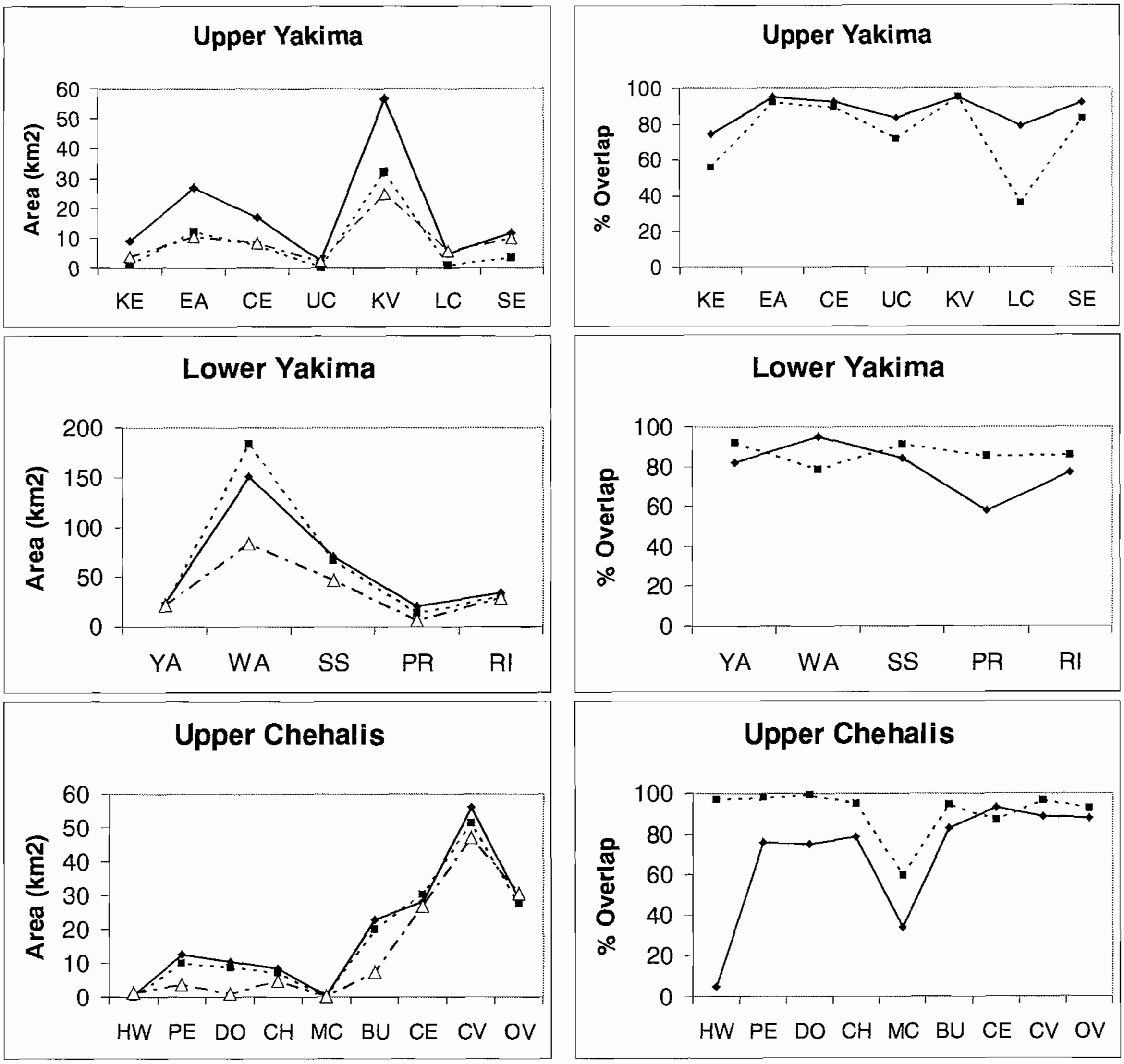


Figure 3.3: Consistency of soil- versus Qa- defined floodplain. Left: Floodplain area (solid line = soils, dashed line = Qa, broken line with white triangles = FEMA). Right: degree of spatial overlap between soil- versus Qa- defined floodplain (solid line = % soils total area common to alluvium, dashed line = % alluvium total area common to soils). Reaches: KE Keechelus, EA Easton, CE Cle Elum, UC Upper Canyon, KV Kittitas Valley, LC Lower Canyon, SE Selah; YA Yakima, WA Wapato, SS Sunnyside, PR Prosser, RI Richland; HW Headwaters, PE Pe Ell, DO Doty, CH Ceres Hill, MC Mill Confined, BU Bunker, CE Centralia, CV Chehalis Village, OV Oakville.

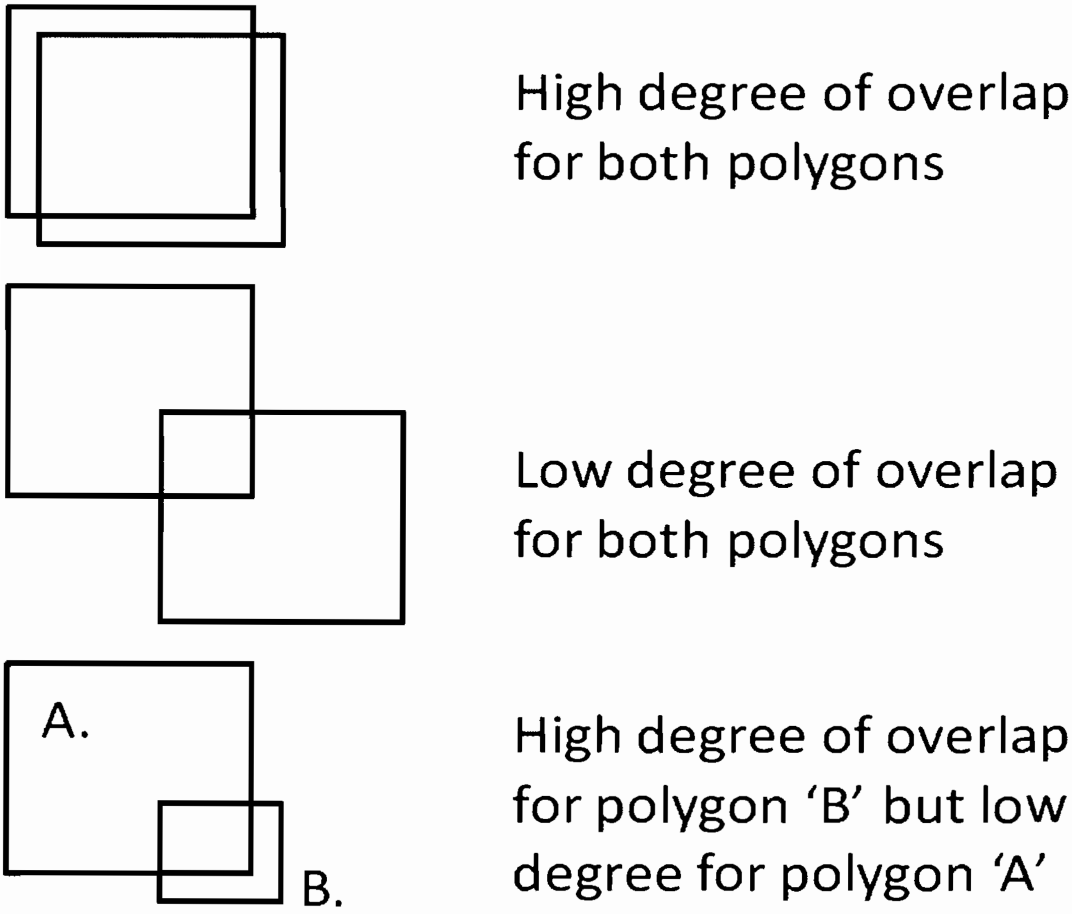


Figure 3.4: Overlap. A high degree of overlap indicates general agreement between the two definitions. Low overlap suggests that closer examination is warranted to explain the disagreement. A discrepancy between the two overlap values indicates a difference in area, with the smaller polygon sharing more common area with the larger polygon.

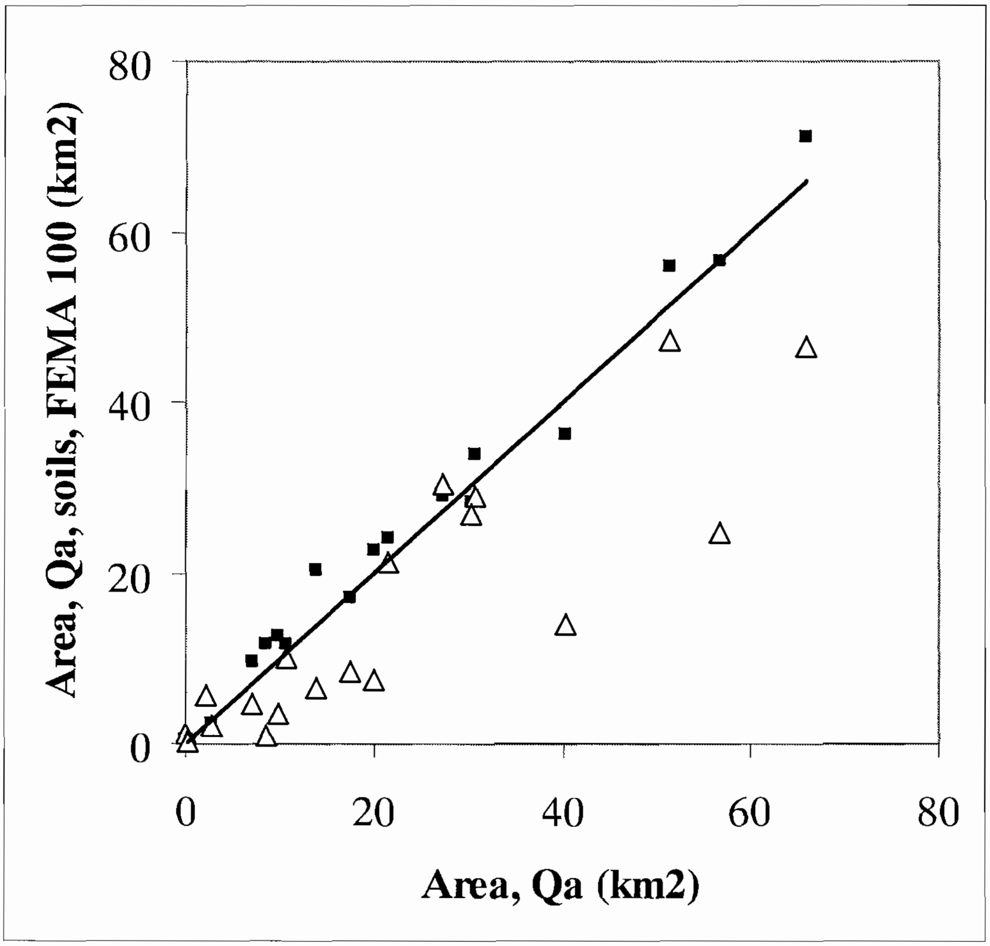


Figure 3.5: Consistency of floodplain definitions based on surficial geology, soils, and FEMA floodplain data. Squares = soils. Triangles = FEMA. Areas of three definitions plotted against Qa (so that Qa plot forms 1-to-1 line).

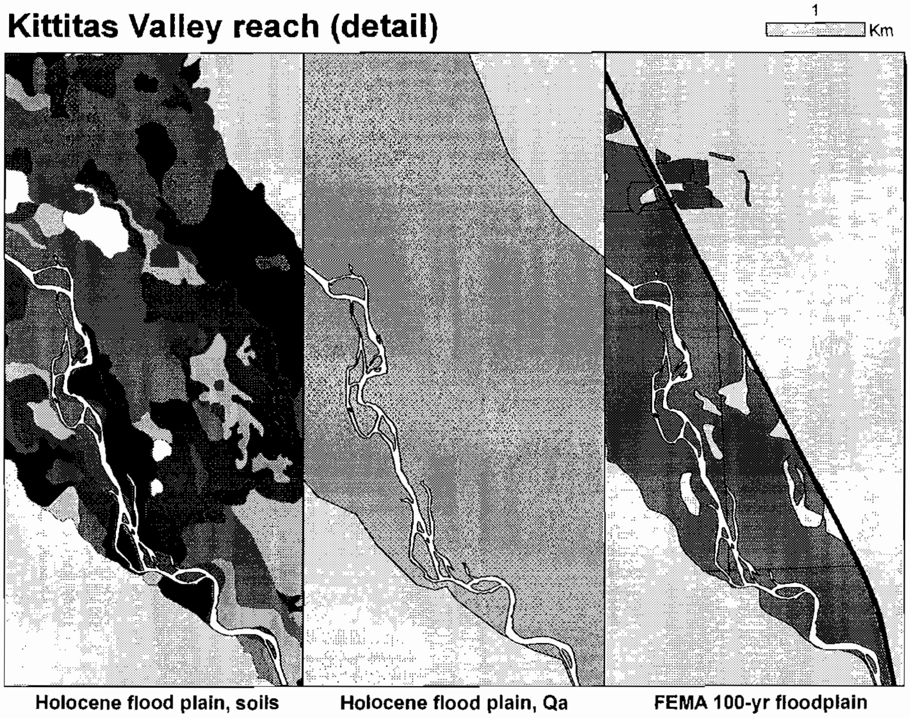


Figure 3.6: Comparison of three floodplain data sets. Geologic data (middle) corresponds well to soils for the purposes of floodplain definition, but is much simpler to manipulate and assess. Extent of FEMA 100-year floodplain is often defined by Class I disconnection (in this case, State Route 821).

The floodplain extents as defined by digital geological data and by the soils are in general agreement with the results of previous studies for the Yakima River (Table 3.4). Previous studies only included data on the Cle Elum, Kittitas, and Yakima reaches, precluding reach-to-reach comparison for the other reaches.

Table 3.4: Comparison of floodplain definition results with those obtained by Snyder et al (2002). Areas in km2.

Reach	**Previous studies**	**This study** **Qa-based**	**This study** **Soil-based**	**FEMA**
Cle Elum	17.5	17.6	17.0	8.3
Kittitas	54.2	56.7	56.7	24.9
Yakima (Union Gap)	23.3	21.6	24.1	21.2

Table 3.5: Extent of lateral floodplain disconnection by disconnection class.

Upper Yakima	**Entire sub-basin**	**Keechelus**	**Easton**	**Cle Elum**	**Upper Canyon**	**Kittitas Valley**	**Lower Canyon**	**Selah**
Class I	44.2	8.0	43.4	43.2	9.9	56.2	39.8	33.8
Class II	8.5	9.8	6.5	16.0	3.6	8.2	0.0	15.7
Class I+II	52.7	17.9	49.9	59.3	13.6	64.4	39.8	49.5

Lower Yakima	**Entire sub-basin**	**Yakima**	**Wapato**	**Sunnyside**	**Prosser**	**Richland**
Class I	32.0	18.6	51.0	1.6	8.3	4.4
Class II	25.5	30.3	24.2	33.9	13.6	17.7
Class I+II	57.5	48.8	75.1	35.6	21.8	22.1

Upper Chehalis	**Entire sub-basin**	**Head-waters**	**Pe Ell**	**Doty**	**Ceres Hill**	**Mill**	**Bunker**	**Centralia**	**Chehalis Village**	**Oakville**
Class I	21.9	0.0	53.2	2.2	39.0	0.0	9.2	46.1	18.5	1.6
Class II	22.2	0.0	5.1	59.0	13.1	0.0	43.6	11.8	22.1	15.7
Class I+II	44.1	0.0	58.3	61.2	52.1	0.0	52.8	57.9	40.6	17.4

Lateral Floodplain Disconnection

Among the three study area river corridors, the Upper Yakima had the highest overall proportion of floodplain disconnected by highways and rail lines (44%), with the Lower Yakima (32%) and Upper Chehalis (22%) exhibiting less corridor-wide Class I disconnection (Table 3.5, Figures 3.7-3.9). Adding local roads (Class II disconnection) slightly increases the proportion of the Upper Yakima that is disconnected to 53%, while the lower Yakima greatly increases to 58% and the upper Chehalis doubles to 44%.

Of the Upper Yakima reaches (Figure 3.7), the Kittitas Valley had the highest degree of overall disconnection (64%), nearly all of which was Class I disconnection. The Cle Elum and Selah reaches had a relatively high level of Class II disconnection (16%). In the lower Yakima, the Wapato reach had the highest overall and Class I disconnection (Figure 3.8); the other reaches in this basin were more impacted by Class II disconnection. In the Upper Chehalis (Figure 3.9), the Pe Ell and Centralia reaches had the highest Class I disconnection. The Bunker and Doty reaches had comparably high overall disconnection, but were predominantly affected by Type II disconnection.

Our Class II disconnection results are generally comparable with those reported by Snyder et al. (2002) (Table 3.6). In the Cle Elum reach, our proportion of area mapped as disconnected is identical to previous results. Our results for the Kittitas and Yakima reaches are slightly lower than, but comparable to previous results.

Assessing Restoration Potential

Table 3.7 indicates reach rankings of habitat potential factors, and limiting factors for habitat restoration. These factors are ranked from best (1) to worst (16). Reaches

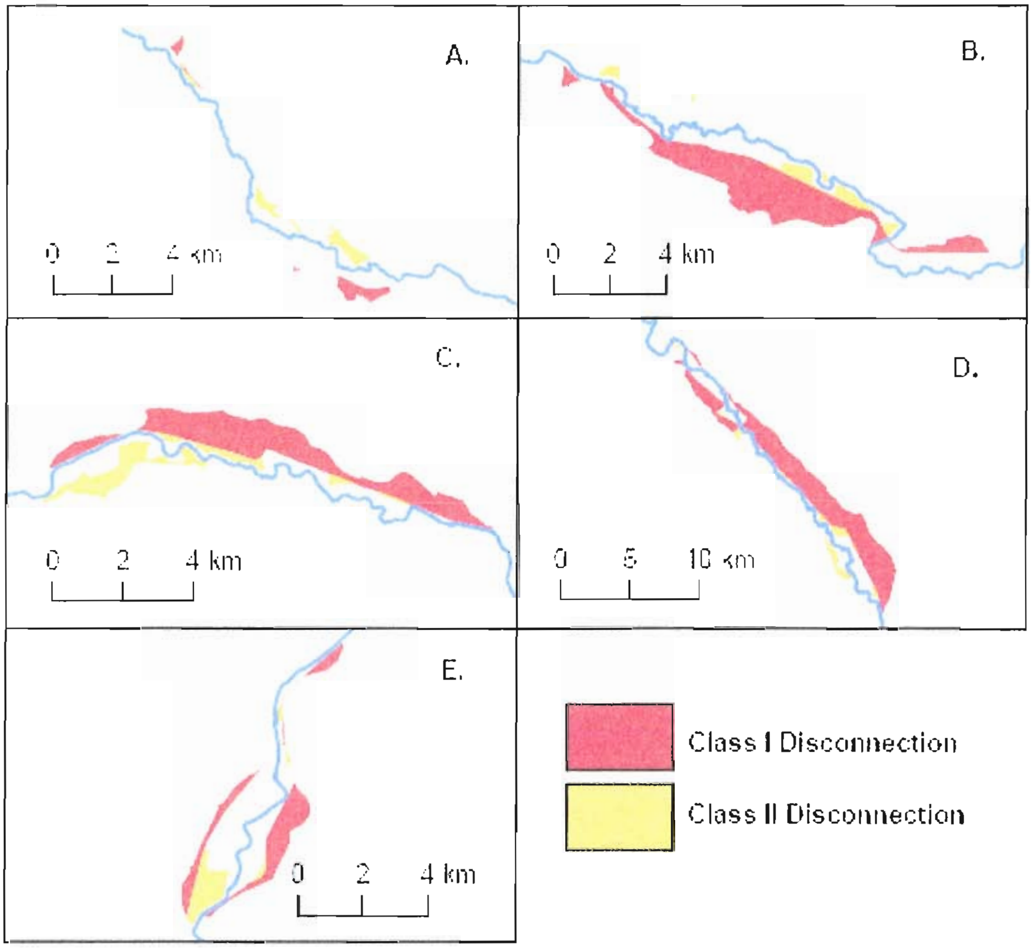


Figure 3.7: Floodplain disconnection, Upper Yakima. A. Keechelus, B. Easton, C. Cle Elum, D. Kittitas, E. Selah.

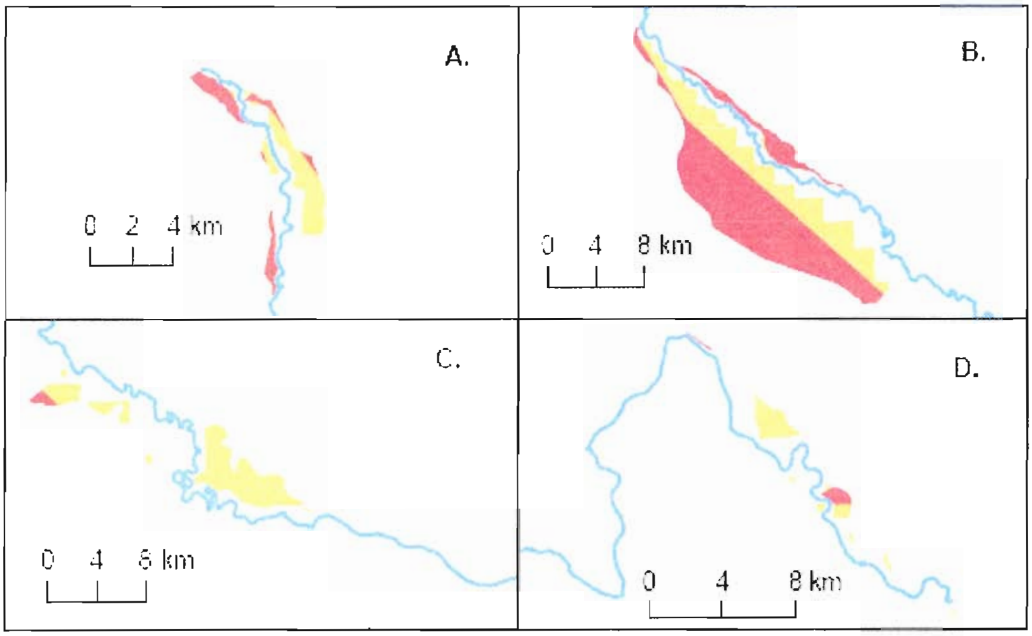


Figure 3.8: Floodplain disconnection, Lower Yakima. A. Yakima, B. Wapato, C. Sunnyside, D. Richland. Symbology identical to Figure 7.

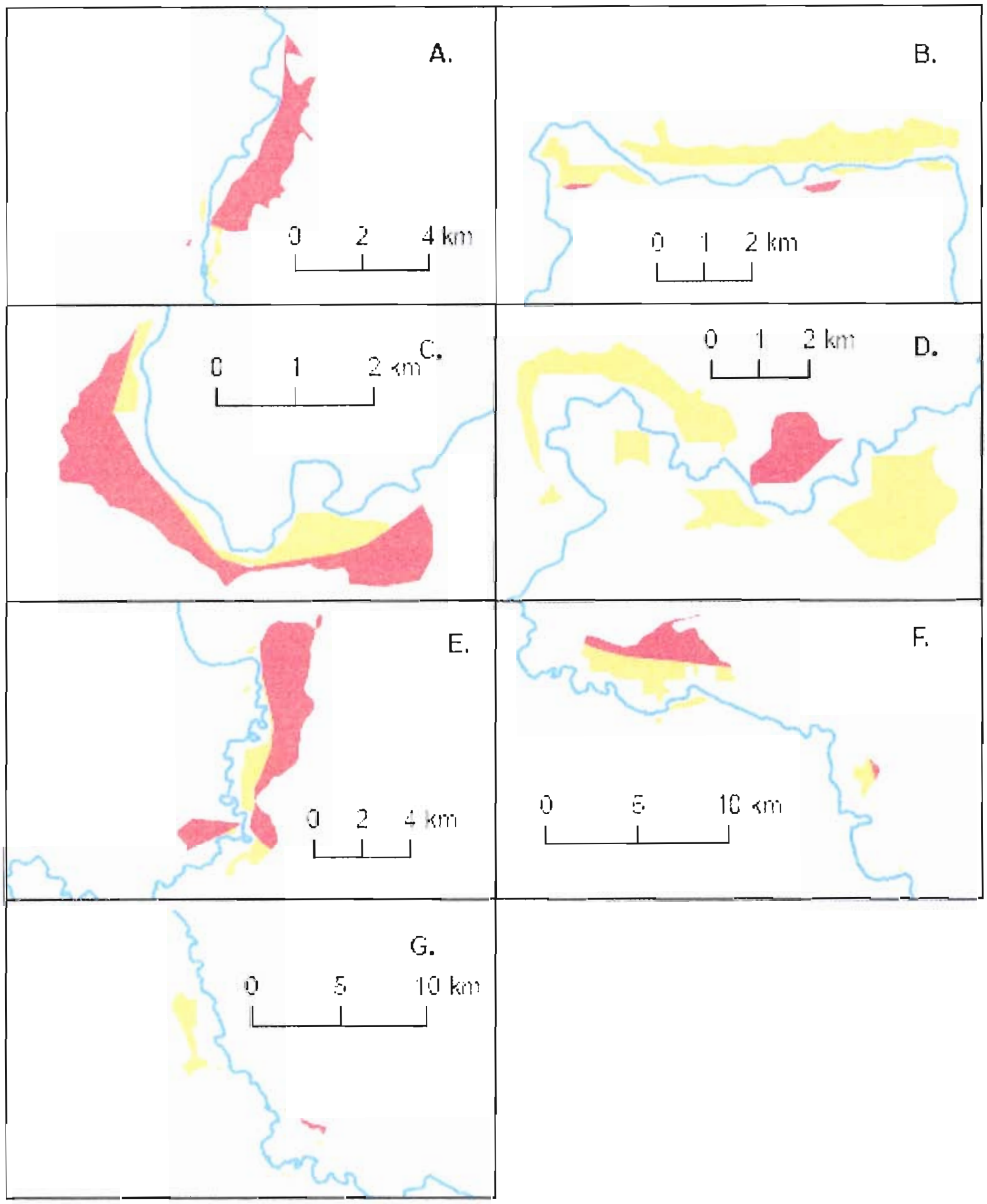


Figure 3.9: Floodplain disconnection, Upper Chehalis. A. Pe Ell, B. Doty, C. Ceres Hill, D. Bunker, E. Centralia, F. Chehalis Village, G. Oakville. Symbology identical to Figure 7.

Table 3.6: Comparison of lateral disconnection results with those obtained by Snyder et al (2002). (% floodplain disconnected)

	Percent floodplain disconnected		
		This study	
Reach	**Previous studies**	**Class I**	**Class II**
Cle Elum	59	43	59
Kittitas	69	56	64
Yakima (Union Gap)	61	19	49

ranked best for habitat potential are those with highest number of fish bearing tributaries or the highest channel complexity (length of side channels divided by main channel length). Reaches ranked best for limiting factors have the lowest degree of disconnection (Class I or II) or lowest proportion of connected floodplain classified as impaired (>10% impervious surface).

No basin wide trend emerges in terms of restoration potential. In terms of specific reaches, the Centralia, Yakima, and Oakville reaches ranked best in terms of habitat potential based on access to fish-bearing tributary networks, (Table 3.7). By floodplain channel complexity, the Kittitas Valley, Wapato, and Cle Elum reaches are ranked best.

The Centralia reach is more impacted by major roads (Class I disconnection), and is ranked in the middle in terms of impaired floodplain. The Yakima reach is more impacted by class II disconnection, and also has more impaired floodplain. The Oakville reach is not impacted by class I disconnection, and is ranked in the middle in terms of class II disconnection and impaired floodplain.

Table 3.7: Reach scale values and ranks of salmon habitat potential and limiting factors for salmon habitat restoration. Tributary values given in number of tributaries per reach floodplain area. Channel complexity given as side channel length divided by main channel length. All limiting factors given as percent of total floodplain area. Reaches ranked from 1 = best to 16 = worst.

	Habitat Potential		**Limiting Factors**		
Reach	**Fish-bearing tributaries**	**Floodplain channel complexity**	**Class I disconnection**	**Class II disconnection**	**Impaired but connected floodplain**
Upper Yakima					
Keechelus	0.08 (13)	4.4 (4)	8.0 (5)	9.8 (4)	1.84 (4)
Easton	0.18 (5)	3.9 (7)	43.4 (12)	6.5 (2)	1.85 (5)
Cle Elum	0.17 (6)	4.7 (3)	43.2 (11)	16.0 (9)	2.05 (7)
Kittitas Valley	0.09 (10)	7.8 (1)	56.2 (16)	8.2 (3)	1.94 (6)
Selah	0.08 (11)	4.2 (5)	33.8 (9)	15.7 (7)	10.22 (16)
Yakima	0.29 (2)	4.2 (5)	18.6 (8)	30.3 (13)	5.51 (12)
Lower Yakima					
Wapato	0.0 (15)	5.6 (2)	51.0 (14)	24.2 (12)	1.13 (2)
Sunnyside	0.03 (14)	1.5 (16)	1.6 (1)	33.9 (14)	1.27 (3)
Richland	0.0 (15)	1.7 (13)	4.4 (4)	17.7 (10)	10.2 (15)
Upper Chehalis					
Pe Ell	0.10 (9)	2.7 (10)	53.2 (15)	5.1 (1)	6.04 (13)
Doty	0.20 (4)	3.3 (9)	2.2 (3)	59.0 (16)	7.25 (14)
Ceres Hill	0.14 (8)	2.6 (11)	39.0 (10)	13.1 (6)	0.00 (1)
Bunker	0.15 (7)	3.5 (8)	9.2 (6)	43.6 (15)	3.39 (10)
Centralia	0.33 (1)	1.7 (9)	46.1 (13)	11.8 (5)	3.89 (11)
Chehalis Village	0.17 (12)	1.8 (12)	18.5 (7)	22.1 (11)	2.89 (9)
Oakville	0.22 (3)	1.7 (13)	1.6 (2)	15.7 (7)	2.67 (8)

The Kittitas Valley reach is ranked worst of all reaches in terms of class I disconnection, but third best in terms of class II disconnection. It is intermediate in terms of impaired floodplain. The Wapato reach is ranked poorly in both disconnection classes, but is ranked well in terms of impaired floodplain. The Cle Elum reach is ranked intermediately in all limiting factors. In contrast, reaches ranked best in terms of least amount of disconnection or impaired floodplain (Sunnyside and Pe Ell) were not ranked particularly well in terms of either habitat potential ranking. The Kittitas Valley, Yakima, Wapato, and Centralia reaches are discussed in further detail later in the Discussion section as they both exhibit high habitat potential and meet the criteria for disproportionate local significance as described above.

Discussion

Functional Floodplain Mapping

At the scale of an entire sub basin, the soils and geology data produced similar results in terms of floodplain definition. The simpler geologic data thus provides a useful product for defining the functional floodplain at basin scales. Floodplain extent produced by the FEMA maps was 20 to 50% smaller than the soils or geology results.

At the reach scale, the Qa-defined floodplain closely matched the soils-defined floodplain (e.g., the Kittitas floodplain, Figure 3.6). This pattern generally held true for the unconfined floodplain reaches in all three basins (Table 3.3). The FEMA floodplain was generally much smaller in extent with two general exceptions: the confined canyon reaches (e.g. Upper Canyon, Table 3.3) and highly urbanized reaches (e.g. the Yakima, Richland, and Centralia, reaches, Table 3.3).

At reach extents, the poorest agreement among Qa and soils definitions occurred in the confined valley reaches where surficial deposits are often landslide deposits rather than alluvium. As these map units were excluded from the geology-based floodplain definition, the geology-defined floodplain was underestimated in confined reaches. The minimal floodplain surface in the confined settings also exacerbated the percent difference in overlap for the two data sets (Figure 3.3).

The results from the geology and soils maps are comparable with those of Snyder et al. (2002), further indicating that these publicly accessible digital data are comparable in quality to more intensive air photo and field-based surveys. In contrast, reach-by-reach comparison of the FEMA 100-yr floodplains corresponded poorly to the geologic and soils data and to the Snyder et al. (2002) results. In our study area, FEMA floodplain maps therefore are not useful for delineating the full extent of the potentially functional floodplain surface.

However, the FEMA-based floodplain extents are a product of anthropogenic confinement and correspond closely to the floodplain extent where there is a dominant transportation structure such as a highway or rail grade. In settings like the Kittitas Valley, where the floodplain is bisected by Class I disconnection, such structures define the extent of the connected floodplain (Figure 3.6).

While the extent of the FEMA 100-year floodplain thus provides a reasonable picture of the contemporary floodplain as limited and defined by human activities (particularly in urban areas), it is not useful for establishing the potential floodplain extent to which connectivity could be restored. Also, human alteration of the landscape results in increase of impervious surface such that the dynamics of flood routing to the channel has changed. In some places what used to be the 100-year event is now the 20-year event (e.g., recent repeated flooding in the Chehalis basin) – a lesson still not fully appreciated by society.

Lateral Floodplain Disconnection

In terms of basin-scale disconnections, the Yakima basins had a relatively high degree of disconnection, reflecting the fact that both the upper and lower Yakima basins contain interstate, US, and state highways along with rail lines. Even though the lower Yakima has large, wide valleys, it also has major structures built out or on the margins of the floodplain and local roads throughout the floodplain. With the exception of the area near Centralia, the Chehalis generally has less Class I infrastructure and is therefore more affected by local roads (Class II disconnection).

The lower disconnection values in our results relative to previous studies is likely because our results are missing small dikes and levees (without roads) that were mapped by Snyder et al. (2002) using detailed photo interpretation and local knowledge. However, our results capture the landscape disconnection caused by structures that are far less likely to be removed or modified than these smaller structures. In addition, the presence of transportation lines is a limitation on the possibilities for removing the smaller structures and other restoration efforts, as is discussed in the following section.

Assessing Restoration Potential

Evaluation of Potential Between Reaches

Reach-scale maps of disconnection across a basin (Figures 3.7-3.9) are useful for providing a context for restoration and management. Qa maps can be used to map potentially functional floodplain, and transportation infrastructure data may be used to show types and locations of disconnecting features, as well as the extent of disconnection. When combined with rankings of simple landscape scale metrics tailored to particular issues (such as salmon habitat), these maps may be used to assess reaches along a river corridor in terms of relative restoration potential. The NLCD impervious surface data can also help identify landscape-scale opportunities and obstacles for restoration by showing the degree of impairment of still connected floodplain surface.

Restoration potential is a complex issue that is not reducible to a simple value, for instance by summing the ranks in Table 3.7. A reach could have habitat potential indicated by tributary access, channel complexity, or a combination of the two. Likewise, a reach may be limited by any one of the three limiting factors, with different consequences for management, including what kind of restoration work could or should be done, and how likely restoration efforts will succeed given the nature and extent of local transportation infrastructure.

The key issue for fish-bearing tributaries is simply access from the main channel. Effective bridges and culverts that do not impede fish movement are important in reaches ranked well for this metric. Impaired connected floodplain is not as much of an issue, as long as access is open. A reach with a higher number of Class II disconnections may be more problematic than one with a single class I disconnection in this context, as there are more possible blockages. In terms of channel complexity, where class I disconnection is high, identification of key spots of still intact habitat is paramount, and where class II disconnection is more common more options such as structure modification or removal are potentially available.

Ultimately, reaches ranked poorly in both tributary access or floodplain channel complexity are likely poor candidates for restoration efforts, regardless of how well they are ranked in terms of limiting factors. In reaches with a relatively large amount of impaired connected floodplain, such as parking lots and other paved areas, ecological function in the floodplain is likely more impaired than analysis of the transportation network alone would suggest. Reaches with both habitat potential and low impervious surface have a higher restoration potential.

The discussion of access to tributary habitat and habitat along the channel highlights a key philosophical issue for fish management in regulated rivers. If main-stem rivers are laterally confined, is the best management option to treat them as 'transport reaches' and maintain them to the degree that fish can find passage to them to better quality upstream tributary habitat for spawning and rearing? If that is the case, perhaps tributary access, and identification of a few key areas along the way that the fish could use for rest and cover would be most important. In addition, the release of environmental flow from reservoirs to enhance habitat along confined reaches is likely counterproductive.

The Kittitas reach (Figure 3.10 A, Table 3.7) is ranked poorly (16th) for its high degree of Class I disconnection. It is much less impacted (ranked 3rd) by Class II disconnection. The Yakima reach (Figure 3.10 B) is similar, but its habitat potential is via tributary access (ranked 2nd) rather than side-channel complexity (ranked 13th).

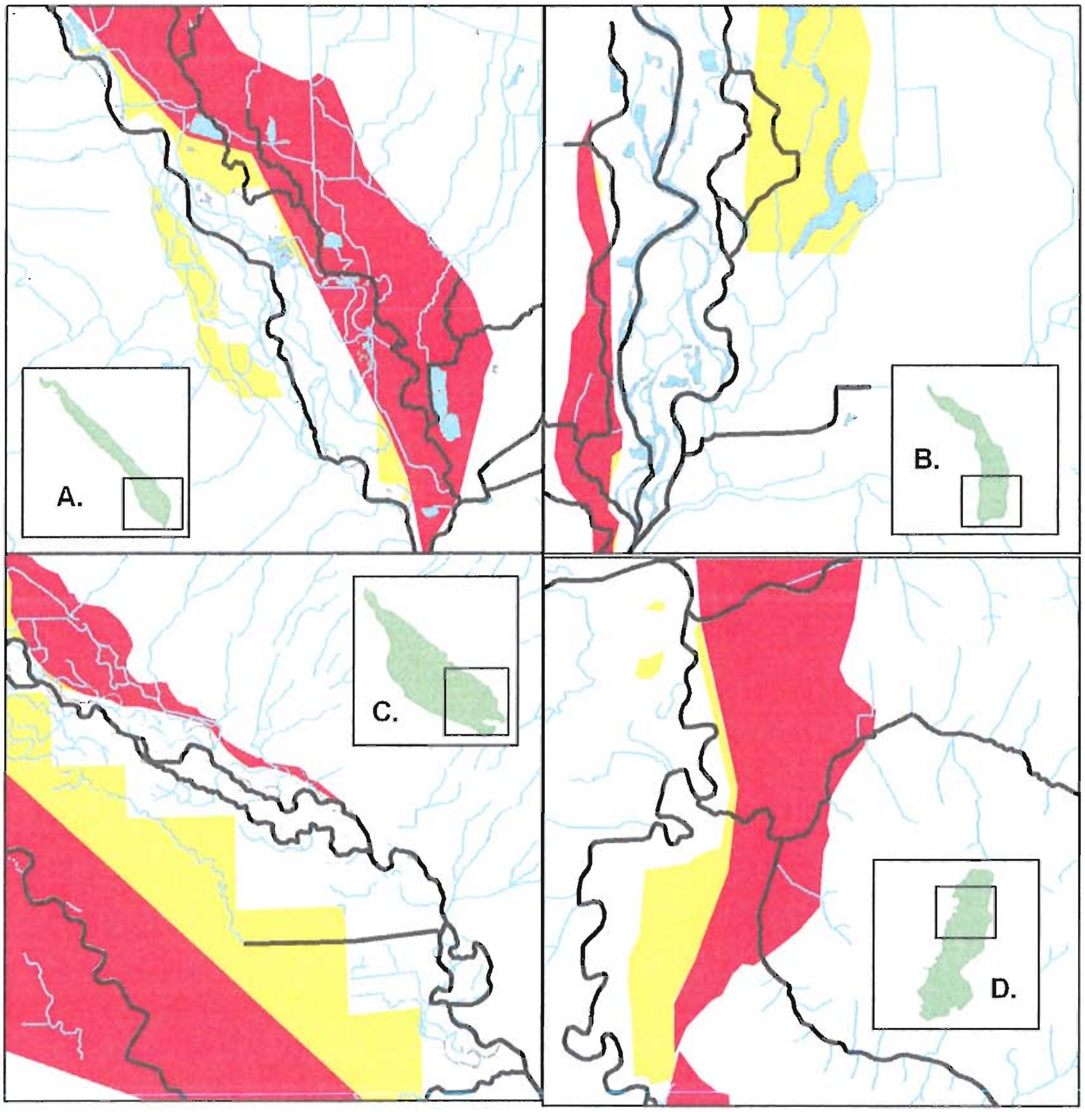


Figure 3.10: Lateral disconnection and preservation/restoration potential of subsections of reaches in terms of salmon. A. Kittitas, B. Yakima, C. Wapato, D. Centralia. See text for explanation.

The Wapato reach (Figure 3.10 C) has a high degree of disconnection. It ranks 14th and 12th for class I and II, respectively. However, it still has a relatively large floodplain and riparian zone with functional vegetation and side channels. It is ranked 2nd for channel complexity. This reach does not have as much tributary access as other reaches (ranked 16th), but its off-channel habitat is important for migrating fish.

The Centralia reach (Figure 3.10 D) is an urban reach, with a high degree of impairment, and minimal side channel complexity. This reach is important from a management perspective, as it contains access to major fish bearing tributaries (ranked 1st), such as the Skookumchuck River.

Within Reach Assessment of Restoration Potential

Within-reach analysis of habitat for an individual reach is perhaps even more important from a managerial perspective (Stanford et al. 2002)., For example, the Kittitas reach (Figure 3.11) exhibits a high degree of overall impairment, but contains a key location at its downstream end with extensive side-channel complexity, access to fish-bearing tributaries, and riparian gallery forest in place (Figure 3.12). In addition, such locations at the downstream end of valleys are likely locales of groundwater upwelling which make them areas likely to have high value for preservation.

Comparison With Previous Studies

Snyder et al (2002) found that in the Yakima basin, increased macroinvertebrate richness and diversity suggestive of floodplain habitat function was found in the upstream

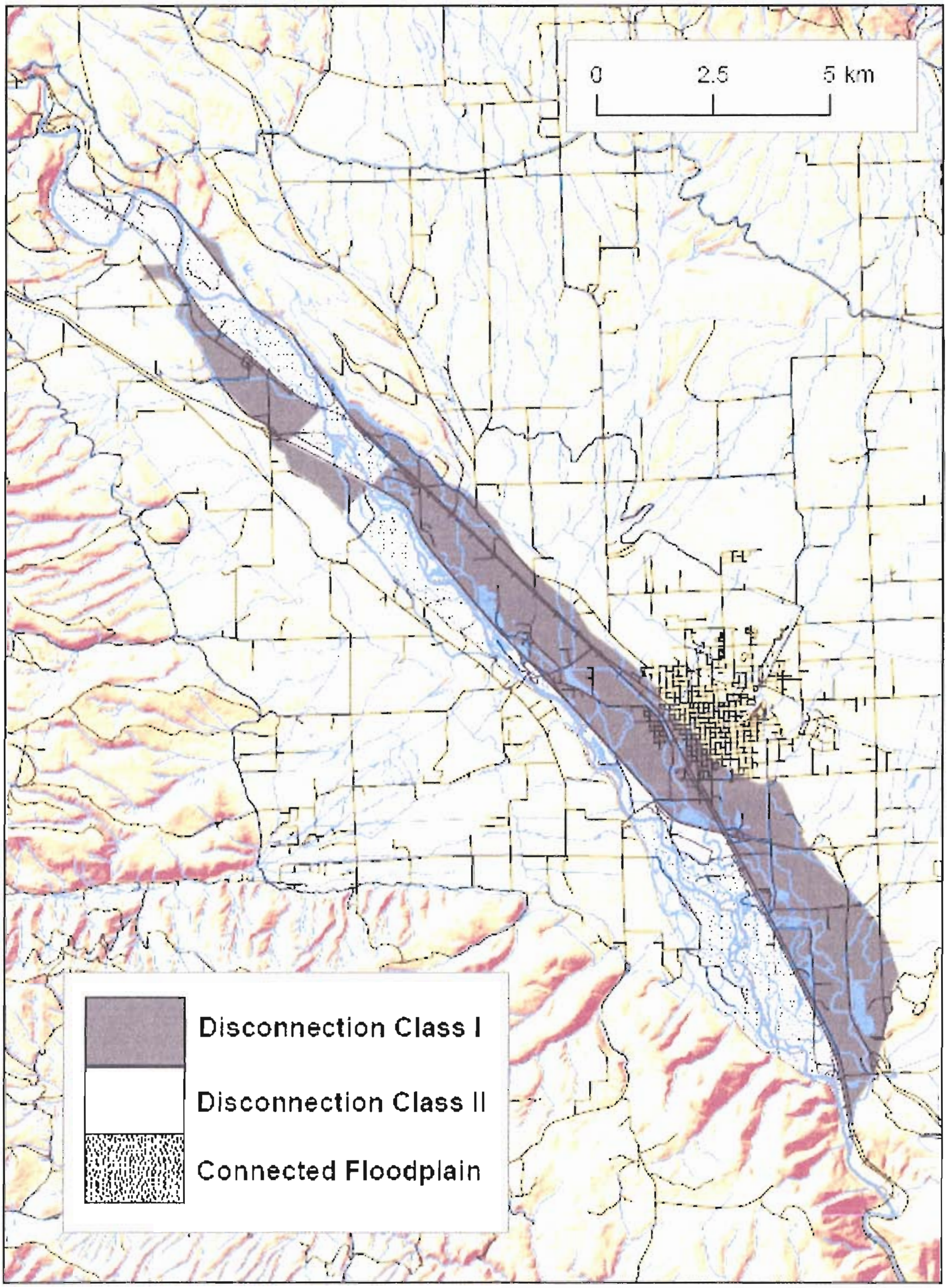


Figure 3.11: Kittitas reach, Yakima River, WA.

Figure 3.12: Downstream end of Kittitas reach, just upstream of canyon entrance. This location has high channel complexity, relatively healthy riparian forest, and bars and islands.

portion of valley reaches. Macroinvertebrate counts were lower in the downstream portions of the reaches, presumably because of increased anthropogenic impact. Yet at the same time, habitat heterogeneity was increased in downstream portions of floodplain reaches, probably because these are areas of strong upwelling (Stanford and Ward, 1993). These apparently contradictory results are a logical outcome of the mix of physical and human factors at work in these floodplains. Snyder et al. (2002) thus concluded: 1) that prioritization of entire floodplain reaches for restoration or preservation is problematic, and 2) that relatively un-impacted floodplain areas in the downstream portions of floodplain reaches should be given priority for preservation and restoration efforts. Subsequent studies (Stanford et al., 2002) reinforced these statements, and further argued for the importance of lateral and vertical connectivity (areas of upwelling) for habitat restoration. Where possible, the removal of roads and other structures such as culverts, dikes, and rip-rap, along with flow modification was prescribed for habitat restoration in these areas (Stanford et al., 2002). Our findings reinforce this pattern for the large floodplain reaches across the study areas, and demonstrate the utility of our methods to do a more rapid connectivity assessment, perhaps at larger regional scales.

Geographic Setting

Our results indicate a high degree of lateral floodplain disconnection in medium to large alluvial valleys in areas of overall rugged topography as suggested by previous studies (Blanton and Marcus, 2009). The study areas in this study are representative of valley corridor settings throughout the Western U.S., where confined valley reaches alternate with unconfined alluvial valleys; the 'beads on a string' pattern described by Stanford and Ward (1993). The wide alluvial valleys in these generally rugged settings are both hotspots of biodiversity, as well as often being major transportation corridors, and thus likely areas of disconnection. This disconnection is a significant limitation for stream restoration, specifically in the context of salmon habitat. In these and similar settings with similar management issues in other regions, the methods and results discussed here will be directly applicable.

Although more confined valley settings are less important in terms of disconnection of floodplain habitat, particularly for salmon (the key ecological management issue addressed in this study), in other regions and for other management issues, rapid assessment of confined valley settings may be important. Here, our results suggest that the Qa maps will be problematic, and the soils data should be used instead. Although the soils data is more complex, the small floodplain area in these settings makes their use manageable. And, in these settings the transportation infrastructure data will be of similarly utility.

In different river landscapes with different physical and human components, the simplicity and flexibility of the methods used here still make them useful with a minimum of modification. These include regions with less rugged topography, and those with different river landscapes such as arid and high elevation locations with braided streams, for example. Floodplains with either incised or artificially channelized streams may be problematic settings, as the channel will be vertically as well as laterally disconnected from the Qa deposits or soil units used to define the potential active floodplain. These settings are essentially confined floodplain landscapes, similar to canyon reaches, where transportation-related disconnection is less of an issue.

Also, other settings (e.g., Eastern U.S., Europe) have a longer and more complex history of anthropogenic modification of the floodplain. Floodplain disconnection caused by transportation infrastructure will be just one out of many impacts. But as in the study areas considered here, transportation lines, particularly highways and rail grades (Class I disconnections) will limit potential for channel and floodplain restoration efforts. Therefore, the landscape-based methods used here for the mapping of floodplains, analysis of road and railroad disconnection, and identification of related obstacles and opportunities for restoration are still applicable and useful in these settings.

Conclusions

This study demonstrates how freely available GIS data may be used to relatively quickly and inexpensively map the extent of modern floodplain surface prior to human modification, map the impacts of transportation infrastructure along river corridors, and use these results along with land cover data to assess restoration potential. These methods are intended to complement other approaches such as field surveying, modeling, and site-scale collection of biological data. Our results show a large degree of floodplain disconnection caused by transportation infrastructure across the study areas and demonstrate how transportation lines limit opportunities for restoration efforts. Our results also support the contention of Snyder et al (2002) that corridor-scale ecological description and analysis of habitat preservation and restoration may be problematic. An outcome of our reach-scale study is the identification of locations where and how transportation infrastructure is the driving factor influencing potential for management actions such as structure modification or removal, environmental flow releases, and riparian and channel habitat restoration.

We suggest that another promising avenue for further research is the quantification of the physical processes (hydrologic and geomorphic) that ultimately drive the form and function of aquatic and riparian habitat as they are impacted by lateral floodplain disconnection. In disconnected locations we would expect a decrease in channel width, sinuosity, channel complexity, proportion of bank with riparian gallery forest, and large woody debris. In addition, lateral disconnection likely leads to channel, side channel, and floodplain habitat simplification and degradation. Floodplain mapping analysis, as outlined here, provides a template for the identification of sites for such analysis. In addition, disconnection analysis may be combined with detailed fish data (e.g., fine-scale biological fish presence and usage data as well as habitat survey data) to assess the impacts of disconnection on particular aquatic and riparian species.

Landscape-scale approaches like those employed in this study have the potential to help integrate fine-scale data such as fish or habitat survey data with data such as land use typically collected at the basin scale. As remote sensing and analytical techniques continue to evolve and allow for the up scaling of fine scale or patch data to larger scales, and the down scaling of regional data, the challenge is to develop new methods and metrics to assess linkages between anthropogenic and physical/biological processes in the riverscape. The robust understanding this will provide will be beneficial for management and policy at the local, regional, and national scale. In particular, an honest and sober assessment of limitations to restoration in the river landscape will lead to more realistic policy goals, particularly in terms of habitat for endangered species, and more effective restoration projects at the local scale.

In addition to assessing the utility of different approaches to map floodplain extent and disconnection caused by roads and railroads, I also show the importance of the study of floodplain disconnection in the context of salmon habitat restoration potential. In the next chapter, I quantify the specific local impacts of roads and railroads on channel and floodplain habitat used by salmon and other important aquatic species. I do this by examining several different river settings used by endangered salmonids in the Pacific

Northwest, applying the lessons learned in earlier chapters to a critical regional management issue.

CHAPTER IV

ROADS, RAILROADS AND LATERAL DISCONNECTIONS, YAKIMA AND CHEHALIS RIVERS, WASHINGTON, U.S.A.

This chapter is to be submitted to *River Research and Applications*. This paper was co-authored with W. Andrew Marcus, who provided editorial assistance.

Background

Over the last 20 years, connectivity has emerged as an integrative concept that helps explain ecological function in fluvial systems (Ward, 1989). Connectivity, broadly defined, is the exchange of water, sediment, and biota between and within components of the fluvial landscape (Blanton and Marcus, 2009). Longitudinal connectivity, which refers to linkages between upstream and downstream components of a river and its riparian system, dominates in naturally confined reaches, such as canyons. Vertical connectivity between surface and subsurface components and lateral connectivity between the main channel, floodplain, and surrounding landscape play larger roles in wider alluvial reaches (Hauer and Lorang, 2004).

Lateral connectivity, the focus of this article, is a key control on habitat quality, the health of the riparian corridor and local and regional biodiversity (Naiman et al., 1993). Unfortunately, the widespread presence of transportation lines in river valleys can disrupt lateral connectivity. Poorly designed or malfunctioning culverts and other structures can impede connections between tributaries and the main channel. Railroad grades and road beds can function as confining longitudinal dams in the riparian zone, interrupting flood pulses and the exchange of water, sediment, and biota between channels and their floodplains and within the floodplain.

Over longer time periods, disconnecting structures in the floodplain can impede the natural meandering and migration of channels across their floodplains. This disrupts the erosion and cut-and-fill alluviation that drives the 'shifting habitat mosaic' to create high habitat and biological diversity (Hauer and Lorang, 2003). Moreover, confined channels often concentrate energy, leading to higher shear stress and stream power that can wash out riffles and degrade low-velocity habitat such as pools and alcoves (McDowell, 2000).

Moreover, channel confinement can significantly restrict development and maintenance of a healthy forested floodplain (Fetherson et al., 1995), thus reducing channel shading, bank stability, nutrient inputs, and filtering of pollutants (Gregory et al., 1991) , all of which improve ecological conditions for fish and other species. Loss of riparian forest also results in impaired fluvial wood recruitment, which in turn leads to loss of in-channel and floodplain habitat structures that are particularly important for small fish. In addition, loss of large wood leads to less sediment entrainment, limiting bar and island formation (Gurnell and Petts 2006). The extent and composition of the riparian forest is a useful overall indicator of ecosystem health as the extent is indicative of both surface and ground water connectivity. In addition, a mixture of open and closed riparian forest along with other natural vegetation, active depositional surfaces, and floodplain legacy features such as intermittent and perennial side-channels and oxbow lakes is indicative of active flood disturbance leading to more diverse mix of habitat patches (Hauer et al., 2003).

Lateral disconnection caused by human floodplain structures has been studied in the context of levees (e.g. Bravard et al., 1986, Gergel et al., 2002) and channelization (e.g. Hupp, 1992). However, despite the widespread presence of transportation lines in floodplains (Blanton and Marcus, 2009) and the widespread acknowledgement in the literature that these human causeways disconnect river corridors (Forman et al., 2003), few studies have examined the impacts of roads and railroads in floodplains on geomorphic, hydrologic, and biological processes along river corridors.

Hypothesized Impacts of Transportation Disconnection

In this study, we examine the effects of transportation infrastructure on both the channel and floodplain components of river landscapes. Specifically, for the in-channel environment, we test the hypotheses that:

- H1. *Truncated meanders and lower sinuosity will be associated with confinement by roads and railroads near the channel.* Cut-offs and lower sinuosity are to be expected as meander bends are 'squared off' and channel meandering is impeded by confining transport structures. Channels not fitting a meandering stream pattern (e.g. multi-threaded streams) should still exhibit a lower sinuosity as they are forced to take a straighter path where they abut confining features.
- H2. *Wetted channel areas and widths will be smaller in transportation-impacted systems, resulting in less channel geomorphic complexity with fewer bars and*

islands. Confining of channels should lead to deeper and narrower channels and, perhaps, to down cutting and channel degradation (Montgomery and Buffington, 1998), resulting in less sediment deposition, smaller and fewer bars, and impeded island formation (Gurnell et al., 2001).

- H3. *There will be fewer clusters of large wood where roads and railroads are present.* We anticipate that transportation disconnections will physically block wood from entering the channel and that the degraded riparian forest will reduce wood supply (Gurnell and Gregory, 1995).

In the floodplain environment, we test the hypotheses that:

- H4. *The proportional area of off-channel habitat will be smaller in the disconnected floodplain than in the connected floodplain.* Floodplain habitat units such as ponds, sloughs, oxbows, and paleochannels with hydrophilic vegetation will lose their water supply as they are disconnected from the channel and therefore be reduced in size or disappear. Impacted habitats units will include side channels as well as periodically connected habitat units that are only connected during high flows (Poff et al., 1997).

- H5. *The disconnected floodplain will contain a proportionally smaller area in riparian forest, a narrower riparian zone, and a lower proportion of stream banks with riparian gallery forest:* The proportion of the floodplain with a healthy riparian gallery forest will be reduced by several factors, including direct road and railroad impacts, isolation from flows, and the reduction of depositional areas for seed germination.

We used a paired reach approach to test the hypothesized impacts of lateral disconnection in the study areas, following the model of Graf (2006), who used this approach to document the downstream impacts of dams. Comparison of paired experimental and control reaches has a long history as a methodological approach in hydrology and geomorphology for the isolation of a single causal variable (Graf 2006). In its ideal form, the paired reach approach controls for factors (i.e. holds them constant) that might affect habitat variability with the exception of the experimental factor. For the purposes of this study, paired reaches therefore should be in similar topographic, hydrologic and climatic settings and be subject to similar human impacts (e.g. reservoir releases) with the exception of the presence or absence of transportation lines near the riparian zone. Differences in measured variables between the reaches therefore may be attributed to lateral disconnection due to transportation infrastructure. Specific elements of the control reaches are described later in the Methods and Results sections.

Study Basins

The Yakima basin stretches from the crest of the Cascades to its confluence with the Columbia (Figure 4.1). Most of the basin is semiarid, with a snowmelt-driver hydrologic regime punctuated by short duration, high intensity runoff events in the summer months. The Chehalis River is closer to the Pacific Coast and has a hydrologic regime dominated by winter rain or rain on snow events (Table 4.1) (Stanford et al., 2002; Chehalis Basin Partnership Habitat Work Group, 2008).

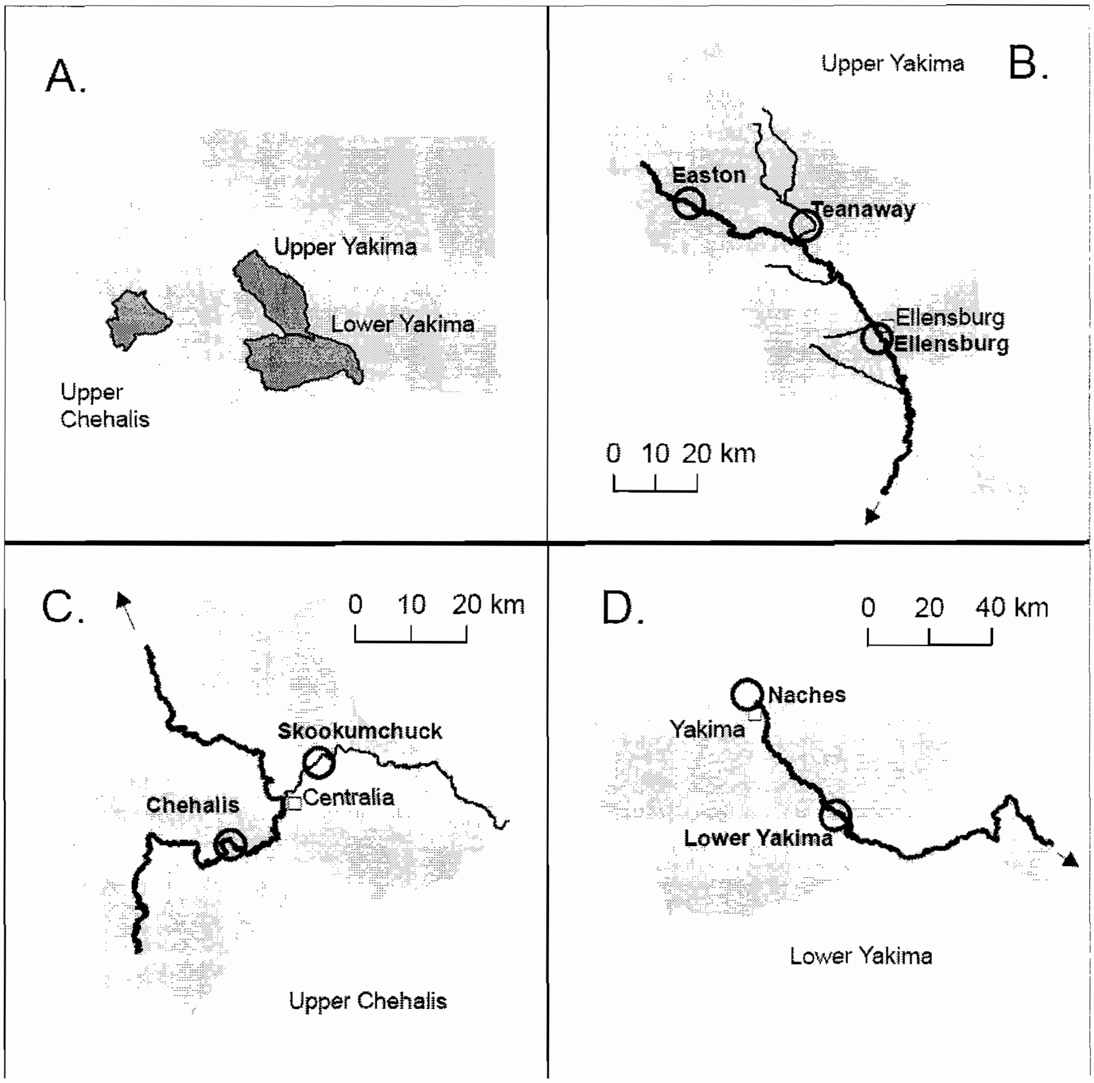


Figure 4.1: Study sites. Paired reach locations circled. Direction of flow indicated by arrows.

Both the Yakima and Centralia watersheds exhibit the typical valley configuration common to Western U.S. watersheds of alternating confined valleys or canyons and wider alluvial valleys with extensive floodplains (Hauer et al., 2003). The Yakima's substrate mostly consists of large gravel to small cobbles, while the Chehalis includes finer material with a complex mix of unconsolidated sand and gravel, glacial deposits, and modern alluvium that in places is proximal to older marine sedimentary terraces (Stanford et al., 2002; Chehalis Basin Partnership Habitat Work Group, 2008). The Yakima's substrate, with its greater pore space between gravels and cobbles, is more conducive to surface-groundwater exchange. Consequently, hyporheic or vertical connectivity as related to the 'shifting habitat mosaic' is more important in the Yakima floodplain reaches than in the Chehalis reaches (Stanford et al., 2002; Hauer et al., 2003; Chehalis Basin Partnership Habitat Work Group, 2008).

Table 4.1: General geomorphic and hydrologic characteristics of the study basins, Washington, USA. Weather station given for precipitation; gaging station given for discharge statistics (calculated by author).

	Upper Yakima	**Lower Yakima**	**Upper Chehalis**
Drainage area (km2)	5,423	7,603	3,358
Maximum elevation (m)	2,429	2,127	1,138
Minimum elevation (m)	330	191	8
Mean annual ppt. (mm/yr)	225 (Ellensburg)	206 (Yakima)	1,170 (Centralia)
Mean annual flood (cms)	69 (Umptanum)	99 (Kiona)	115 (Porter)
100-year flood (cms)	950 (Umptanum)	1,682 (Kiona)	2,260 (Porter)

Both watersheds historically supported large numbers of salmonids, with contemporary numbers a fraction of historic returns. The riparian zones along these rivers have been impacted by many land uses since the 19th century. Along the Yakima River, land uses including agriculture, urbanization, and anthropogenic confinement, are all cited as factors degrading the riparian and floodplain systems (Stanford et al., 2002). The mainstem Yakima is also a regulated river, with seven low head dams, and six storage reservoirs (Stanford et al., 2002).

In the Chehalis, riparian zones have been heavily impacted by logging activities, leading to the removal of vegetation as well as poorly constructed culverts. Removal of riparian vegetation (via logging or agriculture) is a major limiting factor for fish, with reduced shade leading to higher stream temperature and lower dissolved oxygen levels. The Chehalis experiences exacerbated high winter flows and low flows during the summer caused by ditching, filling, and armoring of stream banks as well as summer withdrawals. Large-scale urbanization is centered in Centralia. In contrast with the Yakima, the Chehalis is not dammed (Chehalis Basin Partnership Habitat Work Group, 2008).

Methods

Paired Reach Selection

We defined a ‘reach’ for the purposes of this study as lengths of channel with similar geomorphic and vegetative characteristics throughout their extent. Reaches selected as paired reaches had relatively uniform valley gradients, lithology, and channel bank materials, and comparable Holocene floodplain widths, valley gradients, and discharge regimes. No major tributary streams entered the main stem between the paired reaches.

The difference between ‘experimental’ and ‘control’ reaches was the degree of artificial confinement caused by transportation infrastructure. In the experimental reaches, a paved road or railroad grade abutted the riparian zone. To quantify the difference between experimental and control reaches in term of artificial confinement, we used GIS to calculate nearest distance between the centerline of the main channel and transportation infrastructure at 30 evenly spaced points along the experimental and control reaches. The average distance between transportation lines and channel center lines was significantly different ($p = 0.05$) for each pair of control and experimental reaches, indicating a significant difference in artificial confinement. We chose seven study reaches that captured a variety of settings in their watersheds, including position in the upper and lower portion of the watershed (Figure 4.1). Streams in question were at least 4th order streams and mapped as used by endangered or threatened anadromous or resident fish species. Reaches were 2-8 km in length.

Data Sets and Analytical Approach

In order to compare channel and floodplain characteristics between paired reaches, we had to: (1) define the functional floodplain extent for each reach; (2) classify and map the channel and floodplain habitats; and (3) measure features and derive metrics indicative of geomorphic processes driving habitat form and function in the channel and floodplain. Mapping and analysis was performed using Arc-Map 9.3 All digital data sets used in this study are freely available from on-line sources (Table 4.2).

Table 4.2: Data sets used in study.

Data Type	Source
2006 NAIP (National Agricultural Imagery Program) orthophotographs, 18 inch spatial resolution	http://www.geography.wa.gov/
1:100,000 scale surficial geology data, Washington State	http://www.dnr.wa.gov/ResearchScience/Topics/GeosciencesData/Pages/gis_data.aspx
10m digital elevation data	http://seamless.usgs.gov/
NHD (National Hydrography Dataset)	http://nhd.usgs.gov/

Using procedures described here and in more detail in Blanton and Marcus (*in prep.*), we used geologic maps of the Quaternary alluvium (Qa) layer to map the functional floodplain in each reach prior to human impact. These floodplain maps define geomorphic surfaces exposed to fluvial processes in the last ~10,000 yr. We extracted the Qa layer from the digital 1:100,000 scale geological map of the state of Washington, then used the National Hydrographic Data (NHD) data set, the 10m digital elevation model (DEM), and National Agricultural Imagery Program (NAIP) imagery to remove portions of the Qa layer associated with the floodplains of tributary streams. Alluvial fans and other non-floodplain features were removed from the Qa layer based on analysis of the elevation data, NAIP imagery and topographic maps. The remaining floodplain area provides a good indicator of the potentially functional floodplain prior to human confinement (Blanton and Marcus, *in prep.*).

We then overlaid the Holocene floodplain extents on the NAIP imagery and classified key channel and floodplain features within this extent using the categories in Table 4.3. This relatively simple classification captures some key components of riparian ecological function, including: 1) differences in land cover (Decamps et al., 1988), 2) the extent and structure of vegetation types in the riparian zone (Marston et al., 1995), 3) planform channel characteristics (Hauer and Lorang, 2004), 4) active depositional geomorphic surfaces (Graf, 2006), and 5) refugia (Sedell et al., 1990). Field visits further refined the image-based mapping and corrected polygon boundaries.

Table 4.3: Mapped landscape units. Schema used to classify entire river corridor, beginning with 'Developed' vs. 'Undeveloped', then undeveloped is further classified by sub-categories, reading left to right across table. Grey indicates no further division. The division results in 12 total map units.

Developed	▨	▨	▨
Undeveloped	Floodplain	Riparian forest	Closed, (understory not visible)
			Open, (understory visible)
		Shrubs, forbs, grasses	▨
		Water features	Side-channel, slough
			Abandoned side channel
			Pond
			Alcove
	Channel	Wetted channel	▨
		Bar	Mid-channel
			Attached
		Island	▨

We used GIS to measure metrics of the mapped landscape units in experimental and control reaches. To test the hypotheses, we compared relevant metrics between the experimental and control stretches for each paired reach (Table 4.4). Statistical comparisons were precluded for metrics other than wetted channel and riparian zone width because there was just one metric per reach (e.g. one measure of total pond area for each reach) and because there were only seven control or experimental reaches. Although metrics such as ‘bar area’ and ‘wetted width’ are flow-dependent, the imagery was from the same date for each pair of reaches, and pairs of reaches were not compared with other pairs.

Table 4.4: The hypotheses and associated riverine landscape metrics used to test the hypotheses.

Hypothesis	Metric	Definition	Hypothesized change
Channel			
H1	Truncated meanders	Length of meanders truncated by roads and railroads divided by total channel length	More truncated meanders
H1	Sinuosity	Channel centerline length divided by valley centerline length	Straightened channel
H2	Wetted channel area	Area mapped as 'wetted channel'	Decreased area
H2	Wetted channel width	See text	Narrowed channel
H2	Bar and island area	Bar and island area divided by total wetted channel area	Decreased area
H3	Woody debris count	LWD features observable on imagery per river km	Decreased
Floodplain			
H4	Off-channel habitat (refugia)	Area of ponds and alcoves	Decreased area
H4	Channel complexity	Length side channels divided by length of main channel	Decreased
H5	Land cover change	Area mapped as 'developed'	Increased area
H5	Riparian zone width	See text	Narrower riparian zone
H5	Riparian forest area	Area mapped as 'riparian forest'	Decreased area
H5	Forested banks	% of bank length bordered by riparian gallery forest	Decreased length

Results

Figures 4.2-4.8 display the functional floodplain surfaces of the paired reaches as defined by Quaternary alluvium, as well as the channel and floodplain based on the landscape units shown in Table 4.3. Channel and floodplain metrics derived from these maps are given in Table 4.6. Results are presented below in terms of the study's hypothesized differences between experimental and control reaches.

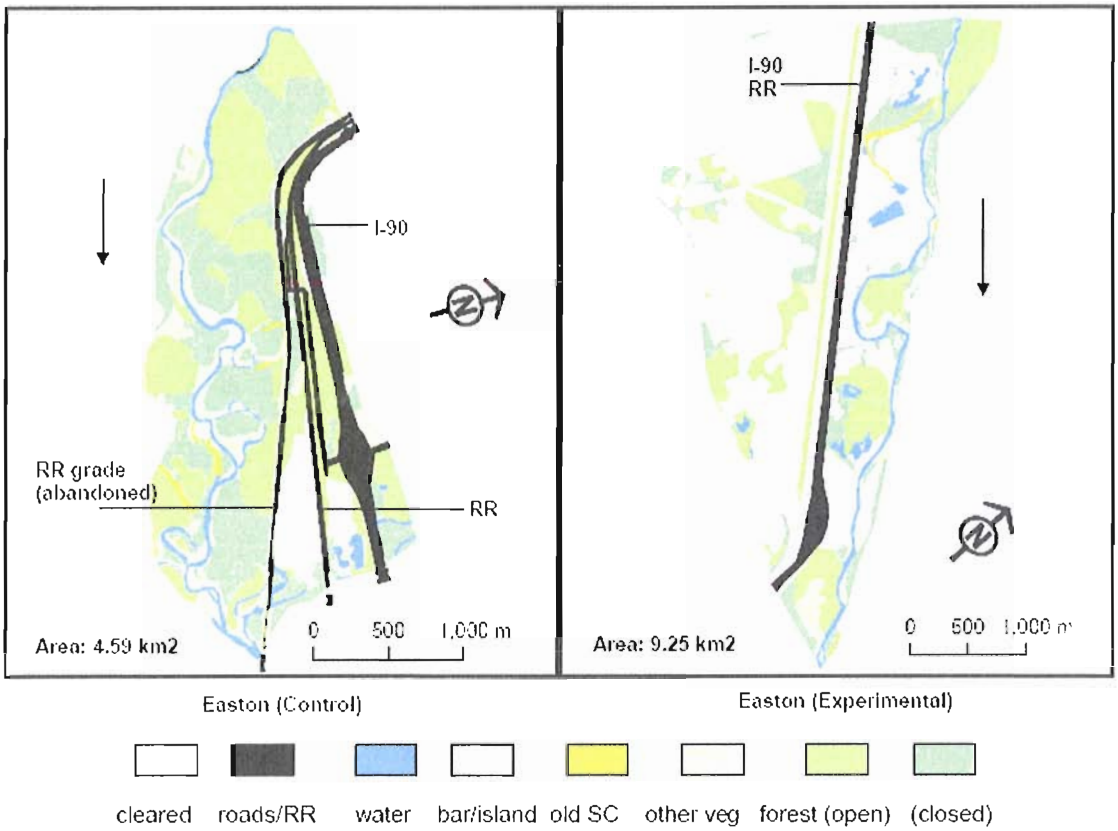
H1. *Truncated meanders and lower sinuosity will be associated with confinement by roads and railroads near the channel.* All pairs of reaches showed an increase in length of truncated meander bends (table 4.5) with the exception of Easton (figure 4.2), which had no truncated meander length in either reach. All experimental reaches had lower sinuosity; for example, the Skookumchuck (Figure 4.7) experimental reach clearly demonstrates how transportation structures are straightening the river.

H2. *Wetted channel areas and widths will be smaller in transportation-impacted systems, resulting in less channel geomorphic complexity with fewer bars and islands.* All experimental reaches had less wetted channel area with the exception of Naches (figure 4.5). In all experimental reaches, mean wetted channel width was narrower ($p<0.05$). All experimental reaches with the exception of Naches and Lower Yakima Valley had less bar area. For example the Easton reaches exhibited a sevenfold difference in bar area between the experimental and control reaches (Figure 4.2, table 4.5). All reaches with any island area exhibited reduced island area, with the most striking difference found in the Naches reaches (Figure 4.5, table 4.5).

H3. *There will be fewer clusters of large wood where roads and railroads are present.* Experimental reaches all showed a lower incidence of LWD (Table 4.5).

H4. *The proportional area of off-channel habitat will be smaller in the disconnected floodplain than in the connected floodplain.* All experimental reaches showed a decrease in alcove habitat area and channel complexity in the floodplain. The Skookumchuck and Chehalis experimental reaches essentially had no side channels (Figures 4.7 and 4.8). The Easton and Ellensburg reaches show a large reduction in channel complexity (Figures 4.2 and 4.4). Reach pairs with any pond area had lower pond area in the experimental reach (Table 4.5).

H5. *The disconnected floodplain will contain a proportionally smaller area in riparian forest, a narrower riparian zone, and a lower proportion of stream banks with riparian gallery forest:* In all experimental reaches, the mean width of the riparian zone and the proportion of streambanks lined with riparian forest decreased. This trend is particularly well shown in the Easton reaches (Figure 4.2). The area of riparian forest decreased in all experimental reaches with the exception of Naches (Figure 4.5, Table 4.5).



Easton (Control)

Easton (Experimental)

Figure 4.2: Easton paired reaches. Main disconnecting features labeled; unlabeled features small local roads. Water = main channel, side channels, ponds, alcoves. Old SC = abandoned side channels and paleochannels. Direction of flow indicated by arrows. Figures 4.3-4.7 have identical symbology. Reaches representative of high elevation main channel setting in semi-arid setting.

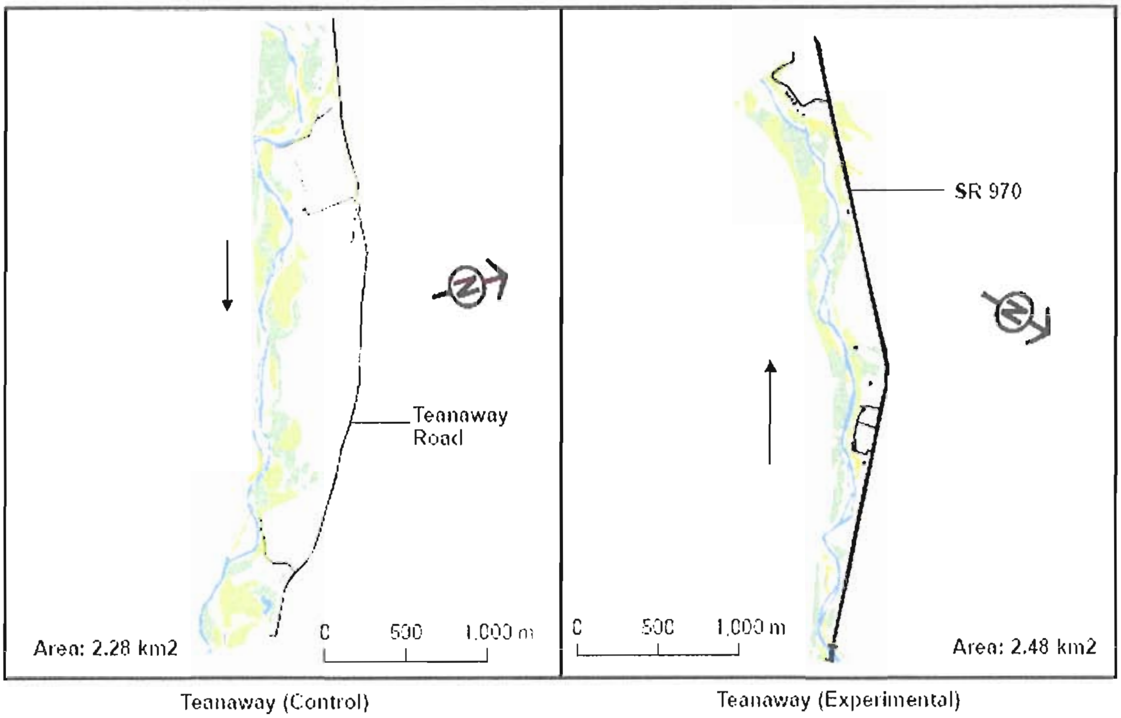
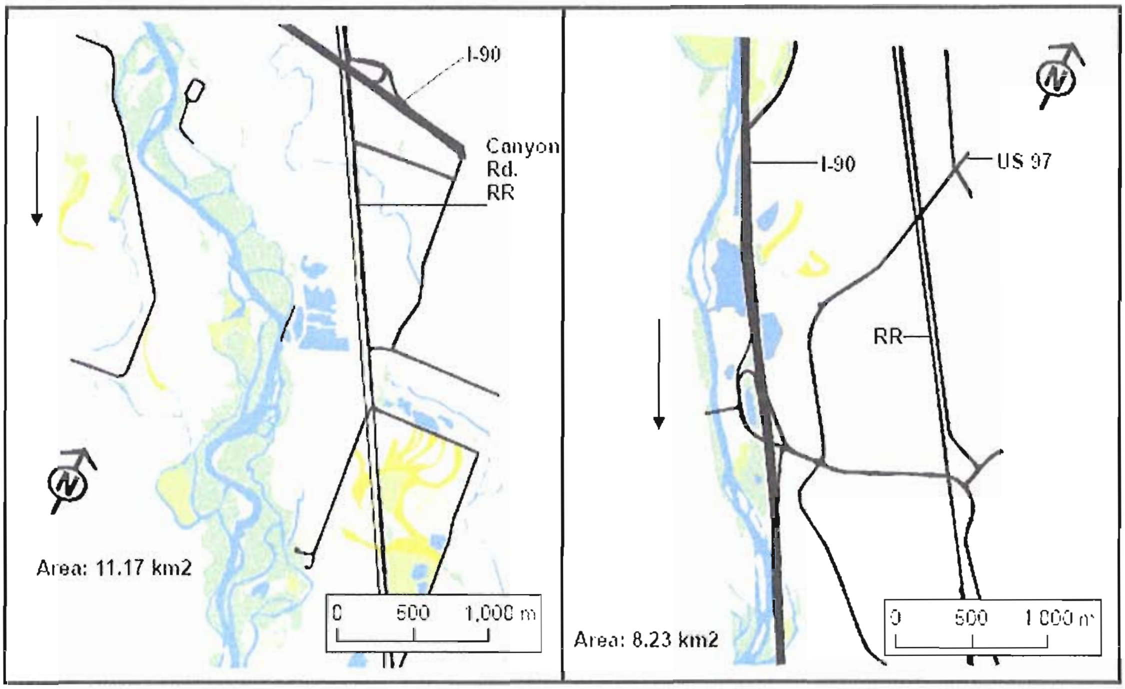


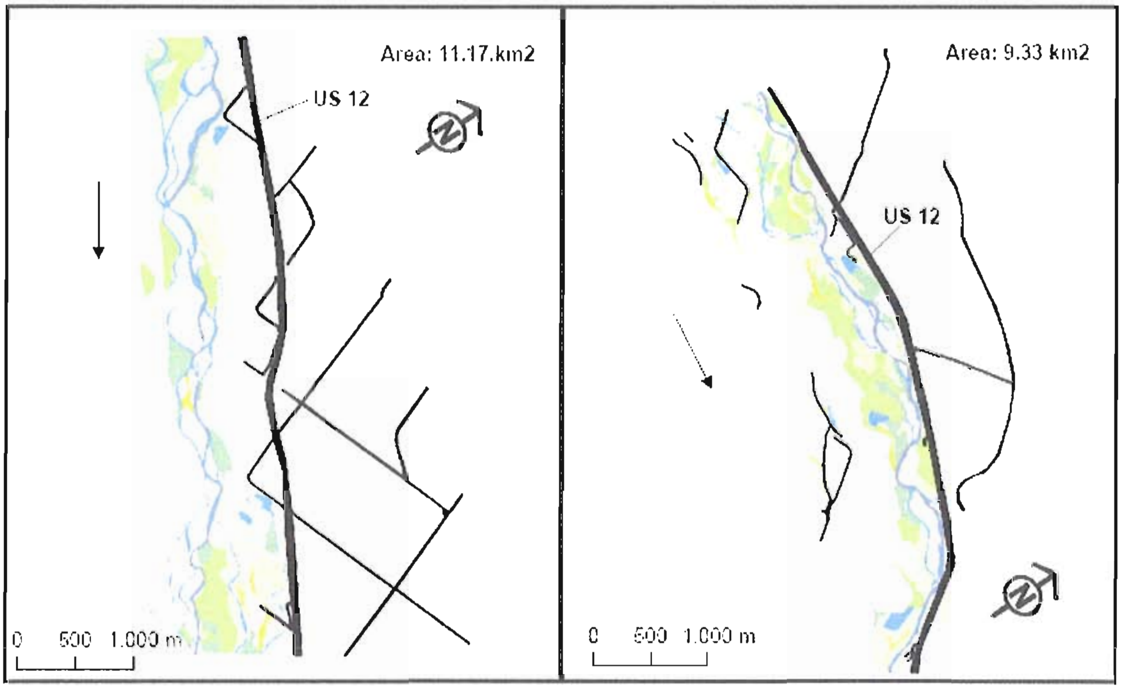
Figure 4.3: Teanaway paired reaches. Representative of tributary stream valley disconnected by road.



Ellensburg (Control)

Ellensburg (Experimental)

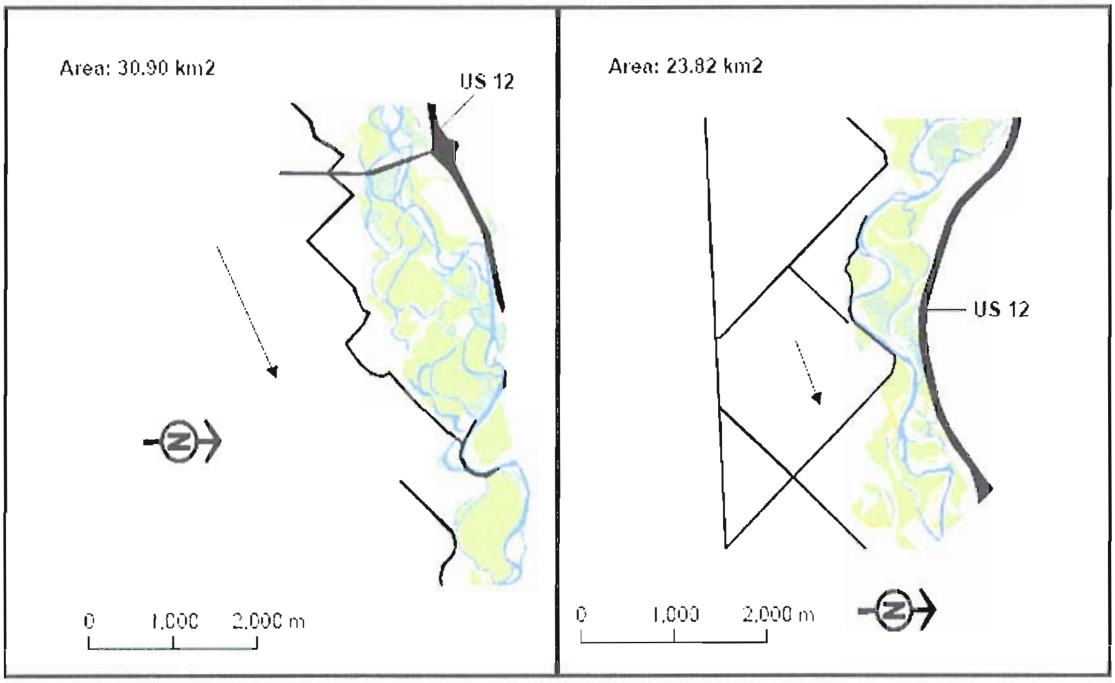
Figure 4.4: Ellensburg paired reaches. This reach pair is the most extreme example of transportation-caused lateral disconnection in the study area.



Naches (Control)

Naches (Experimental)

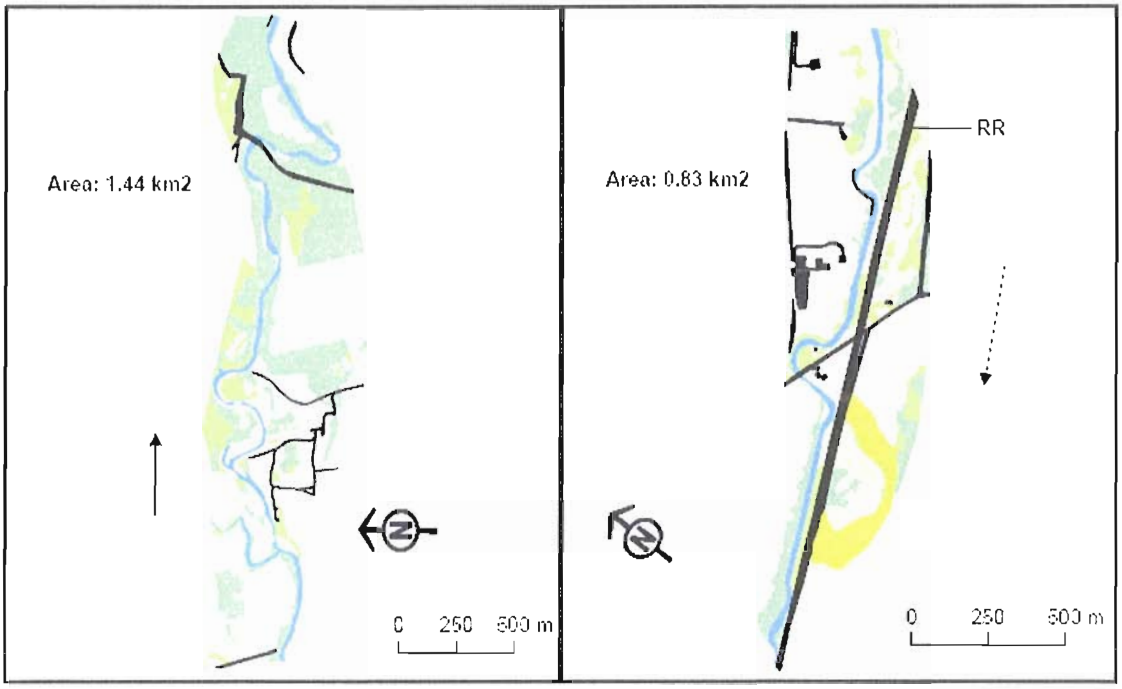
Figure 4.5: Naches paired reaches. The Naches is the only multi-threaded actively mobile channel represented here.



Lower Yakima Valley (Control)

Lower Yakima Valley (Experimental)

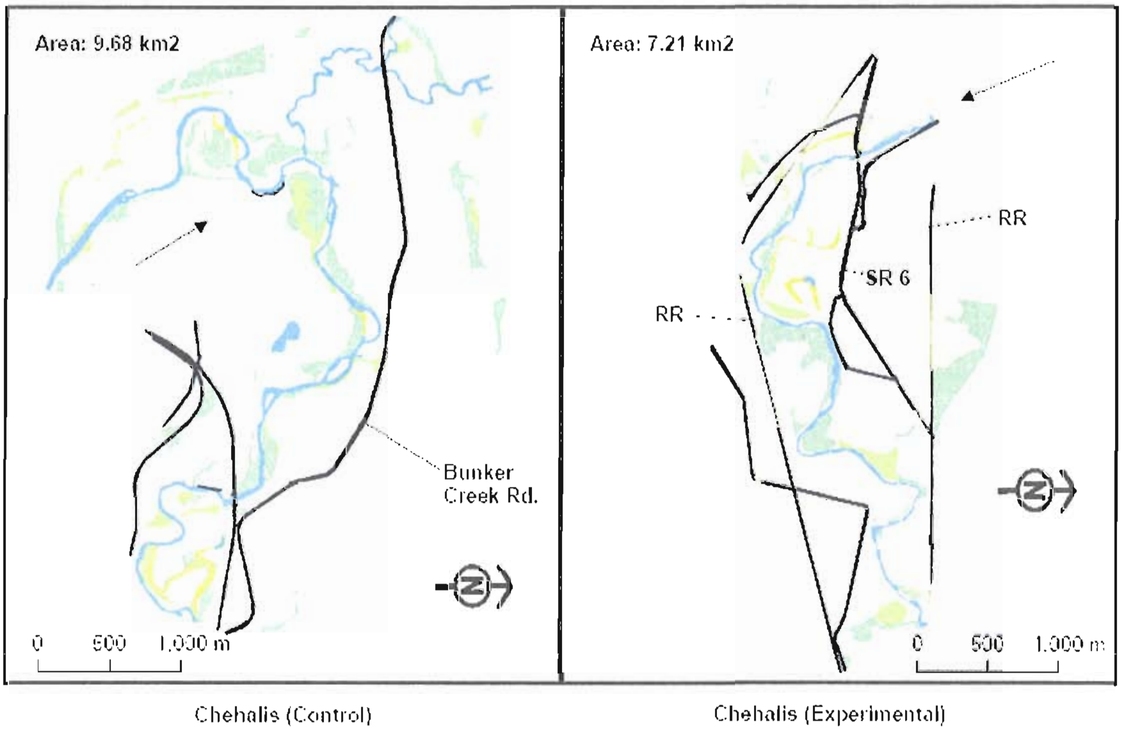
Figure 4.6: Lower Yakima Valley paired reaches. The Lower Yakima valley is the broadest valley setting of the study sites, with a complex mix of different surficial deposits, and historically supported a broad riparian zone with high side channel complexity.



Skookumchuck (Control)

Skookumchuck (Experimental)

Figure 4.7: Skookumchuck paired reaches. Example of a small tributary stream valley disconnected by a railroad grade.



Chehalis (Control)

Chehalis (Experimental)

Figure 4.8: Chehalis paired reaches. The Chehalis reaches are representative of an underfit stream in a glacial valley.

Table 4.5: Comparison of riverine landscape disconnection metrics, experimental and control reaches

	Easton		Teanaway		Ellensburg		Naches	
	Control	Exp.	Control	Exp.	Control	Exp.	Control	Exp.
Channel metrics								
L. truncated bends	0.00	0.00	0.00	0.12	0.00	0.16	0.00	0.26
Sinuosity	1.39	1.31	1.18	1.06	1.21	1.04	1.19	1.12
Wetted channel area (km^2)	0.17/3.70%	0.22/2.38%	0.08/3.51%	0.08/3.23%	0.38/3.33%	0.22/2.67%	0.19/1.70%	0.16/1.71%
Average WCW (m)*	59 ± 1.62	45 ± 1.08	66.3 ± 2.41	54.8 ± 2.37	96.91 ± 3.49	76.71 ± 3.03	31.26 ± 1.06	25.8 ± 0.88
Bar area/MC area	0.41	0.06	1.57	0.95	0.08	0.05	1.24	1.70
Island area/MC area	0.00	0.00	0.02	0.00	2.84	0.18	3.19	0.47
LWD (#/channel length)	3.97	1.64	0.85	0.00	2.85	0.69	0.99	0.32
Floodplain metrics								
Refugia (ponds, ha/% floodplain)	0/0%	0/0%	0/0%	0/0%	11.55/1.0%	0.00/0%	0/0%	0/0%
Gravel ponds/pits (ha/ % floodplain)	2.88/0.6%	7.41/0.8%	0.45/0.2%	0/0%	7.7/0.7%	16.82/2%	5.28/0.5%	7.26/0.8%
Refugia (alcoves, ha/% floodplain)	0.82/0.2%	0.22/0.2%	0.36/0.2%	0.09/0.0%	0.96/0.1%	0.16/0.0%	3.88/0.3%	1.25/0.1%
Channel complexity	0.45	0.02	0.18	0.15	3.39	1.14	1.34	1.29
Developed area (% of floodplain)	19.99	57.31	49.95	66.01	66.59	82.13	72.07	74.59
Riparian zone width/WCW	24.24 ± 1.67	7.36 ± 1.83	13.55 ± 1.15	7.03 ± 0.69	6.86 ± 0.63	1.98 ± 0.39	10.09 ± 0.89	7.65 ± 0.67
Riparian zone area (km^2/% of floodplain)	3.00/65%	3.16/34%	0.72/32%	0.52/21%	1.68/15%	0.47/6%	0.84/7%	0.91/10%
% bank w/gallery forest	100%	58%	95%	82%	83%	39%	49%	26%

Table 4.5 (continued)

	Lower Valley		Skookumchuck		Chehalis	
	Control	Exp.	Control	Exp.	Control	Exp.
Channel metrics						
L. truncated bends	0.00	0.23	0.00	0.09	0.00	0.17
Sinuosity	1.51	1.40	1.4	1.13	1.32	1.28
Wetted channel area (km2)	0.40/1.29%	0.27/1.13%	0.10/6.94%	0.05/6.02%	0.27/2.80%	0.16/2.22%
Average WCW (m)*	92 ± 5.6	63 ± 2.33	38.11 ± 1.14	27.1 ± 0.76	66.23 ± 1.89	46.93 ± 1.7
Bar area/MC area	0.52	0.65	0.17	0.01	0.34	0.19
Island area/MC area	0.00	0.00	0.00	0.00	0.05	0.00
LWD (#/channel length)	1.66	0.90	1.35	0.68	1.55	0.83
Floodplain metrics						
Refugia (ponds, ha/% floodplain)	0.66/0.02%	0/0%	0/0%	0/0%	2.56/0.09%	0.51/0.07%
Gravel ponds/pits (ha, % floodplain)	0/0%	0.12/0.01%	0/0%	0/0%	0/0%	0/0%
Refugia (alcoves, ha/% floodplain)	3.6/0.12%	0.9/0.01%	0.13/0.09%	0/0%	0.83/0.09%	0.13/0.02%
Channel complexity	0.99	0.63	0.14	0.00	0.16	0.01
Developed area (% of floodplain)	78.71	86.10	42.34	51.52	71.89	75.18
Riparian zone width/WCW*	25.21 ± 1.46	14.97± 1.66	10.61 ± 1.03	4.55 ± 0.64	8.15 ± 0.81	5.87 ± 0.56
Riparian zone area (km2/% of floodplain)	4.03/13%	2.10/9%	0.65/45%	0.18/22%	1.51/16%	0.82/11%
% bank w/gallery forest	86%	79%	59%	24%	50%	28%

* all differences significant at $p<0.05$

Discussion

Overview of Disconnection Impacts

Our results show both impacts to the channel and floodplains in the study areas, with serious consequences for ecological function. Channels became straighter, narrower, simpler in planform pattern, and contained less active depositional surfaces including bars and islands. The decrease in channel width and general straightening suggests that in the confined reaches the channels are likely deepening. Lack of in-channel depositional features and wood is also indicative of concentrated flow and stream power, and the lack of habitat or the inhibition of new habitat formation. In the floodplain, off channel habitat important to both aquatic and terrestrial biota, including side-channels and ponds are degraded. Taken together, the results shown here are suggestive of degradation of the shifting habitat mosaic, and by extension to channel and floodplain habitat structure and function.

Disconnection Impacts and River Setting

Our results show impacts of lateral disconnection across a range of river landscape settings and characteristics, including: (1) valley width index; (2) size and position of confining features; (3) large alluvial valleys vs. smaller tributary valleys; (4) higher vs. lower elevation basin settings; and (5) multi-threaded vs. single channels. Following paragraphs provide examples from each of these different varieties of settings.

The valley width index, which is the ratio of the functional floodplain to channel width, was on the order of 20 to 30 for the study reaches, far above the standard 4x threshold for channel confinement (Bisson et al., 1996). All reaches therefore have at least the potential to behave as unconfined rivers. The riparian zone in the control reaches, as defined by the riparian gallery forest, was 10-15x channel width, and thus the floodplain could contain ~2 riparian zone widths (Table 4.6).

Table 4.6: Valley confinement indices. FFP = width of functional floodplain, RZ = riparian zone width, WCW = wetted channel width. FFP values given in meters; all other values are dimensionless ratios, rounded to nearest whole number. See text for further explanation.

Reach	FFP con.	FFP exp.	RZ/ WCW con.	RZ/ WCW exp.	FFP/ RZ con.	FFP/ RZ exp.	FFP/ WCW con.	FFP/ WCW exp.
Easton	1178	1687	24	7	1	5	20	38
Teanaway	633	657	14	7	1	2	10	12
Ellensburg	2391	2322	7	2	3	10	25	30
Naches	1993	1950	10	8	2	3	18	24
Lower Valley	4969	4803	25	15	2	5	54	76
Skook-umchuck	525	460	11	5	1	3	14	17
Chehalis	1914	1816	8	6	3	6	29	39
Average			14	7	2	5	23	33

In the Easton site (Figure 4.2), the channel in the experimental reach is not directly confined in comparison with other sites, yet the riparian zone is confined and degraded. Transportation infrastructure alters the degree of confinement of the floodplain, riparian zone, and channel relative to 'natural' valley confinement as expressed by VWI. Each of these types of confinement are relatively more or less critical from reach to reach, and are not adequately captured by a single confinement metric.

The Ellensburg reaches (Figure 4.4, Table 4.5) are the most extreme example of artificial confinement, both visually and in terms of metrics. On the aerial imagery for the Ellensburg experimental reach, meander scars and paleochannels are evident in the disconnected portions of the floodplain (Figure 4.9). Nearly all the experimental reach floodplain is disconnected, with degraded conditions both in-channel and in the floodplain. A single structure proximal to the channel (I-90) is responsible for the majority of the floodplain disconnection. Both reaches have extensive gravel ponds, however, which when reconnected may provide essential refugia habitat for fish.

The tributary reaches are no less affected by disconnection than the main channel reaches. The Skookumchuck (Figure 4.7) and Teanaway (Figure 4.3) experimental reaches have both degraded riparian zones; the main difference is that the rail line in the Skookumchuck experimental reach drastically straightens the channel. Rail lines are more likely to be the major disconnection type in smaller valley settings; their impacts are especially important in other geographic regions such as the Appalachians, where rail lines along streams in small valleys are common (Blanton and Marcus, 2009).

The Easton reaches (Figure 4.2) are representative of higher elevation reaches where, even in semi-arid climates, the riparian forest also maintains connectivity with

Figure 4.9: Yakima River at Ellensburg, WA. I-90 bisects floodplain, running SE to NW through image. River and riparian zone are confined to the left of I-90. At this location, river is also confined by terrace immediately above and SE of present riparian zone (1). Meander scars and paleochannels (e.g., 2) are evident in the disconnected portions of the floodplain (to the right of I-90).

upland forests in the control reaches. This is in contrast with lower elevation semi-arid settings such as the Naches (Figure 4.5), where the steep environmental gradient from channel to upland results in a ribbon of riparian forest separated from upland forest by more xeric vegetation.

Lower elevation valley reaches in the Yakima basin (e.g. Figures 4.4 and 4.6) are located in broad valleys with fan deposits of varying ages interspersed with alluvial and mass-wasting deposits to create a complex valley fill. In the Lower Yakima reaches in the Yakima Valley, for example (Figure 4.6), the extent of the Holocene floodplain is much greater than at the other paired reaches, and there is visual evidence of past channel activity far away from the channel (even more than in the Ellensburg reaches). Both reaches have roads; the difference is that I-82 is mostly on a terrace outside the floodplain in the control reach, and is on the floodplain in the experimental reach.

Lower elevation reaches in the Chehalis (e.g., figure 4.8) are representative of an under-fit stream in a glacial valley. Although the proportionally larger functional floodplains in these settings are more likely to be developed, the riparian zone is also 'under fit' relative to valley width. Therefore, even though both reaches are cleared for agriculture across the valley floor, the potential exists in the control reach for a more natural disturbance regime that would engender the maintenance of the shifting habitat mosaic with minimal land use change.

The Naches (Figure 4.5) differs from the other sites in that it is multi-thread actively mobile channel. Its floodplain metrics, particularly its riparian forest metrics are less effected than its channel metrics. The extent of the Holocene floodplain, connected floodplain, and disconnected floodplain are all similar in the two reaches—the difference is channel proximity to the road.

Just as valley confinement is argued as controlling river planform, habitat type and quality, and hyporheic exchange (Montgomery and Buffington 1998, Stanford et al. 1993), this study furthers the point that human modification of the floodplain and subsequent confinement also drive these processes and need to be components of a landscape-oriented approach to the analysis of river systems. Channel confinement, riparian zone confinement, and floodplain confinement are all different but interrelated concepts, and their complex interaction is not captured by simple buffer zones.

Managing for Disturbance

This study highlights contemporary issues relating to the application of ecological theory and insights to the management of aquatic resources (Tockner et al., 2010). Instead of adopting a static view of channels as ditches conveying water, sediment, and animals, contemporary stream ecology takes a dynamic disturbance-centered perspective, where the flow regime and shifting habitat mosaic are the physical basis for habitat creation and maintenance. This perspective is part of a larger, holistic watershed- or riverscape- based approach that is concerned with how rivers (and their floodplains) fit into the larger physical and cultural landscape. Hauer et al. (2003) outline three major themes in the restoration of river ecosystems: restoration of natural or normalized hydrologic regimes, restoration of the floodplain and its shifting habitat mosaic, and the restoration of adjoining upland landscapes using a watershed scale perspective along with concepts from landscape ecology. Central to all three of these themes is the issue of managing river landscapes for disturbance.

The most promising contemporary restoration efforts of salmonid habitat in the Pacific Northwest reflect this disturbance-based ecological perspective; focusing on making flows available (through water banking, instream flow protection, and the acquisition of water rights), releasing environmental flows from dams to mimic components of the natural flow regime, and the acquisition of floodplain property for preservation and restoration efforts. For example, releasing flows from dam reservoirs timed and sized for ecological purposes is a key component of downstream in-channel and riparian habitat preservation and restoration (Stevens et al., 2001, Richter et al., 2003). All of these components require the outlay of substantial capital, and political risk if they are ineffective or counterproductive. Blanton and Marcus (2009) argue that Hynes (1975) famous statement that ‘the valley rules the stream’ should be modified to include the massive impact that human structures have on confining the valley, floodplain, and channel: that is, valley rules the transportation network — and the transportation network rules the stream. Without adequate consideration of how human modifications of floodplain landscapes affect and interact with different flows, restoration efforts are doomed to fail. Managing systems for connectivity and disturbance is difficult but fundamental question in contemporary landscape ecology, whether in the context of mass wasting, fire, or flooding (or in some riparian systems, all three). In terms of fish habitat, patch connectivity is more important than habitat size or quality (Isaak, et al. 2007).

The Channel Migration Zone approach adopted by Washington State (Rapp and Abbe, 2003) is an example of a more dynamic approach to floodplain assessment and management. The REACHES project (Stanford et al.. 2002) is a good example of an extensive watershed-scale assessment of aquatic management that includes studies of hydrologic, geomorphic, and biologic connectivity, linking flows with the potential to accomplish geomorphic work, biological and biophysical data, and assessment of land use change along with other factors. Both of these approaches explicitly include human modifications of the floodplain as confining factors.

Conclusions

The results of our study support our hypothesized impacts of floodplain roads and railroads on channel and floodplain habitat in the study areas. Roads and railroads disrupt the natural disturbance regime of river and floodplain systems, particularly in the riparian zone, and the shifting habitat mosaic that through shorter term flooding and flow pulses, along with longer term fluvial geomorphic processes is a major control on ecological function along the river corridor. Our results suggest that a disturbance-based perspective of confinement and connectivity is critical to better understanding of human impacts on rivers.

Advances in computer technology and data availability offer two complementary pathways for the study of the abiotic, biotic, and cultural components of river landscapes and how they interact over space and time. For initial stages of analysis, or relatively simple problems, GIS and freely available digital data allow for rapid and inexpensive assessments (Blanton and Marcus, in prep). On the other hand, the rapid explosion of relatively high-resolution geospatial data along more sophisticated models and other analytical tools open up possibilities for the study of variables that drive connectivity, habitat form, and function at fine scales across the entire riverscape, such as sediment size and stream power in combination with multi-scale biological data (Fonstad and Marcus 2010). The challenge to river science is to not only to integrate physical and biological data across a variety of spatiotemporal scales in a landscape-centered approach that recognizes the fundamental importance of natural disturbance as well as human alteration of the landscape, but to do so in a way useful for managers and policy makers.

CHAPTER V

SUMMARY

In this dissertation, I examined the spatial distribution and impact of floodplain roads and railroads on the river landscapes of the coterminous United States at the continental, regional, and local scales. The goals of the research were to show what kinds of disconnection occur in different geographic regions and types of landscapes, to develop relatively simple spatial analysis techniques to map floodplain surfaces and floodplain disconnection to perform rapid assessments of disconnection impacts, and to quantify the specific impacts that floodplain disconnection has on the physical and biological processes that drive habitat form and function in river channels and adjoining riparian zones and floodplains. The overarching objective of this study was to provide information that would help inform decision-making in regards to management and policy in the context of aquatic resources.

At the continental scale, I divided potential impacts of floodplain roads and railroads into two categories: 'crossing' impacts such as bridges and 'lateral disconnection' impacts where roads and railroads run parallel to stream channels, effectively disconnecting them from their floodplains. I used GIS analysis and national-scale hydrologic and transportation data to map the distribution of these impacts, aggregating the results to the 18 water resource regions of the U.S. to facilitate interregional comparison. I used continental-scale elevation data and a simple index of topographic ruggedness to investigate landscape controls on disconnection impacts, and showed that crossing impacts are dominant in areas of gentle relief (such as the mid-U.S.) and lateral disconnection impacts are dominant in more rugged landscapes (such as the West and the Appalachians).

At the regional scale, I used GIS and freely available digital data to map functional floodplain areas and transportation-driven disconnections and evaluate these maps relative to field-based results from previous studies, assessing restoration potential along floodplains of two river systems in Washington State. I compared maps of the functional floodplain based on soils, geology, and FEMA floodplain data sets. I then mapped disconnections in two classes: major structures such as highways and railroads (Class I disconnections), and smaller local roads (Class II disconnections). I combined these maps with remotely-sensed impervious surface data and a simple ranking system for salmon habitat potential I developed based on access to fish-bearing tributaries and floodplain channel complexity. I used these results to analyze opportunities and constraints for salmon habitat restoration. In unconfined alluvial floodplains, soils and geologic data produce similar floodplain areas and concur with results from previous studies. The FEMA data delineates a smaller floodplain area, often bounded by large structures. Disconnection mapping results also were in general agreement with previous results. Disconnection is more of a limitation for channel complexity than for tributary access, provided that floodplain structures have passable culverts or bridges. I showed how pre-existing digital data and GIS may be used to quickly and inexpensively delineate potential or historic floodplain surfaces, as well as to analyze lateral floodplain disconnection, and its implications for restoration and management of aquatic and riparian systems.

At the local scale, I compared pairs of similar floodplain reaches along the Yakima and Chehalis rivers in Washington State, with and without floodplain transportation infrastructure confining the riparian zone. Both channel and floodplain habitat were degraded in the disconnected reaches, and commonly used hydrogeomorphic metrics indicative of channel and floodplain processes were significantly different. Confined channels were narrower, deeper, simper in planform, and relatively devoid of depositional surfaces such as bars and islands. Floodplains adjacent to confined channels exhibited degraded riparian forest, and less refugium habitat such as side channels, ponds, and alcoves important for endangered salmonids and other biota.

At multiple spatial scales I demonstrate the utility of methods that use GIS, free or inexpensive geospatial data, and relatively simple metrics to map and analyze floodplain disconnection caused by roads and railroads. The simplicity of these methods allows for their application across other geographic regions and landscapes. In addition my results show the importance of simple landscape-based analysis as a complement to other methods and techniques (particularly more complex and data intensive remote sensing and modeling techniques, as well as time and labor intensive field data collection) in multi-scale assessments of human impacts on river systems.

This dissertation documents the widespread and potential massive potential ecological impact of floodplain roads and railroads, and highlights their significance for river science and management. My results support hypotheses about the relationship between flow regime, connectivity, and the ‘shifting habitat mosaic’ and how human modification of the floodplain landscape disrupts the disturbance regime required for maintaining the high habitat and biological diversity associated with riparian corridors. Valley confinement, a critical driver of fluvial geomorphic processes, needs to include artificial confinement, and confinement of the riparian zone and active floodplain surface needs to be included as well as confinement of the channel. Better understanding of floodplain connectivity and confinement makes for more effective management in river systems, informing issues such as the design of ecological flow releases from dams, the prioritization of habitat preservation and restoration projects, and the establishment of land use buffer zones.

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