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Railroads, roads and lateral disconnection in the river landscapes of the continental United States

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ABSTRACT

Railroads and roads are ubiquitous features in the river corridors of the United States. However, their impact on hydrologic, geomorphic, and ecological processes in fluvial and riparian landscapes has not been systematically explored at regional or continental extents. This study documents the geographic distribution of roads and railroads in the alluvial floodplains of the continental United States and the regional variability of their potential impacts on lateral connectivity and resultant channel and floodplain structure and function. We use national scale data sets and GIS analysis to derive data on stream–transportation network interactions in two broad categories: (1) crossing impacts, such as bridges and culverts, and (2) impacts where transportation infrastructure acts as a longitudinal dam along the stream channel, causing lateral floodplain disconnection. Potential stream crossing impacts are greatest in regions with long histories of road and railroad development and relatively low relief, such as the Mid-Atlantic, New England, and the Lower Mississippi and Ohio Valleys. Potential lateral disconnections are more prevalent in rugged regions such as the Western U.S. and Appalachians where transportation routes follow river corridors along valley bottoms. Based on these results, we develop a conceptual model that suggests that the area of lateral disconnection due to transportation infrastructure should be most extensive in mid-sized alluvial valleys in relatively rugged settings. The result of this disconnection is the disruption of the long-term, cut-and-fill alluviation and of the shorter-term flood and flow pulse processes that create and maintain ecosystem function in river landscapes. The tremendous extent of transportation infrastructure in alluvial valleys documented in this study suggests a revision to H.B.N. Hynes' statement that the valley rules the stream. Instead, it appears that in modern landscapes of the U.S. the valley rules the transportation network — and the transportation network rules the stream.

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 (Montgomery et al., 2003; Hauer 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.

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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., Hancock, 2002; Amoros and Bornette, 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; Ward et al., 2002; Amoros and Bornette, 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 44–69% 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, 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., 2004) 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. 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.

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

Fig. 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.

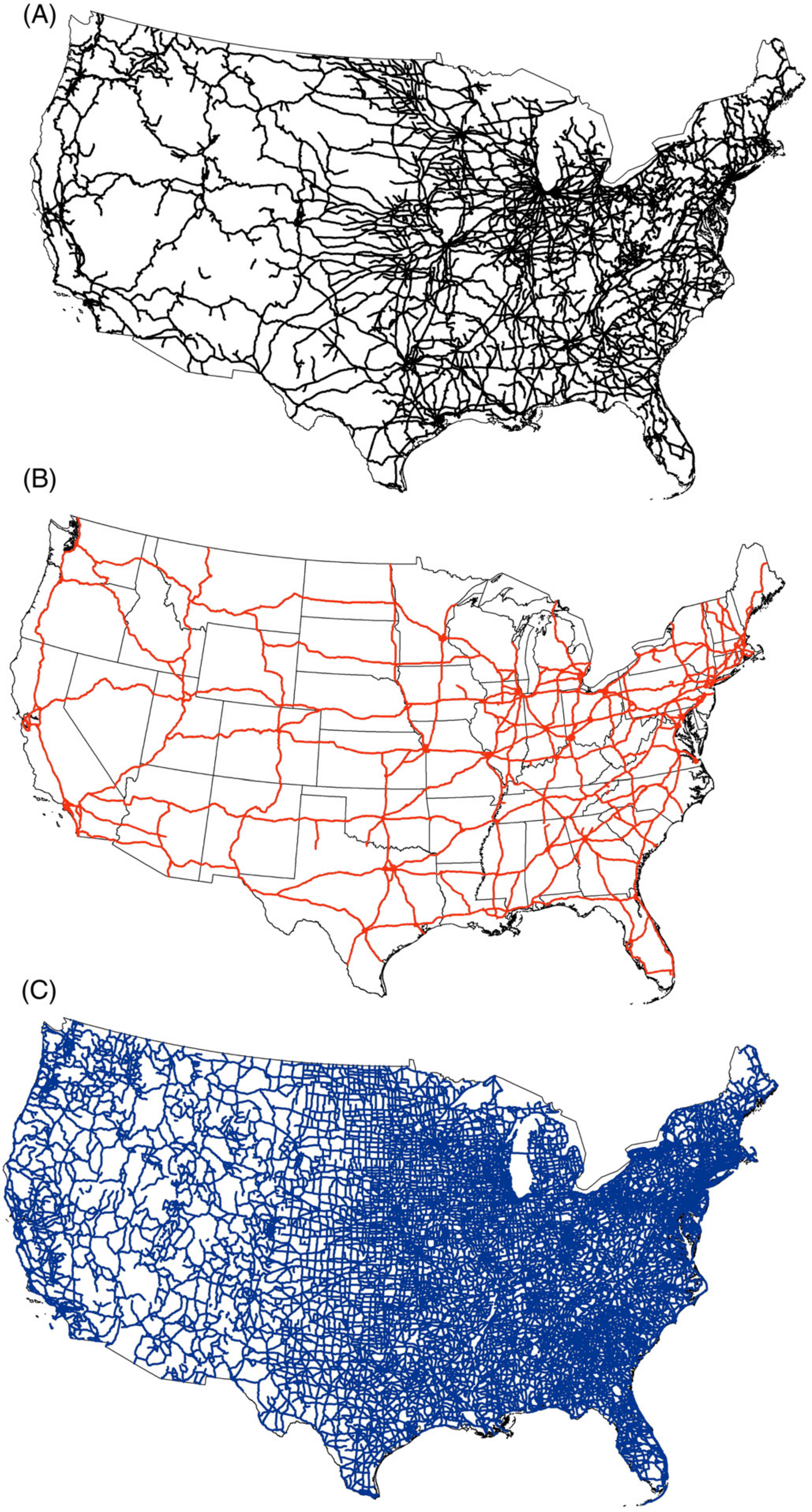

Fig. 2. GIS data sources used in analysis. (A) Railroads. (B) Interstate Highways. (C) U.S./state Highways. Source: National Atlas of the United States.

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) 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.

3.1. Data

3.1.1. 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. 3). The highest level consists of 18 continental U.S. water resource regions (Table 1), the most common watershed-based, large-scale regions used in hydrologic analysis (Graf, 1999). 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).

Table 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	6016	2869	14,882
2	Mid-Atlantic	287,515	30,431	15,365	5944	37,351
3	South Atlantic-Gulf	697,932	62,606	29,097	9325	78,269
4	Great Lakes	461,341	28,426	15,569	4814	30,691
5	Ohio	422,094	41,895	23,812	6823	46,905
6	Tennessee	106,038	10,500	4160	1445	10,870
7	Upper Mississippi	491,756	48,231	25,561	6176	50,813
8	Lower Mississippi	262,301	30,781	8613	2444	22,351
9	Souris	153,763	10,848	5826	615	9459
10	Missouri	1,323,996	118,386	27,886	8548	68,693
11	Arkansas	641,599	52,473	18,797	3953	44,156
12	Texas-Gulf	464,434	35,262	12,835	3727	32,296
13	Rio Grande	343,991	21,178	4507	1980	12,549
14	Upper Colorado	293,472	28,293	1945	924	8535
15	Lower Colorado	362,758	20,654	4166	2544	9641
16	Great Basin	367,602	17,807	3959	2039	11,015
17	Pacific Northwest	710,011	50,899	12,125	3772	27,756
18	California	417,417	23,548	9464	3808	20,440

3.1.2. 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. 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

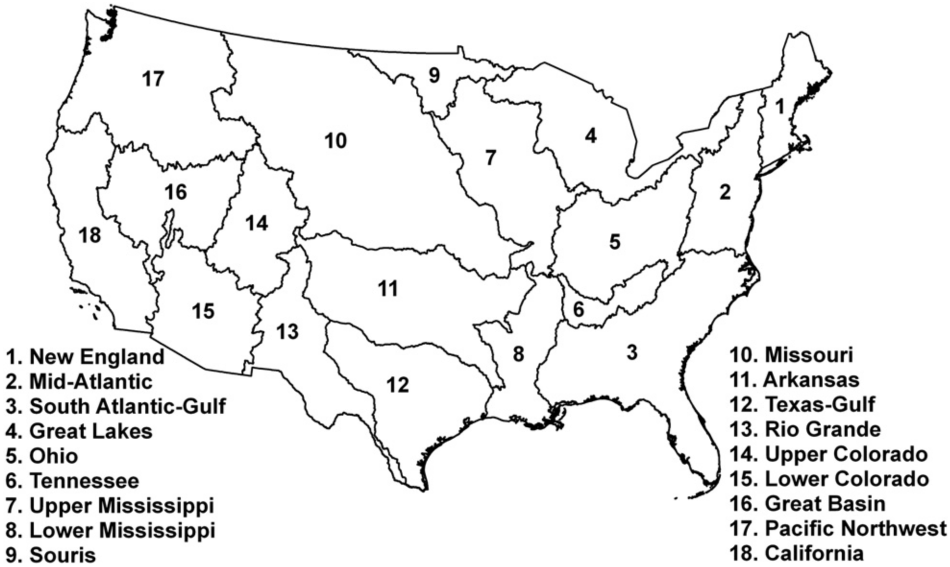

Fig. 3. Water resource regions of the continental United States.

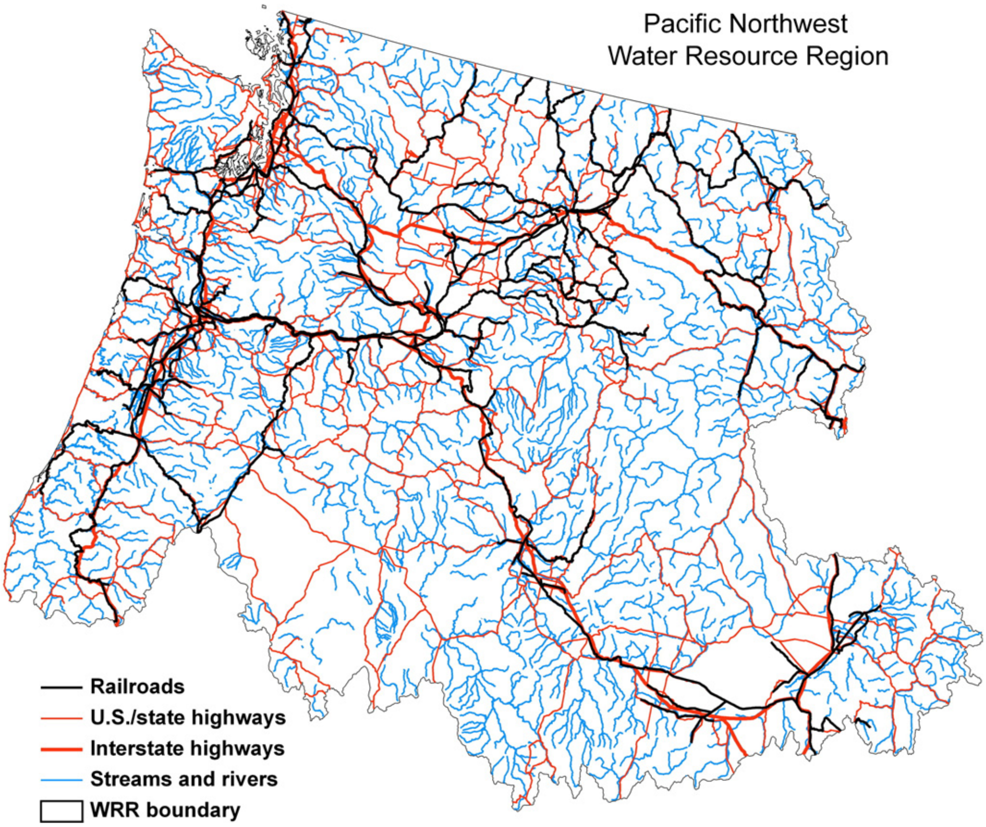

Fig. 4. Example of transportation and stream data at the water resource region scale.

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 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.

3.1.3. 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. 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.

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

$$RRCI = L_s / L_{sf} \tag{1}$$

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.

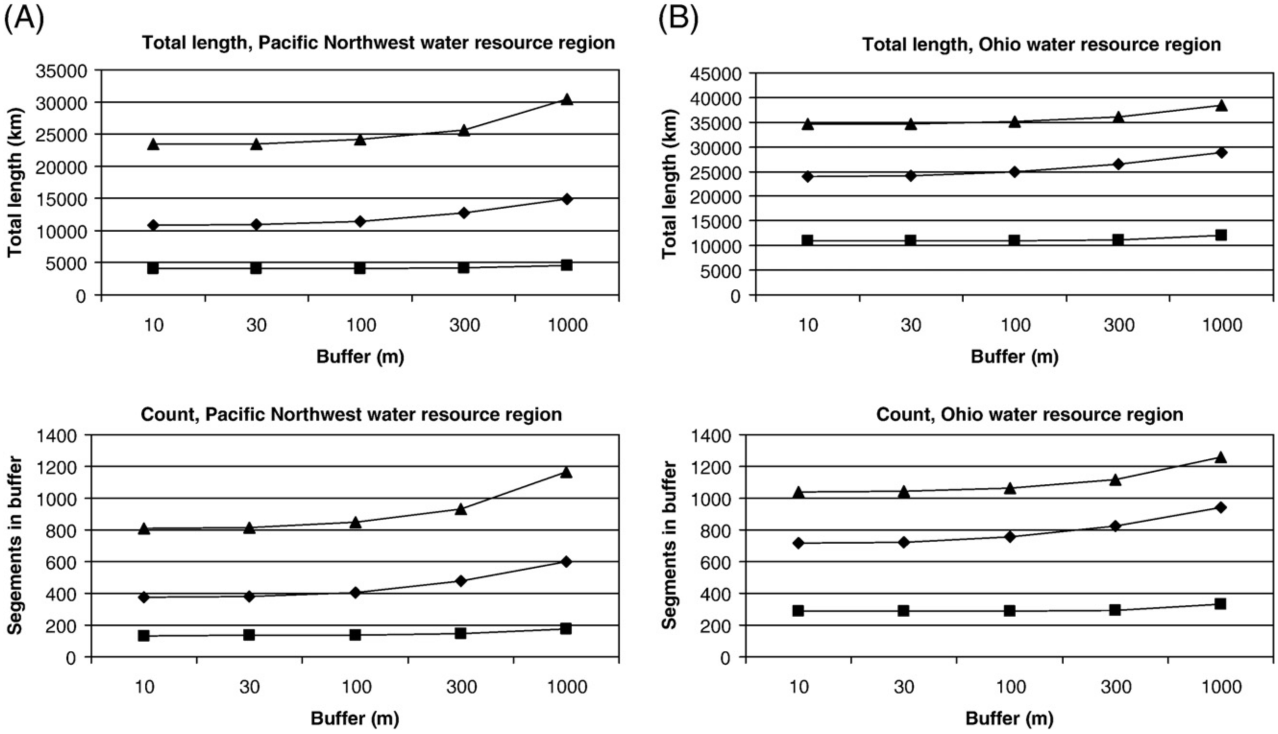

Fig. 5. (A) Sensitivity analysis of transportation line buffer width. Top: sensitivity of total length of stream segments within buffer to buffer width, Pacific Northwest region. Bottom: sensitivity of count of stream segments within buffer to buffer width, Pacific Northwest region. (B) Sensitivity analysis 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.

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. 6). We isolated transportation lines with curvature ≥1.1 as portions of the transportation network with a high potential for lateral 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 ≥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 ≥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 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 least difference between stream and rail densities (Table 2; Fig. 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 Souris interstate density ranks 17th compared to a ranking of 7th for rail densities. Interstate density values are generally much lower than the values for rail lines and smaller highways (Table 2; Fig. 7). U.S./state highway density values are higher than stream density values for several regions (Table 2; Fig. 7), and again the general east–west pattern persists.

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

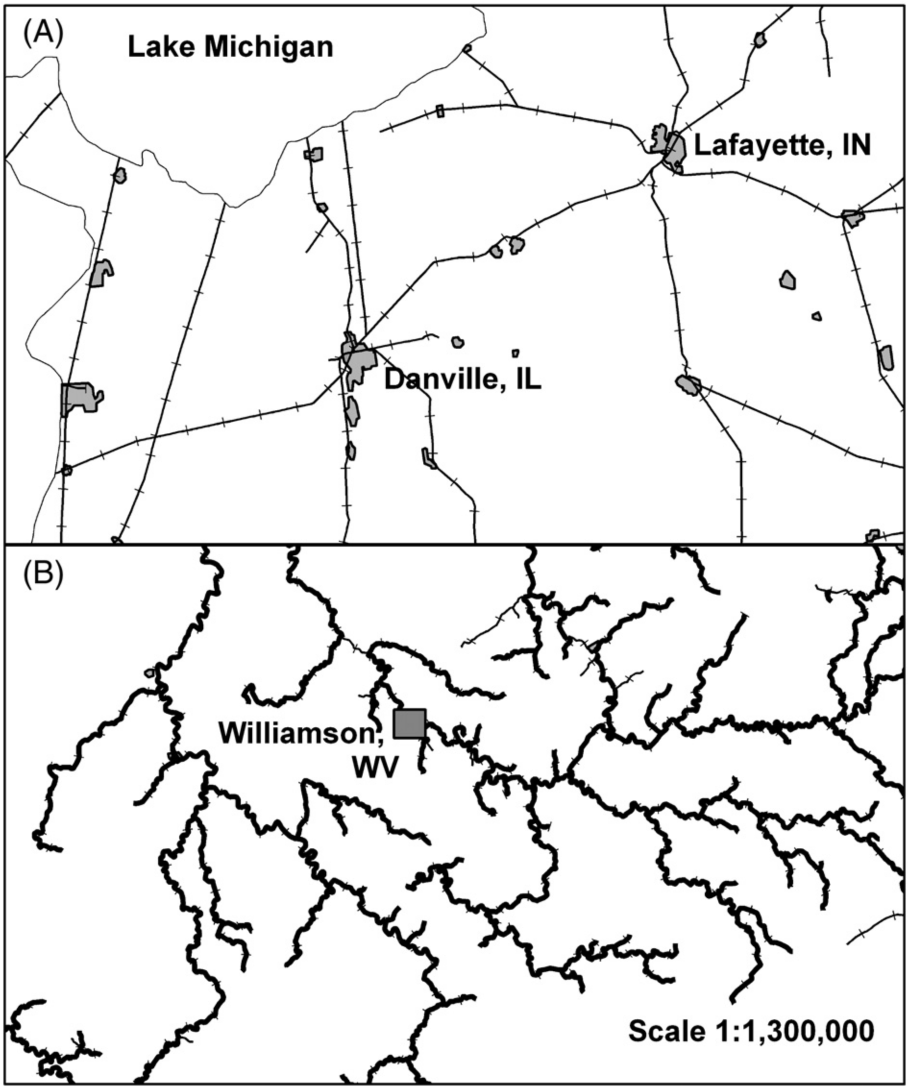

Fig. 6. Railroad lines in two different landscapes. All lines with curvature value >1.1 are bolded. A curvature index value of 1.1 effectively distinguishes linear radial transportation network patterns (top, Northern Indiana and Illinois) where no curvature values are >1.1 from sinuous, dendritic patterns where almost all lines have curvature values >1.1 (bottom, West Virginia–Kentucky border).

Table 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

gradient, with the highest values in the Upper Midwest and Northeastern continental United States (Table 3; Fig. 8). 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 buffer values for all three transportation types are higher relative to other regions than are the intersection values (Table 3; Fig. 8).

4.4. Near-distance analysis

Table 3 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 (Fig. 8), 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. 8), but is somewhat 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 4). No other pairs of metrics correlated strongly for roads, although median nearest distance correlated with buffer and curvature metrics for rail lines.

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 5).

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. 9), 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 6).

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 4) 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.

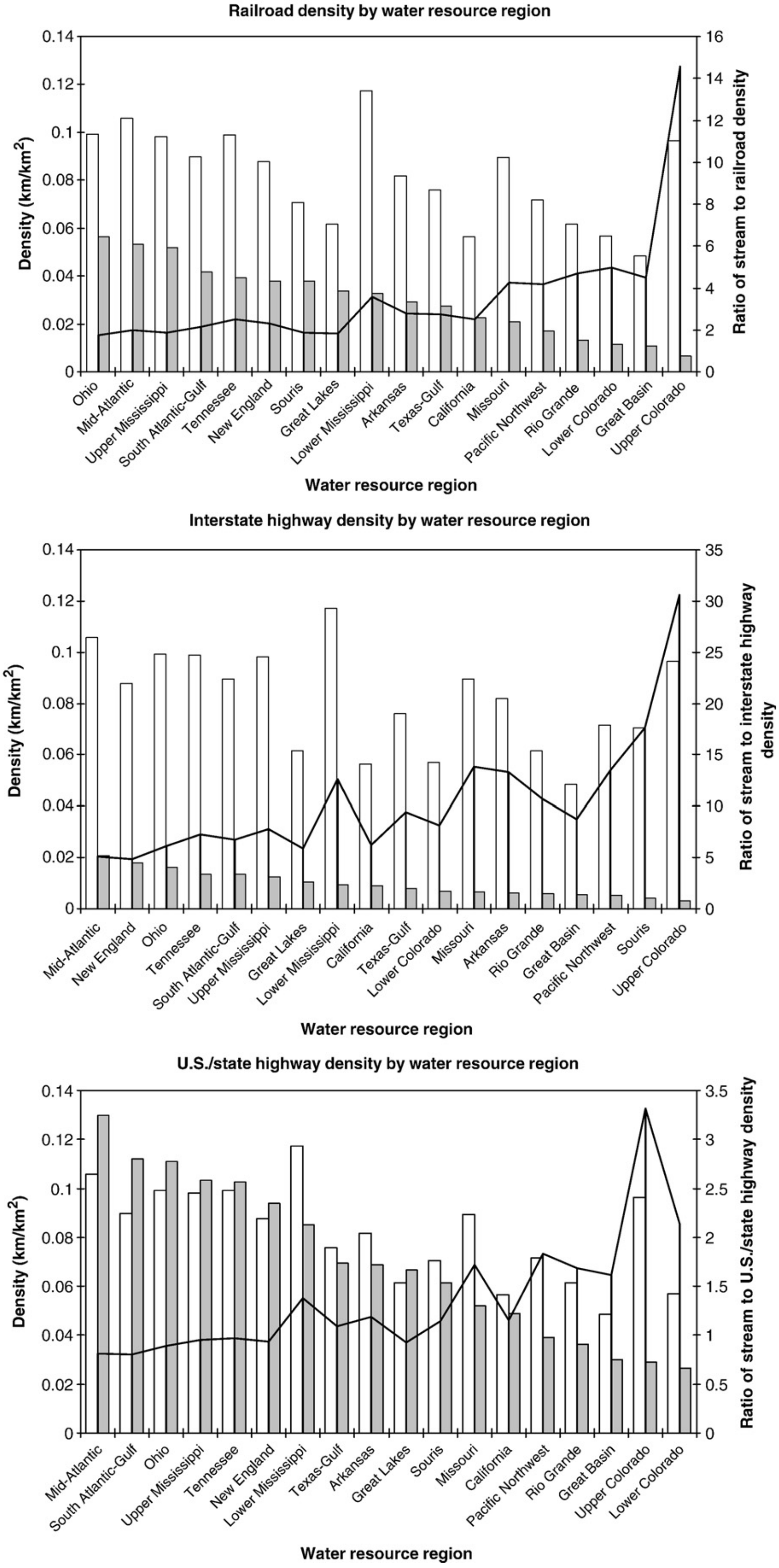

Fig. 7. Density of stream and transportation networks of the continental U.S. by water resource region. Top: stream and railroad network density. Middle: stream and interstate highway density. Bottom: stream and U.S./state highway density. Density = total length of lines in network/region area. Ratio of stream to transportation network density is also plotted to facilitate interregional comparison. White columns = stream density. Grey columns = transportation line density. Line = ratio of stream to transportation network density .

Table 3
Median nearest distance, intersections/area, stream length within 30 m buffer of transportation line for railroads, interstate highways, and U.S./State highways for the 18 water resource regions of the continental United States.

	Water resource region	Railroads	Interstate highways	U.S./State highways
Median nearest distance, transportation line to stream				
1	New England	1073	2133	1805
2	Mid-Atlantic	1207	2160	2179
3	South Atlantic-Gulf	3077	3480	3665
4	Great Lakes	2279	2463	2602
5	Ohio	1567	2900	2498
6	Tennessee	1943	2182	2412
7	Upper Mississippi	2347	2796	2640
8	Lower Mississippi	2496	3106	2688
9	Souris	3503	3063	3301
10	Missouri	1719	2262	2449
11	Arkansas	2977	3136	3416
12	Texas-Gulf	3450	3522	3680
13	Rio Grande	3616	3914	3665
14	Upper Colorado	511	1319	1526
15	Lower Colorado	3071	4138	3781
16	Great Basin	2595	3012	3864
17	Pacific Northwest	1160	1905	1799
18	California	3950	5005	3944
Intersections/area (number of intersections per 10,000 km^2)				
1	New England	21.7	10.8	47.9
2	Mid-Atlantic	29.0	11.3	60.8
3	South Atlantic-Gulf	15.4	6.0	41.2
4	Great Lakes	17.5	5.4	31.5
5	Ohio	27.6	8.2	48.3
6	Tennessee	17.5	5.9	44.3
7	Upper Mississippi	25.6	6.1	48.2
8	Lower Mississippi	13.7	4.7	36.6
9	Souris	13.8	2.0	23.4
10	Missouri	9.6	3.2	24.4
11	Arkansas	10.5	2.6	25.5
12	Texas-Gulf	10.5	3.9	25.0
13	Rio Grande	3.5	1.8	11.2
14	Upper Colorado	4.2	1.6	14.2
15	Lower Colorado	3.5	2.0	7.1
16	Great Basin	3.0	1.7	8.5
17	Pacific Northwest	7.4	2.6	16.1
18	California	6.6	2.9	13.4
Stream length within 30 m buffer of transportation line per total stream length (m/km)				
1	New England	8.8	5.4	1.6
2	Mid-Atlantic	11.2	5.4	2.1
3	South Atlantic-Gulf	1.8	22.5	0.1
4	Great Lakes	3.6	8.8	0.4
5	Ohio	10.9	4.4	2.5
6	Tennessee	6.4	6.9	1.0
7	Upper Mississippi	4.5	10.8	0.4
8	Lower Mississippi	1.3	28.2	0.1
9	Souris	2.0	11.6	0.2
10	Missouri	1.9	12.7	0.2
11	Arkansas	1.6	15.6	0.1
12	Texas-Gulf	1.4	18.6	0.1
13	Rio Grande	1.3	8.5	0.2
14	Upper Colorado	2.0	7.0	0.3
15	Lower Colorado	1.5	4.7	0.3
16	Great Basin	1.8	4.8	0.4
17	Pacific Northwest	4.2	3.9	1.1
18	California	2.2	6.2	0.4

The ratio of total length of transportation line with a curvature value ≥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 $r_s = 0.83$), interstates ($r_s = 0.90$) and U.S./state highways ($r_s = 0.83$; Fig. 10). 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 Fig. 10 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 (Fig. 10).

At the landscape scale, the potential for river floodplain disconnection is thus primarily a function of topographic relief (Fig. 11). 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. 11A) the geographic pattern of transportation infrastructure is 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. 11B), 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. 11C), 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. 11D), the rail lines in particular follow stream courses and lateral disconnection is highly likely. These patterns are summarized graphically in Fig. 12.

The high degree of correlation for all transportation types by metric (Table 5) 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. 11 and 12) 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 11A), and to a lesser degree in wide alluvial valleys (Fig. 11B), 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. 11C) 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

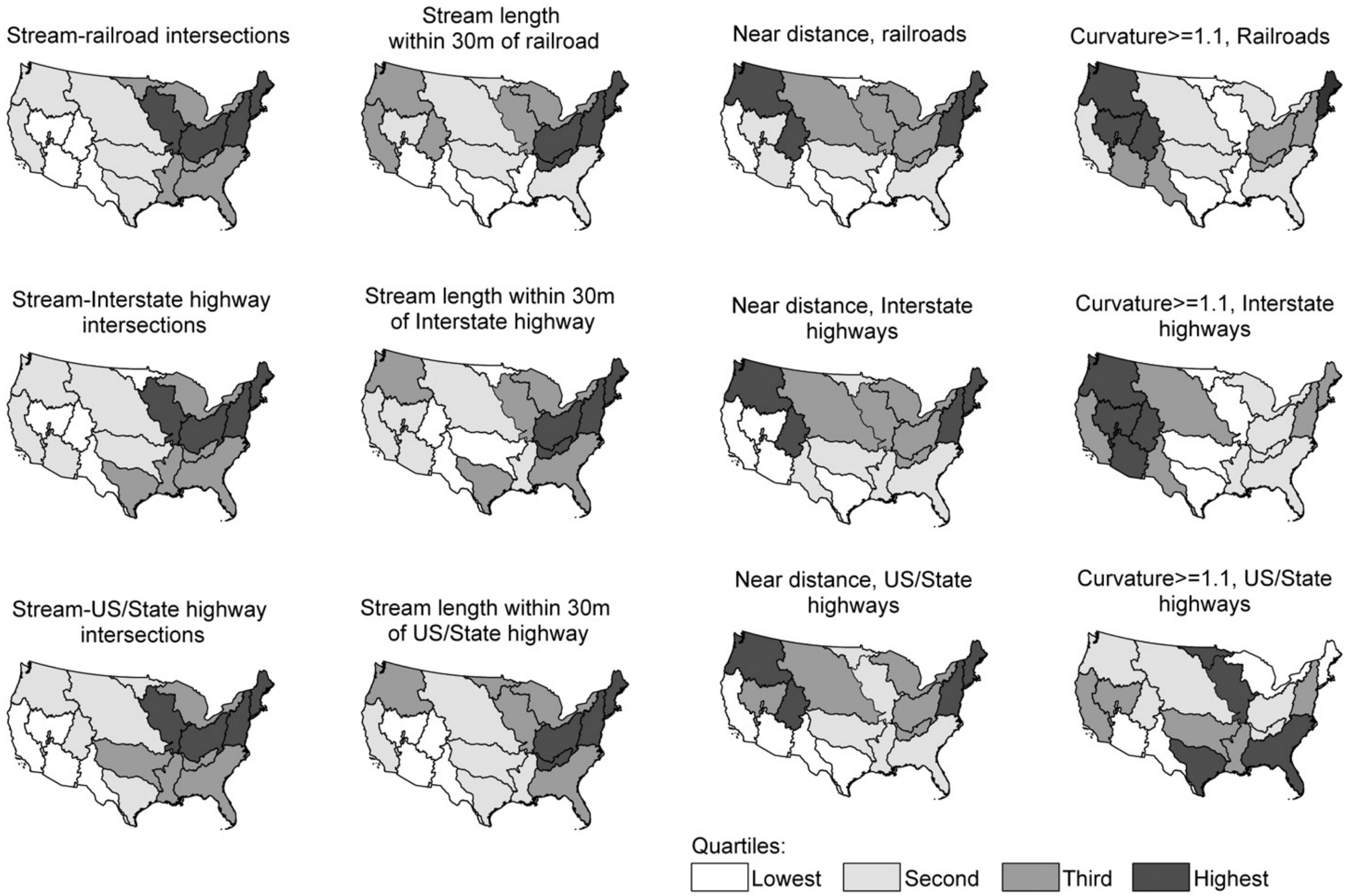

Fig. 8. Quartile maps of stream-transportation network interaction metrics. The "highest" quartile ranking for the nearest distance maps indicates the highest impact, which is the shortest distance between transportation lines and rivers.

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

Table 4
Correlation of interaction metrics for each transportation line type.

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

Values given are Spearman's Rho (r_s) where 0 indicates no correlation and 1 or −1 indicates perfect correlation.
*Denotes significance at $p = 0.05$.

Table 5
Correlation of transportation line type for each interaction metric.

	Number of crossings	Length inside buffer	Median nearest distance	% curvature >1.1
Railroad × interstate highways	0.90*	0.68*	0.93*	0.81*
Railroad × U.S./State highways	0.97*	0.76*	0.90*	−0.51*
Interstate highway × U.S./State highways	0.92*	0.86*	0.93*	−0.55*

Values given are Spearman's Rho (r_s) where 0 indicates no correlation and 1 or −1 indicates perfect correlation.
*Denotes significance at $p = 0.05$.

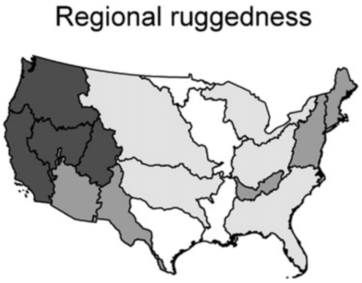

Fig. 9. Quartile map of regional ruggedness by water resource region. Regional ruggedness based on TRI of Riley et al. (1999). See text for explanation. Symbology identical to Fig. 8.

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

Table 6
Spearman rank correlation of topographic ruggedness and transportation impact metrics.

% 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*

Values given are Spearman's Rho (r_s) where 0 indicates no correlation and 1 or −1 indicates perfect correlation.
*Denotes significance at $p = 0.05$.

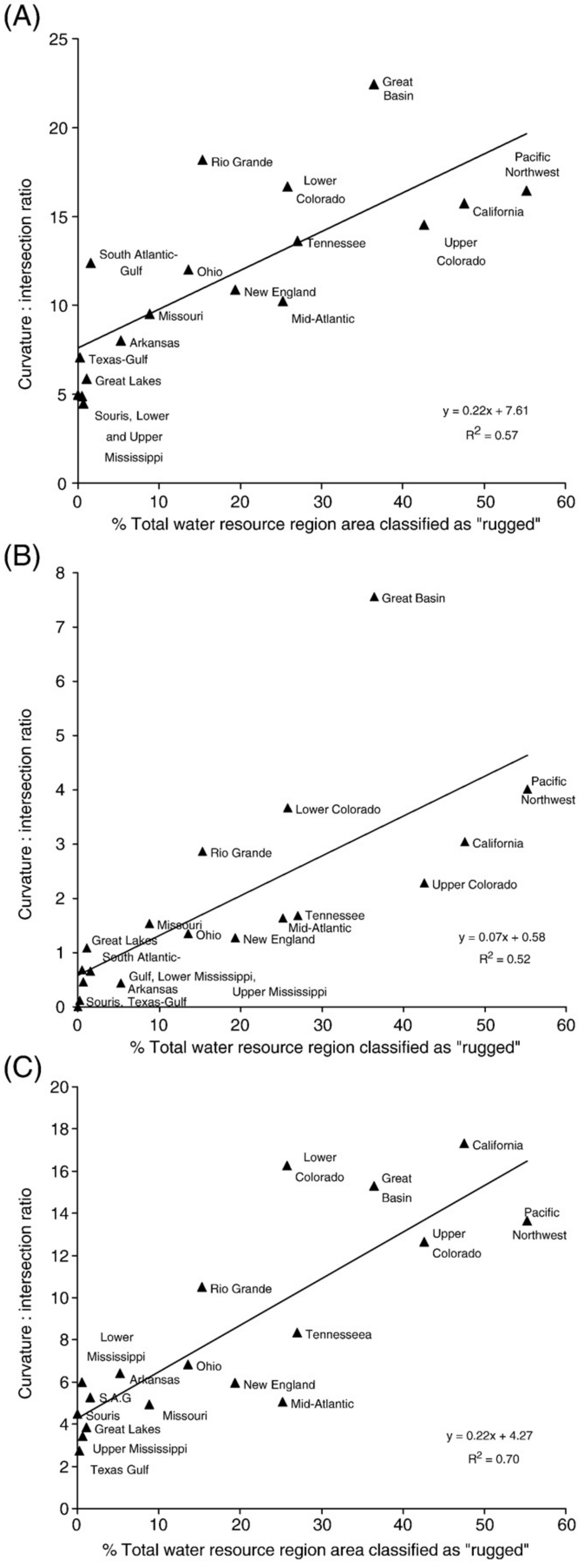

Fig. 10. (A) Relationship of regional ruggedness to ratio of potential point to diffuse linear impacts, railroads. (B) Relationship of regional ruggedness to ratio of potential point to diffuse linear impacts, interstate highways. (C) Relationship of regional ruggedness to ratio of potential point to diffuse linear impacts, U.S./state highways.

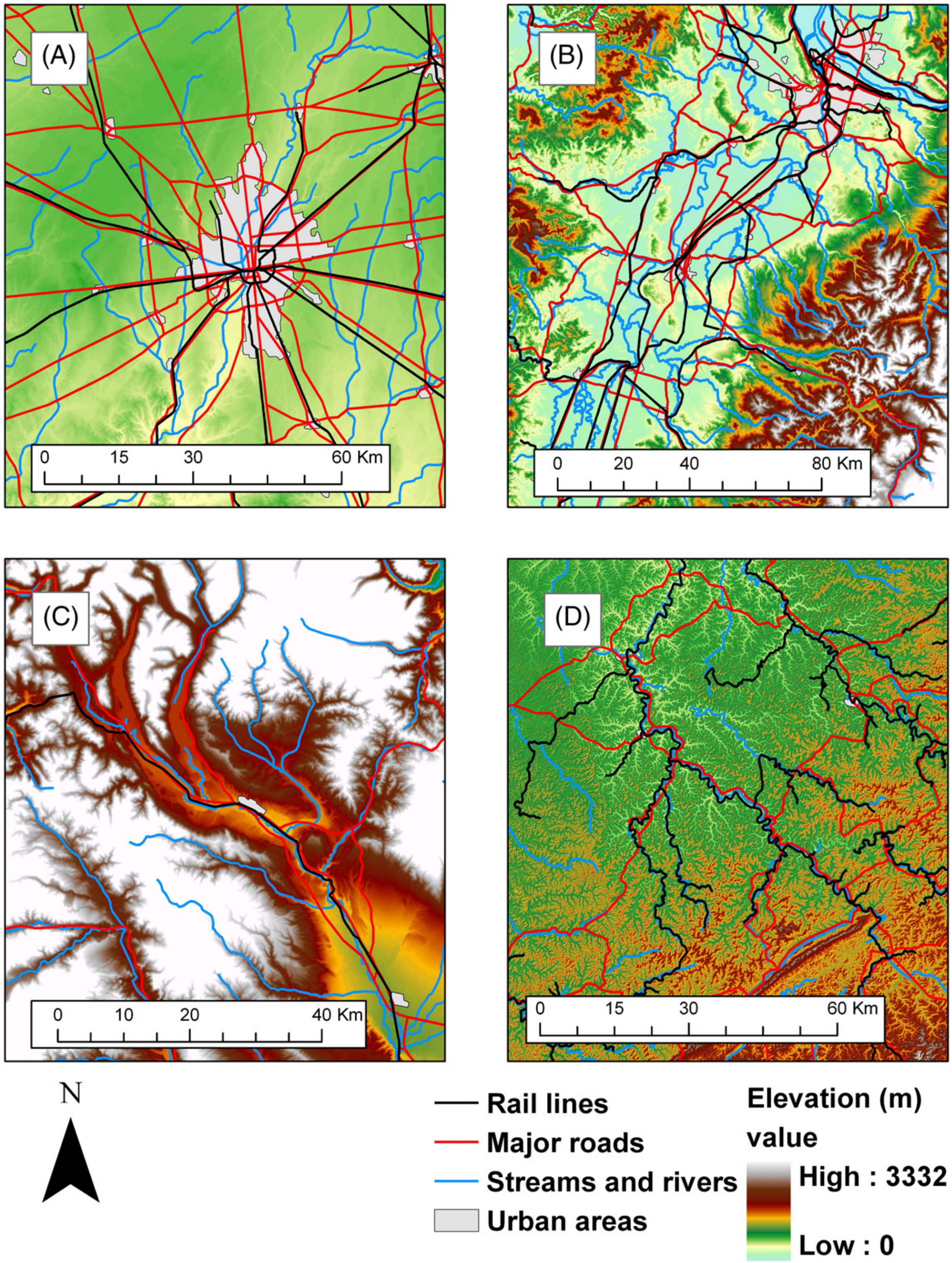

Fig. 11. Four landscapes distinguished in terms of relative potential for disconnection: (A) plains, (B) wide alluvial valleys, (C) intermediate alluvial valleys, and (D) narrow alluvial valleys. See text for explanation.

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

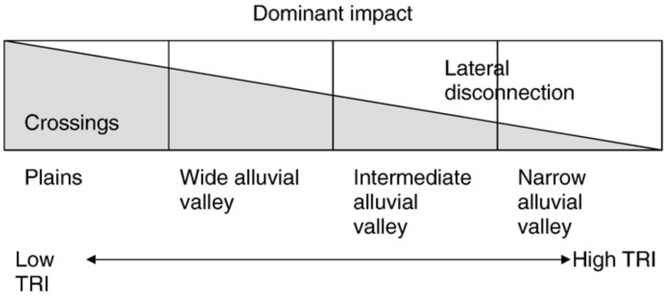

Fig. 12. Conceptual model of topography and potential for transportation line–stream interaction.

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. 10). 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. 8). The highest values of the linear diffuse impact metrics are found in more rugged terrain, particularly in the West (Fig. 8). 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 be 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; Brierley and Fryirs, 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.

Acknowledgements

This work was inspired by Will Graf's national scale study of dam impacts, and Bill Renwick's work on small impoundments as land uses “hidden in plain sight.” We wish to thank Patricia McDowell, Dan Gavin, and Josh Roering for their methodological suggestions. We also wish to thank Martin Doyle, Jean-Paul Bravard, and an anonymous reviewer for their insightful and helpful comments.

References

Amoros, C., Bornette, G., 2002. Connectivity and biocomplexity in waterbodies of riverine floodplains. Freshwater Biology 47 (4), 761–776.

Amoros, C., Roux, A.L., Reygrobellet, J.L., 1987. A method for applied ecological studies of fluvial hydrosystems. Regulated Rivers-Research & Management 1, 17–36.

Bailey, R.G., 1983. Delineation of ecosystem regions. Environmental Management 7 (4), 365–373.

Baxter, C.V., Frissell, C.A., Hauer, F.R., 1999. Geomorphology, logging roads, and the distribution of bull trout spawning in a forested river basin: implications for management and conservation. Transactions of the American Fisheries Society 128 (5), 854–867.

Bisson, P.A., Montgomery, D.R., 1996. Valley segments, stream reaches, and channel units. In: Hauer, F.R., Lamberti, G.A. (Eds.), Methods in Stream Ecology Academic Press. San Diego, CA, pp. 23–52.

Bravard, J.P., Amoros, C., Pautou, G., 1986. Impact of civil engineering works on the successions of communities in a fluvial system — a methodological and predictive approach applied to a section of the upper Rhone River, France. Oikos 47 (1), 92–111.

Brierley, G.J., Fryirs, K.A., 2005. Geomorphology and River Management: Applications of the River Styles Framework. Blackwell. Malden, MA. 398 pp.

Brown, T.G., Hartman, G.F., 1988. Contribution of seasonally flooded lands and minor tributaries to the production of coho salmon in Carnation Creek, British Columbia. Transactions of the American Fisheries Society 117 (6), 546–551.

Décamps, H., 1988. Historical influence of man on the riparian dynamics of a fluvial landscape. Landscape Ecology 1 (3), 163.

Deiller, A.F., Walter, J.M.N., Tremolieres, M., 2001. Effects of flood interruption on species richness, diversity and floristic composition of woody regeneration in the upper Rhine alluvial hardwood forest. Regulated Rivers-Research and Management 17 (4–5), 393–405.

Doyle, M.W., Stanley, E.H., Havlick, D.G., Kaiser, M.J., Steinbach, G., Graf, W.L., Galloway, G.E., Riggsbee, J.A., 2008. Aging infrastructure and ecosystem restoration. Science 319, 286–287.

Dunbar, S., 1915. A History of Travel in America. Bobbs-Merrill Co., Indianapolis. 1529 pp.

Eitemiller, D.J., Uebelacker, M.L., Plume, D.A., Arango, C.P., Clark, K.J., 2000. Anthropogenic Alteration to an Alluvial Floodplain Within the Yakima Basin, Washington. In: Wigington, P.J., Beschta, R.L. (Eds.), Proceedings of the 2000 Summer International Specialty Conference on Riparian Ecology and Management in Multi-land Use Watersheds, Portland. OR. AWRA, Middleburg, VA, pp. 239–244.

Forman, R.T.T., Sperling, D., Bissonette, J.A., Clevenger, A.P., Cutshall, C.D., Dale, V.H., Fahrig, L., France, R., Goldman, C.R., Heanune, K., Jones, J.A., Swanson, F.J., Turrentine, T., Winter, T.C. (Eds.), 2003. Road Ecology: Science and Solutions. Island Press, Washington DC. 481 pp.

Gergel, S.E., Turner, M.G., Miller, J.R., Melack, J.M., Stanley, E.H., 2002. Landscape indicators of human impacts to riverine systems. Aquatic Sciences 64 (2), 118–128.

Graf, W.L., 1999. Dam nation: a geographic census of American dams and their large-scale hydrologic impacts. Water Resources Research 35 (4), 1305–1311.

Graf, W.L., 2006. Downstream hydrologic and geomorphic effects of large dams on American rivers. Geomorphology 79 (3–4), 336–360.

Gregory, S.V., Swanson, F.J., McKee, W.A., Cummins, K.W., 1991. An ecosystem perspective of riparian zones. BioScience 41 (8), 540–551.

Haggett, P., 1967. Network models in geography. In: Chorely, R.J., Haggett, P. (Eds.), Models in geography. Methuen & Co., London, pp. 609–688.

Hancock, P.J., 2002. Human impacts on the stream–groundwater exchange zone. Environmental Management 29 (6), 763–781.

Harper, D.J., Quigley, J.T., 2005. No net loss of fish habitat: a review and analysis of habitat compensation in Canada. Environmental Management 36 (3), 343–355.

Hauer, F.R., Lorang, M.S., 2004. River regulation, decline of ecological resources, and potential for restoration in a semi-arid lands river in the western USA. Aquatic Sciences 66 (4), 388–401.

Hauer, F.R., Dahm, C.N., Lamberti, G.A., Stanford, J.A., 2003. Landscapes and ecological variability of rivers in North America: factors affecting restoration strategies. In: Wissmar, R.C., Bisson, P.A. (Eds.), Strategies for Restoring River Ecosystems: Sources of Variability and Uncertainty in Natural and Managed Systems. American Fisheries Society, Bethesda, MD, pp. 81–105.

Heinz Center, 2002. Dam removal: science and decision making. Heinz Center for Science, Economics and the Environment, Washington DC. 221 pp.

Heinz Center, 2003. Dam Removal Research: Status and Prospects. Heinz Center for Science, Economics and the Environment, Washington DC. 165 pp.

Hohensinner, S., Habersack, H., Jungwirth, M., Zauner, G., 2004. Reconstruction of the characteristics of a natural alluvial river–floodplain system and hydromorphological changes following human modifications: the Danube River (1812–1991). River Research and Applications 20 (1), 25–41.

Horton, R.E., 1945. Erosional development of streams and their drainage basins; hydrophysical approach to quantitative morphology. Geological Society of America Bulletin 56 (3), 275–370.

Hughes, F.M.R., 1997. Floodplain biogeomorphology. Progress in Physical Geography 21 (4), 501–529.

Hupp, C.R., Osterkamp, W.R., 1996. Riparian vegetation and fluvial geomorphic processes. Geomorphology 14 (4), 277–295.

Hynes, H.B.N., 1975. The stream and its valley. Verhandlungen der Internationalen Vereinigung für Theoretische und Angewandte Limnologie 19, 1–15.

James, L.A., Marcus, W.A., 2006. The human role in changing fluvial systems: retrospect, inventory and prospect. Geomorphology 79 (3–4), 152–171.

Jones, J.A., Swanson, F.J., Wemple, B.C., Snyder, K.U., 2000. Effects of roads on hydrology, geomorphology, and disturbance patches in stream networks. Conservation Biology 14 (1), 76–85.

Junk, W.J., Bayley, P.B., Sparks, R.E., 1989. The flood pulse concept in river–floodplain systems. In: Dodge, D.P. (Ed.), Proceedings of the International Large River Symposium (LARS): Canadian Special Publication of Fisheries and Aquatic Science, vol. 106, pp. 110–127.

Kondolf, G.M., Boulton, A.J., O'Daniel, S., Poole, G.C., Rahel, F.J., Stanley, E.H., Wohl, E., Bang, A., Carlstrom, J., Cristoni, C., Huber, H., Koljonen, S., Louhi, P., Nakamura, K., 2006. Process-based ecological river restoration: visualizing three-dimensional connectivity and dynamic vectors to recover lost linkages. Ecology and Society 11 (2), 1–17.

Leyer, I., 2004. Effects of dykes on plant species composition in a large lowland river floodplain. River Research and Applications 20 (7), 813–827.

Lowe, J.C., Moryadas, S., 1975. The Geography of Movement. Wavelend Press, Prospect Heights, IL. 333 pp.

Marston, R.A., Girel, J., Pautou, G., Piegay, H., Bravard, J.P., Arneson, C., 1995. Channel metamorphosis, floodplain disturbance, and vegetation development — Ain River, France. Geomorphology 13 (1–4), 121–131.

Meehan, W.R., Bjornn, T.C., 1991. Salmonid distributions and life histories. In: Meehan, W.R. (Ed.), Influences of Forest and Rangeland Management on Salmonid Fishes and Their Habitats. In: American Fisheries Society Special Publication, vol. 19. American Fisheries Society, Bethesda, MD, pp. 47–82.

Montgomery, D.R., 1994. Road surface drainage, channel initiation, and slope instability. Water Resources Research 30 (6), 1925–1932.

Montgomery, D.R., Buffington, J.M., 1998. Channel processes, classification, and response. In: Naiman, R.J., Bilby, R.E. (Eds.), River Ecology and Management: Lessons from the Pacific Coastal Ecoregion. Springer, New York, pp. 13–42.

Montgomery, D.R., Grant, G.E., Sullivan, K., 1995. Watershed analysis as a framework for implementing ecosystem management. Water Resources Bulletin 31 (3), 369–386.

Montgomery, D.R., Bolton, S., Booth, D.B., Wall, L. (Eds.), 2003. Restoration of Puget Sound Rivers. University of Washington Press, Seattle WA. 512 pp.

Nanson, G.C., Beach, H.F., 1977. Forest succession and sedimentation on a meandering river floodplain, Northeast British Columbia, Canada. Journal of Biogeography 4 (3), 229–251.

National Research Council, 2005. Assessing and Managing the Ecological Impacts of Paved Roads. Committee on Ecological Impacts of Road Density, National Research Council, Washington DC. 324 pp.

Nilsson, C., Reidy, C.A., Dynesius, M., Revenga, C., 2005. Fragmentation and flow regulation of the world's large river systems. Science 308, 405–408.

Poff, N.L., Ward, J.V., 1990. The physical habitat template of lotic ecosystems: recovery in the context of historical patterns of spatio-temporal heterogeneity. Environmental Management 14, 629–646.

Riley, S.J., DeGloria, S.D., Elliot, R., 1999. A terrain ruggedness index that quantifies topographic heterogeneity. Intermountain Journal of Sciences 5 (1–4), 23–27.

Robinson, C.T., Tockner, K., Ward, J.V., 2002. The fauna of dynamic riverine landscapes. Freshwater Biology 47, 661–677.

Rosgen, D.L., 1994. A classification of natural rivers. Catena 22, 169–199.

Schwantes, C.A., 1993. Railroad Signatures Across the Pacific Northwest. University of Washington Press, Seattle, WA. 359 pp.

Seaber, P.R., Kapinos, F.P., Knapp, G.L., 1987. Hydrologic unit maps. U.S. Geological Survey Water-Supply Paper 2294. U.S. Department of the Interior, Geological Survey, Washington DC. 63 pp.

Sedell, J.R., Reeves, G.H., Hauer, F.R., Stanford, J.A., Hawkins, C.P., 1990. Role of refugia in recovery from disturbances — modern fragmented and disconnected river systems. Environmental Management 14 (5), 711–724.

Snyder, E.B., Arango, C.P., Eitemiller, D.J., Stanford, J.A., Uebelacker, M.L., 2002. Floodplain hydrologic connectivity and fisheries restoration in the Yakima River, U.S.A. Verh. Internat. Verein. Limnol. 28, 1653–1657.

Stanford, J.A., Ward, J.V., 1993. An ecosystem perspective of alluvial rivers — connectivity and the hyporheic corridor. Journal of the North American Benthological Society 12 (1), 48–60.

Stanford, J.A., Ward, J.V., Liss, W.J., Frissell, C.A., Williams, R.N., Lichatowich, J.A., Coutant, C.C., 1996. A general protocol for restoration of regulated rivers. Regulated Rivers-Research and Management 12 (4–5), 391–413.

Strahler, A.N., 1952. Hypsometric (area altitude) analysis of erosional topology. Geological Society of America Bulletin (63), 1117–1142.

Switalski, T.A., Bissonette, J.A., DeLuca, T.H., Luce, C.H., Madej, M.A., 2004. Benefits and impacts of road removal. Frontiers in Ecology and the Environment 2 (1), 21–28.

Tockner, K., Malard, F., Ward, J.V., 2000. An extension of the flood pulse concept. Hydrological Processes 14 (16–17), 2861–2883.

Van den Brink, F.W.B., Van der Velde, A., Buijse, A.D., Klink, A.G., 1996. Biodiversity in the Lower Rhine and Meuse river floodplains: its significance for ecological management. Netherlands Journal of Aquatic Ecology 30, 129–149.

Van Looy, K., Honnay, O., Bossuyt, B., Hermy, M., 2004. The effects of river embankment and forest fragmentation on the plant species richness and composition of floodplain forests in the Meuse Valley, Belgium. Belgian Journal of Botany 136 (2), 97–108.

Vannote, R.L., Minshall, G.W., Cummins, K.W., Sedell, J.R., Cushing, C.E., 1980. River continuum concept. Canadian Journal of Fisheries and Aquatic Sciences 37 (1), 130–137.

Ward, J.V., 1989. The four-dimensional nature of lotic ecosystems. Journal of the North American Benthological Society 8, 2–8.

Ward, J.V., Stanford, J.A., 1983. The serial discontinuity concept of lotic ecosystems. In: Fontaine, T.D., Bartell, S.M. (Eds.), Dynamics of Lotic Ecosystems. Ann Arbor Science, Ann Arbor, MI, pp. 29–42.

Ward, J.V., Stanford, J.A., 1995. Ecological connectivity in alluvial river ecosystems and its disruption by flow regulation. Regulated Rivers-Research and Management 11 (1), 105–119.

Ward, J.V., Tockner, K., Arscott, D.B., Claret, C., 2002. Riverine landscape diversity. Freshwater Biology 47 (4), 517–539.

Watts, R.D., Compton, R.W., McCammon, J.H., Rich, C.L., Wright, S.M., Owens, T., Ouren, D.S., 2007. Roadless space of the conterminous United States. Science 316 (5825), 736–738.

Wohl, E.E., 2001. Virtual Rivers: Lessons from the Mountain Rivers of the Colorado Front Range. Yale University Press, New Haven, CT. 210 pp.

Wohl, E.E., 2004. Disconnected Rivers: Linking Rivers to Landscapes. Yale University Press, New Haven, CT. 301 pp.