The Spatial and Temporal Organization of River Habitats

Chapter 2

Development of Salmonid Conservation Strategies
Phase I, Project No T01426T

Presented to:

King County
Water & Land Resources Division
201 South Jackson Street, Suite 600
Seattle, Washington 98104-3855

Prepared by:

Lee Benda
Earth Systems Institute
3040 NW 57th Street
Seattle, Washington 98107

February 6, 2004

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF FIGURES
(continued)

LIST OF TABLES

INTRODUCTION

Riverine habitats are non-uniformly distributed across a range of spatial scales. In steep mountain channels, organization of boulders into discreet clusters leading to alternating "boulder steps" and "pools" occur at the scale of meters (Figure 1) (Grant et al. 1990). In streams and rivers of all sizes, channel meanders form with the spacing of alternating pools and riffles governed by the meander's wavelength, a geometric property that scales with channel width or discharge, ranging from tens of meters in small streams to thousands of meters in larger channels (Leopold and Wolman 1960). Other processes contribute to the fundamentally non-uniform distribution of riverine habitats including log jams, alternating canyons and unconstrained floodplain segments, landslides and rockfalls, bedrock outcrops, and debris-flow- and alluvial-tributary confluences (Figure 1) (Swanson et al. 1988). These larger scale features and their effects in rivers may be separated from one another by kilometers. The downstream change in the spacing and size of riverine features that contribute to physical heterogeneity are known to scale with river size or slope, including boulder steps (Grant et al. 1990), channel meanders (Leopold and Wolman 1960), log jams (Bilby and Ward 1989), and tributary confluence effects (Benda et al., accepted). The scaling properties of the others are less well understood.

Although the patchy nature of riverine habitats is well recognized, the current interest in applying principles of landscape ecology to rivers (e.g., "river landscapes", (Ward et al. 2002; Weins 2002), that includes increasing the spatial scale of analysis to identify the nature of habitat heterogeneity (e.g., "riverscapes", Fausch et al. 2002), motivates us to review the sources and mechanisms of the non uniform distribution of riverine habitats in this paper. The habitat forming agents we review include 1) network geometry via populations of tributary confluences; 2) topographic variations in valley widths leading to alternating canyons and floodplain segments; 3) landslides and rockfalls; 4) log jams, 5) bedrock outcrops; 6) channel meanders, and 7) boulder steps (Figure 1). We explore how the scale of variation in river morphology (i.e., size and separation distance of habitat patches) created by these features scale with size of rivers and vary within and across watersheds. Next, we examine how watershed disturbances (i.e., fires, storms, floods, erosion) either create the agents of riverine heterogeneity or otherwise influence them. Finally, we discuss general principles regarding the spatial and temporal organization of riverine habitats, including identifying the constraining set of watershed conditions that determine the relative importance of the 7 features in river systems. The analysis is limited to single channel, gravel bedded rivers and fluvial process and form in braided channels and in deltas are not addressed.

Causes of the non uniform and patchy distribution of riverine habitats are varied. At small reach scales in relatively steep mountain streams, boulder clusters reflecting congested sediment transport, are separated by pools, the two stream forms alternating downstream (Whittaker 1987). In channel meanders, pools at the outside of bends are separated by depositional riffles, the two forms (pools and riffles) alternating downstream in deformable alluvial beds or in incised bedrock channels. Log jams, canyons, landslides, rockfalls, bedrock outcrops, and fans at tributary confluences all create topographic knick points in rivers (Figure 2). These 6 features can interfere with the downstream transport of sediment and wood leading to increased storage of those materials upstream of them. Increased material storage upstream of obstructions can lead to decreased channel slope, larger floodplains, formation of terraces, and occurrence of side

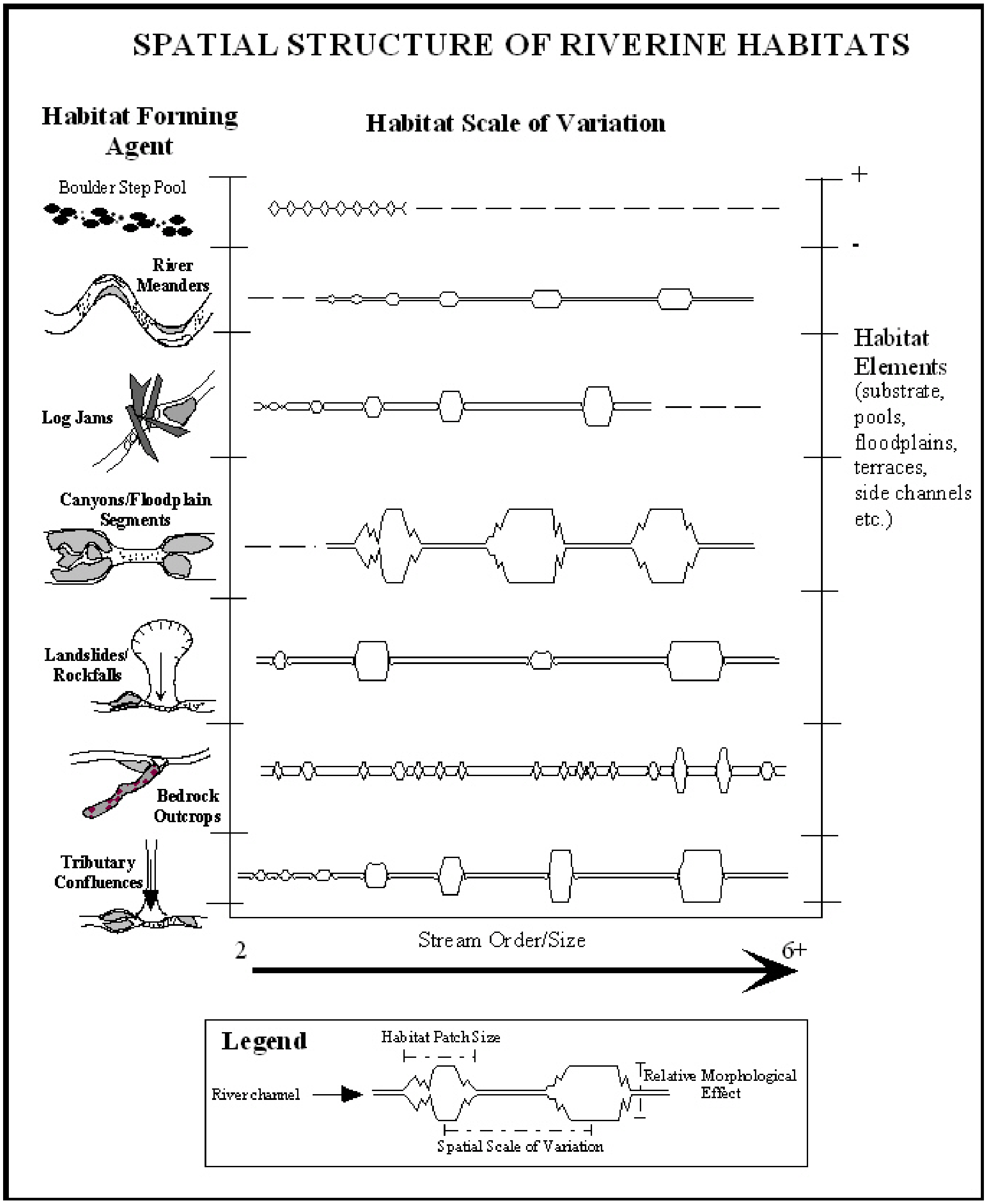

Figure 1. **Seven sources of habitat formation illustrating the size and spacing of their morphological effects in rivers.**

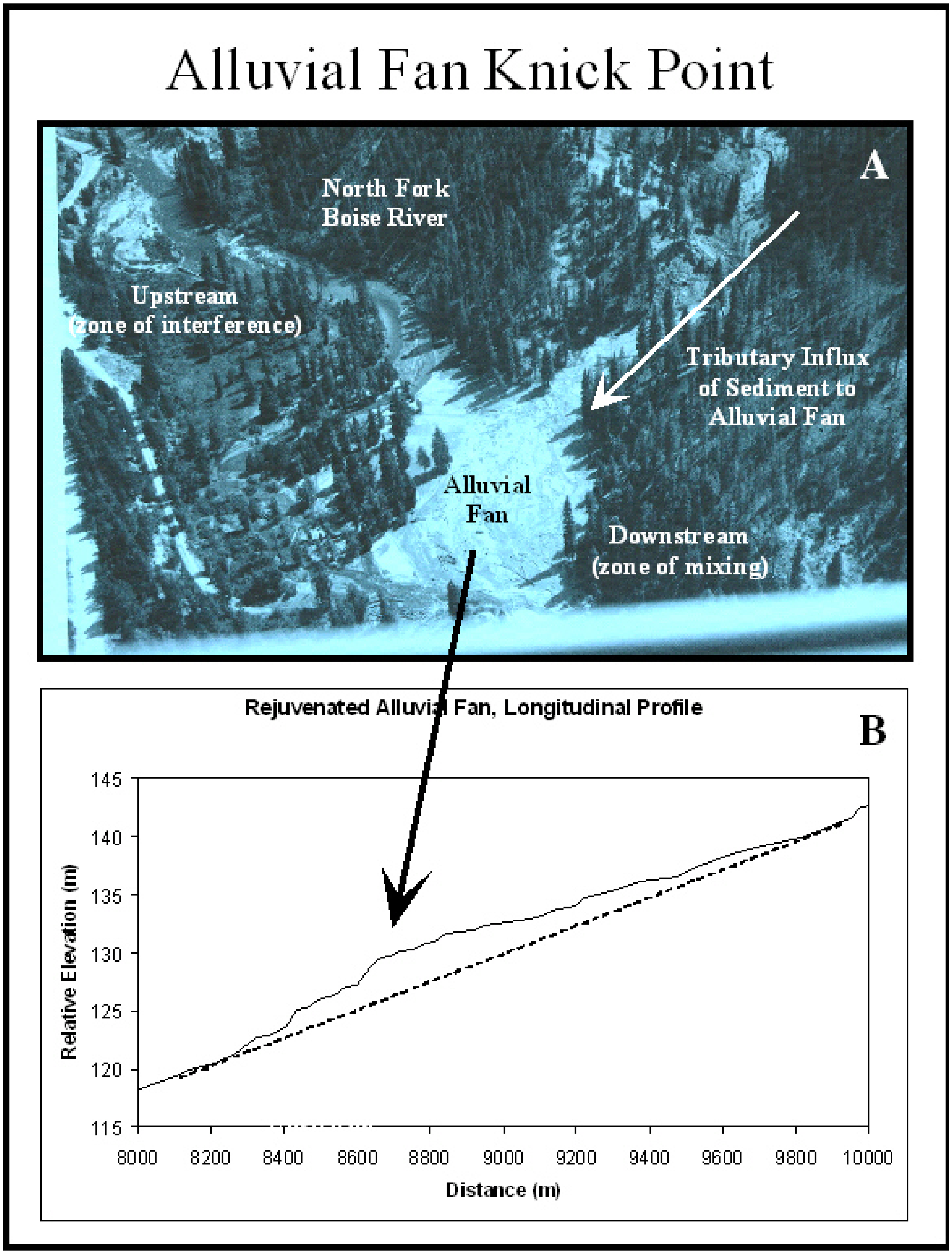

Figure 2. **A rejuvenated alluvial fan in the North Fork Boise River (A) and its effect on the longitudinal profile of the river (B). Adapted from Benda et al. 2003b.**

channels, bars, and ponds (Small 1973; Miller and Cruden 2002; Benda et al. 2003a). Proximal and downstream of topographic knick points, morphological changes may include increases in pool depth and channel width, and formation of bars and rapids (Mosley 1976; Best 1986; Roy and Woldenberg 1986; Meyer et al. 2001). Additionally, large fans or landslides can displace a channel across a valley floor, creating local constrictions in valley width and cause increased channel meandering (Benda 1990; Grant and Swanson 1995). Other interactions of intersecting channels or valleys of different sizes include formation of low gradient habitats at upstream ends of fans (Baxter and Hauer 2000) and development of valley wall tributaries (Bisson et al. 1982), or tributaries flowing parallel to larger rivers because of natural levees (Benda et al. 1992).

In addition to forming knick points, tributaries and landslides also deliver large quantities of sediment and wood to rivers. Abrupt supply of sediment and organic material at confluences and landslides can lead to local changes in bed substrate and increased bar and log jam formation often accompanied by increases in channel slope (Melis et al. 1995; Hogan et al. 1998; Rice et al. 2001). The abrupt merger of two different flow regimes at confluences can also create scour holes and associated mid channel bars (Miller 1958; Best 1986). Changes in channel morphology driven by the 7 river features (e.g., Figure 1) diminish with distance away from them so that they function as agents of morphological heterogeneity (Figure 2). Increased morphological heterogeneity may include increasing variation in substrates sizes, pools depths, floodplains widths, and terraces ages.

Extreme events, or disturbances in the parlance of ecologists, create many aspects of the non uniform distribution and heterogeneity of riverine habitats. Fires, large storms, and floods supply boulders (Benda 1990), trigger landslides (Schwab 1998), form log jams (Hogan et al. 1998), and supply much of the sediment that create fan landforms at tributary confluences (Meyer et al. 2001). In addition, the locally wide and low gradient channels that commonly form in the vicinity of obstructions are highly responsive to fluctuations in the supply of water, sediment, and wood. Response to channelized disturbances at those locations includes cycles of aggradation and degradation that maintain floodplains and side channels and create an age diversity of log jams and terraces (Benda et al. 2003b) and cause increased channel meandering (Church 1983).

The non uniform distribution of riverine habitats occur over different spatial scales. For example, a several meter-long scour pool around a log can be imbedded within a larger one hundred meter pool – riffle sequence within a meander, a habitat unit further contained within an unconstrained floodplain valley segment kilometers long. This well recognized spatial hierarchy of river habitats has been the subject of conceptual frameworks (e.g., Frissell et al. 1986; Bisson and Montgomery 1996), field studies (Grant and Swanson 1995; McDowell 2001; Baxter 2001), and it constitutes a fundamental principle in the study of riverine ecosystems (Naiman et al. 1992).

In the remainder of the paper we briefly review each of the 7 habitat forming agents in turn beginning with the largest ones (i.e., tributary confluences and canyons). Next we review the few general principles on how channelized disturbances create or otherwise effect habitat forming agents. Finally we explore the watershed characteristics that constrain the formation of each of the 7 habitat forming agents.

THE SPATIAL ORGANIZATION OF RIVERINE HABITATS

The spatial organization of riverine habitats refers to the type, location, abundance, diversity, and juxtaposition of different channel morphologies, including pools, riffles, side channels, floodplains, log jams, terraces, and substrates of various sizes. The spatial organization also refers to the size of habitat patches and spacing between various channel and floodplain features, including those that scale with river size such as channel meanders (pool – riffle sequences), log jams, and tributary confluence effects (e.g., Figure 1).

Riverine ecologists have traditionally drawn from principles of fluvial geomorphology in conceptualizing the physical attributes of riverine habitats and their spatial distribution in river networks. Early work in geomorphology focused on gradual downstream gradients in central tendencies of physical processes and forms (i.e., spatial and temporal averages), including channel slope, width, and depth (Dunne and Leopold 1978; Leopold and Maddock 1953; Leopold et al. 1964); flow (Dunne and Leopold 1978); sediment transport and deposition (Schumm 1977); bank erosion (Hooke 1980); and channel process and form (Church and Kellerhals 1978). Downstream central tendencies in hydraulic-geometry were then used by aquatic ecologists to make ecological predictions, such as average downstream changes in ecosystem properties in the River Continuum Concept (Vannote et al. 1980). Moreover, spatially averaged central tendencies in channel slope, sediment supply, transport potential, and channel morphology are used to classify physical channel attributes into geographically-independent domains reflecting basin or stream size (Rosgen 1994; Montgomery and Buffington 1997). Spatially averaged approaches, by definition, do not account for the heterogeneous nature of habitat distribution. In this paper, we take an alternative approach, focusing on morphological variations, rather than mean states.

RIVER NETWORK EFFECTS VIA POPULATIONS OF TRIBUTARY CONFLUENCES

Riverine ecologists have recognized the potential importance of tributary confluences within the context of entire river networks (Bruns et al. 1984; Fisher 1997; Rice et al. 2001; Poole 2002) (e.g., Figure 2). Nevertheless, the role of confluences as sources of habitat and heterogeneity is not well articulated in part because the focus has been on defining central tendencies of river behavior, not quantifying deviations from gradual downstream change.

Consistent flow-related hydraulic changes in channel morphology (i.e., pools and associated bars) at junctions occur when the ratio between tributary discharge (or drainage area) and mainstem discharge (or drainage area) exceeds 0.6 to 0.7, although more random hydraulically related changes can occur at smaller discharge ratios (Rhoads 1987). Similarly, an analysis of 168 junctions spanning 550 km of river and 6 orders of magnitude in drainage area revealed that the likelihood of observing significant fan- or sediment related changes in channel morphology in mainstem rivers at junctions (i.e., changes in substrate size, floodplain width, terrace formation, and logjams) increased with the size of the tributary relative to the mainstem in both humid and semi arid landscapes (Benda et al., accepted) (Figure 3). The field data were used to develop logistic regression equations (Figure 4) in which the probability of tributary junction effects can be predicted (Benda et al. submitted). For example, river networks contain a population of tributaries of varying sizes and the likelihood of junction effects is predicted to vary throughout a network (Figure 5). The undifferentiated morphological effects predicted to

occur at junctions includes increases in substrate size downstream, decreases in substrate size upstream, and floodplain widening and increased occurrence of bars, terraces, and side channels. Because of the changing morphology at junctions, these areas in the network are predicted to have higher morphological heterogeneity, including increased hyporheic flow.

The scale of tributary junction effects, both in the length of channel affected and the distance between junctions, scales with the size of the basin. Larger tributaries are required to create junction effects in larger rivers (Figures 3 and 4). There is a general tendency for tributaries of increasing size to be separated by an increasing distance downstream, particularly in oval shaped basins containing dendritic networks (e.g., Figure 5) (Benda et al., accepted). For instance, at drainage areas less than 10 km^2 the distance separating tributaries with morphological effects (typically debris flow fan effects in humid environments) is on average several hundred meters. In larger drainage areas between 100 and 380,000 km^2, the distance separating tributaries with effects ranges between 2.2 and 66 km (Figure 6). Hence, the downstream increase in spacing between junctions having effects reflects a scale dependency with river size (e.g., Figure 1). The spatial pattern of tributary junction effects also will be influenced by the density of tributary junctions, a property governed in part by drainage density and network geometry (Benda et al. accepted).

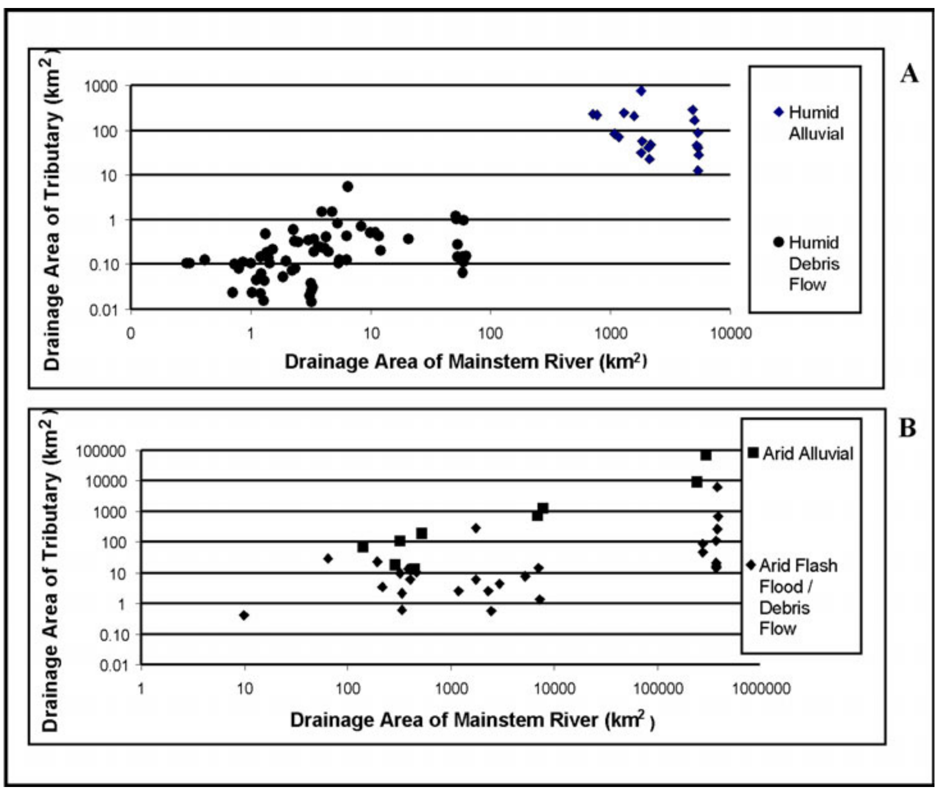

Figure 3. Scaling relationship between tributary basin area and mainstem drainage area for tributaries where junction effects have been documented at 168 sites across 550 km of river in humid and semi arid river systems. The data reveal that larger tributaries are required to impact the morphology of mainstem rivers (adapted from Benda et al. accepted).

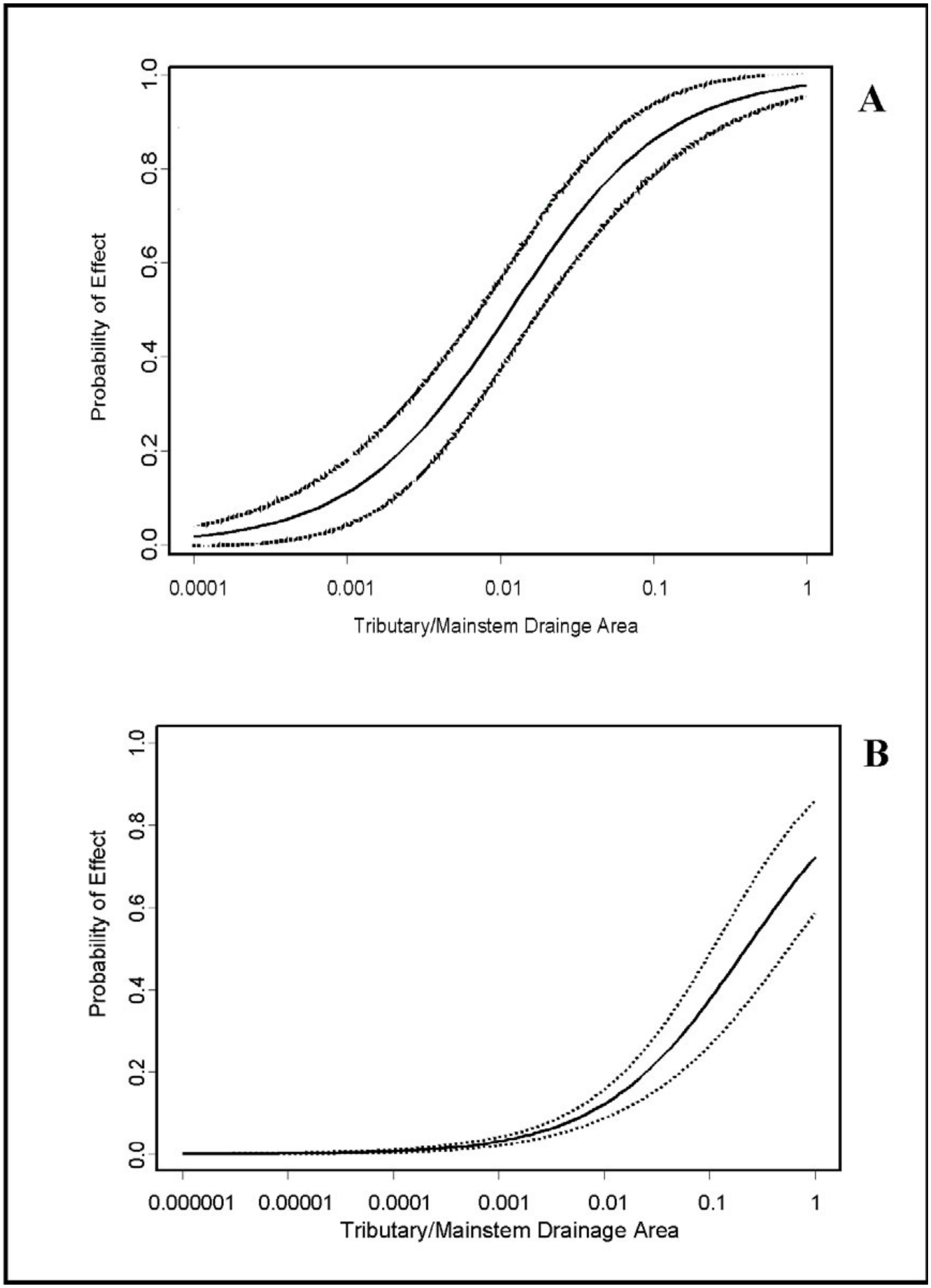

Figure 4. **Logistic equations are used to estimate the probability of confluence effects based on the data shown in Figure 3 for humid (A) and semi arid (B) environments. Dashed lines show 95% confidence limits.**

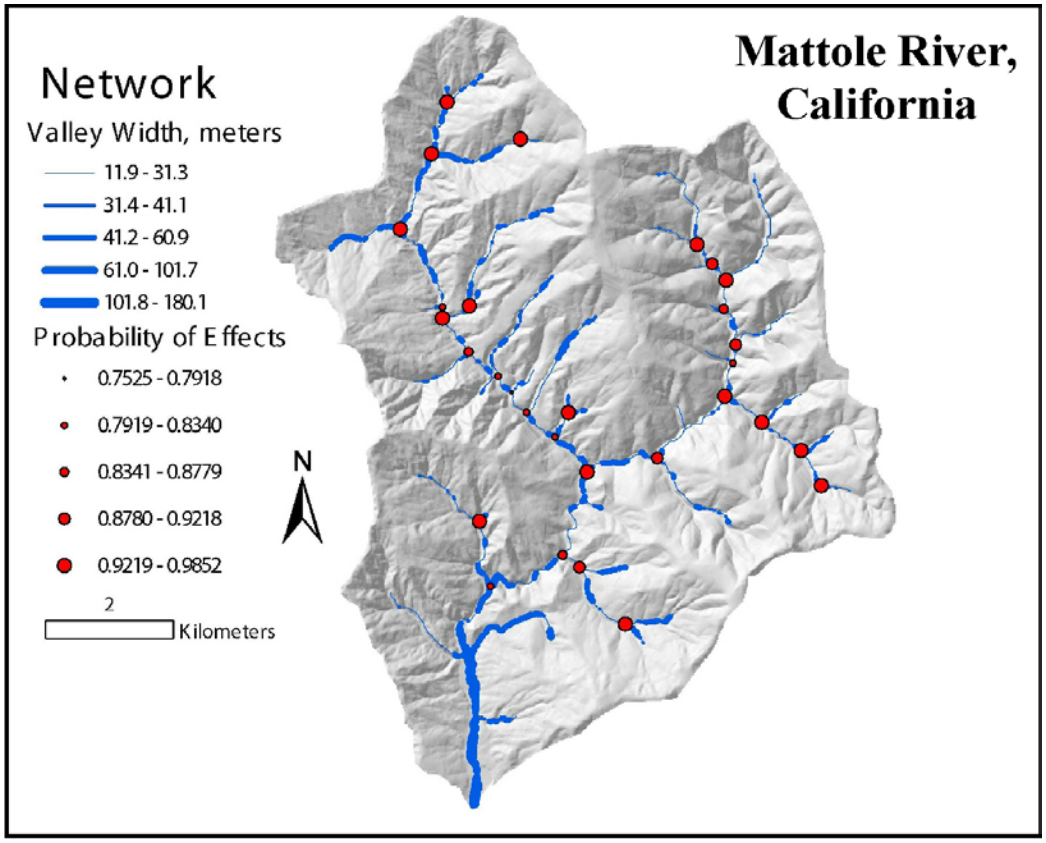

Figure 5. **An illustrative application of the logistic regressions (Figure 4) reveals how basins that contain a diversity of tributary sizes leads to variation in the probability of junction effects.**

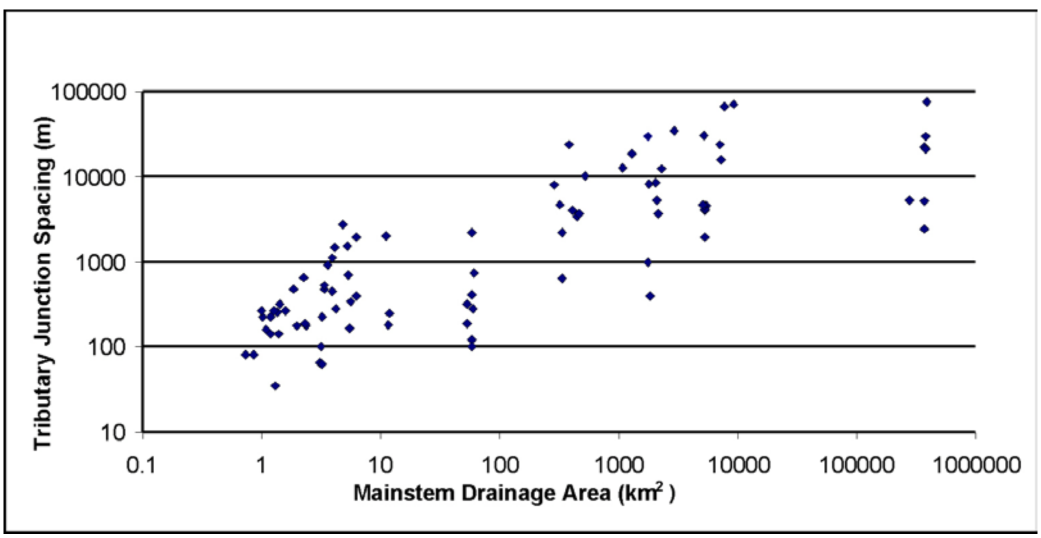

Figure 6. **The distance separating junction effects increases downstream for studies recording more than one confluence. Data used are those in Figure 3. Adapted from Benda et al. submitted.**

ALTERNATING CANYONS AND FLOODPLAIN VALLEY SEGMENTS

The longitudinal sequence of alternating canyons and floodplain segments are sources of habitat development and heterogeneity in watersheds (Frissel et al. 1986) (Figure 1). Although valley width is influenced by sediment deposits that form at tributary confluences (Baxter 2001; Benda et al. 2003a), and by large landslides and earthflows (Grant and Swanson 1995), variation in valley width may also arise from variation in rock types and their erodibility (McDowell 2001). Typically, wide valley floors promote wide floodplains (Grant and Swanson 1995; Benda et al. 2003a,b), higher sinuosity (McDowell 2001), deeper pools (McDowell 2001), greater side channels (Baxter 2001), increased gravel substrate (Perkins 2000; Benda et al. 2003b), and valley parallel channel, often referred to wall-based channels . For example, a 50 km-long segment of the John Day River located in eastern Oregon (Figure 7) consists of alternating canyons and floodplain segments where wide valleys are characterized by higher sinuosity, 80% more pool area, and 40% deeper pools compared to narrow valley segments (McDowell 2001). Furthermore, wide valleys contained more pool – riffle morphology compared to canyons that were dominated by plane bed morphology and cobble beds. Similar patterns have been observed in the Wenaha and Snake Rivers in eastern Oregon (Baxter 2001).

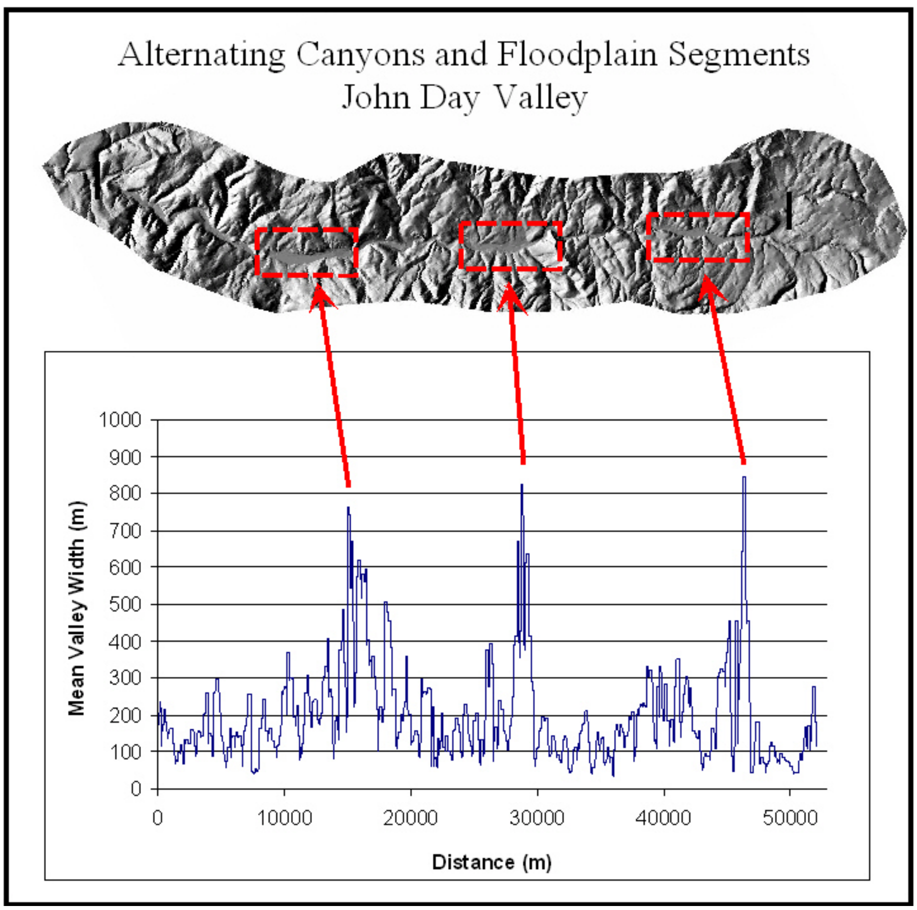

Figure 7. Sequence of alternating canyons and floodplain segments in the John Day River is revealed in digital elevation data showing variation in valley widths. Adapted from McDowell 2001.