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# Confluence effects in rivers: Interactions of basin scale, network geometry, and disturbance regimes

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[1] We reviewed 14 studies documenting the effects of tributaries on river morphology at 167 confluences along 730 km of river spanning seven orders of magnitude in drainage area in western United States and Canada. In both humid and semiarid environments the probability of observing significant confluence-related changes in channel and valley morphology due to tributary influxes of sediment (e.g., changes in gradient, particle size, and terraces, etc.) increased with the size of the tributary relative to the main stem. Effects of confluences on river morphology are conditioned by basin shape and channel network patterns, and they include the nonlinear separation of geomorphically significant confluences in river networks. Other modifying factors include local network geometry and drainage density. Confluence-related landforms (i.e., fans, bars, terraces, etc.) are predicted to be dominated by older features in headwaters and younger features downstream, a pattern driven by the frequency and magnitude of floods and punctuated sediment supply that scale with watershed size. *INDEX TERMS:* 1824 Hydrology: Geomorphology (1625); 1815 Hydrology: Erosion and sedimentation; 1821 Hydrology: Floods; 1848 Hydrology: Networks; *KEYWORDS:* confluences, fluvial geomorphology, river networks

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## 1. Introduction

[2] The abrupt meeting of two channels each having independent flow and sediment discharge regimes creates unique erosional and depositional environments with consequent changes in channel morphology at confluences [*Miller*, 1958; *Best*, 1986]. Previous work on tributary effects on main stem morphology focused primarily on changes in hydraulic geometry (i.e., width, depth, and form ratio) due to changes in flow discharge between tributaries and main stems [*Mosley*, 1976; *Best*, 1988]. Changes in hydraulic geometry at confluences were evaluated in terms of the ratio between discharge (or its surrogate drainage area [*Miller*, 1958]) among the minor tributary ($Q_2$), major tributary ($Q_1$), and the main stem downstream of the confluence ($Q_0$) [*Roy and Woldenberg*, 1986]. Consistent morphological changes in the anticipated directions (i.e., channel width increases below the confluence, etc. [see *Leopold et al.*, 1964]) occurred when the symmetry ratio ($Q_2/Q_1$) approached approximately 0.6 to 0.7, indicating a threshold relationship between tributary and main stem river sizes [*Rhoads*, 1987]. Although others have documented different types of changes in channel and valley morphology (i.e., bars, rapids, terraces, logjams, etc.) due to large influxes of sediment and wood from tributaries [*Small*, 1973; *Church*, 1983; *Benda*, 1990; *Wohl and Pearthree*, 1991; *Pizzuto*, 1992; *Grant and Swanson*, 1995; *Hogan et al.*, 1998; *Benda et al.*, 2003a, 2003b], there has been no similar size threshold analysis.

[3] Abrupt introduction of sediment and organic material at tributaries trigger numerous types of changes in morphology in the vicinity of confluences. Large fans can displace a channel across the valley floor, creating a local constriction in valley width and channel steepening proximal to deposits [*Grant and Swanson*, 1995] and a corresponding valley widening and gradient shallowing upstream [*Small*, 1973; *Benda et al.*, 2003b]. Channel gradient-induced longitudinal variations in sediment transport rate reduce substrate size and increase floodplain width upstream of confluences, offset by other tendencies on the downstream side of confluences including coarser substrates, increased channel width, increased pool depth, and increased occurrence of bars (see Table 1).

[4] Morphological effects at confluences also reflect the occurrence of storms, fires, and floods that trigger transient increases in sediment supply that rejuvenate fans and associated landforms such as bars and terraces. Three main

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**Table 1.** Series of Field Studies Which Have Documented the Morphological Effects of Tributary Confluences on Mainstem Rivers in Both Nonregulated and Regulated (Dammed) Rivers Across the Western United States and Canada[a]

| Location | Source[b] | Climatic Region | Type of Fan[c] | Tributary Stream Area, km$^2$ | Main Stem Stream Area,[d] km$^2$ | Morphological Effects[e] |
|---|---|---|---|---|---|---|
| Olympic Mts., WA, Sekiu | 1 | humid | debris flow (20) | 0.02–0.73 | 0.67–4.2 (4.05 km) | A, B, D, G, K |
| Ash Cr, Arizona | 2 | arid | flash flood (1) | 0.42 | 9.8 | D, F |
| Queen Charolotte Islands, British Columbia | 3 | humid | debris flow (25) | 0.11–5.6 | 0.3–12.0 (11.8 km) | K |
| Olympic Mts., WA, Matheny and Sitkum | 1 | humid | debris flow (2) | 0.37 | 20.3 | A, B, D, G, J, K |
| Coast Range, Oregon | 4 | humid | debris flow (6) | 0.08–0.27 | 0.8–30 (1.26 km) | A, B, C, D, E, F, G, H, J, K, L, N |
| Sheep Creek, Idaho | 5 | semiarid | alluvial (1) | 26.6 | 64.6 | A, B, C, D, G |
| Lookout Creek, Oregon Cascades | 6 | humid | debris flow (10) | 0.11–3.0 | 51–71 (4.4 km) | E, F, G |
| Crooked River, Idaho | 5 | semiarid | alluvial (1) | 3.4 | 219 | A, B, C, D, G |
| Bear Creek, Colorado | 7 | semiarid | flash flood (3) | 5.9–23.9 | 193–407 (22.4 km) | E |
| N. Fk. Boise River, Idaho | 5 | semiarid | alluvial (4) | 0.6–29 | 322–461 (6.6 km) | A, B, C, D, F, G, H |
| Wenaha River, Oregon | 8 | semiarid | alluvial (5) | 18–71 | 446–516 (26.1 km) | F, G |
| Snoqualmie River, Washington | 14 | humid | alluvial (4) | 85–750 | 712–1794 (70 km) | A, B, C, D |
| Pine and Sukunka Rivers, British Columbia | 9 | semiarid | alluvial (8) | 23–203 | 1,579–2,145 (47.2 km) | D |
| South Fork Payette River, Idaho | 10 | semiarid | flash flood (1) | 0.55 | 2,470 | E |
| Bella Coola River, British Columbia | 11 | humid | alluvial (7) | 12.8–285 | 4,779–5,421 (22.4 km) | M |
| Middle Fork Salmon River | 12 | semiarid | debris flow/flash flood (8) | 2.5–295 | 1,176–7,096 (180 km) | A, B, E |
| Grand Ronde, Oregon | 8 | semiarid | alluvial (2) | 764–1342 | 6,953–7,781 (70 km) | F,G |
| Snake River, Oregon | 10 | semiarid | alluvial (1) | 9137 | 240,765 | G, F |
| Colorado River/predam | 13 | Arid | alluvial (1) | 14.3–6076 | 280,000–386,800 | A, D,E, I |
| Colorado River/prior to dam | 13 | arid | debris flow/flash flood (9) | 14.3–6076 | 280,000–386,800 ((265 km) | A, D, E, I |
| Colorado River/postdam | 13 | arid | debris flow/flash flood (48) | 0.02–771 | 280,000–386,800 (265 km) | A, D, E, I |

[a] Sites are arrayed according to increasing drainage area. Site locations are shown on Figure 1.

[b] Sources are as follows: 1, *Benda et al.* [2003a]; 2, *Wohl and Pearthree* [1991]; 3, *Hogan et al.* [1998]; 4, *Everest and Meehan* [1981] and *Benda* [1990]; 5, *Benda et al.* [2003b]; 6, *Grant and Swanson* [1995]; 7, *Grimm et al.* [1995]; 8, *Baxter* [2001]; 9, *Rice et al.* [2001]; 10, *Meyer and Pierce* [2003]; 11, *Church* [1983]; 12, *Meyer and Leidecker* [1999]; 13, *Melis et al.* [1995]; 14, *Booth et al.* [1991].

[c] Number in parentheses indicates the number of confluence effects in study.

[d] Number in parentheses indicates the length of the river surveyed in studies detecting more than one confluence effect.

[e] Effects are as follows: A, gradient steepening; B, gradient lowering; C, upstream sediment deposition; D, changing substrate size; E, boulders–rapids; F, terraces; G, floodplains; H, side channels; I, midchannel bars; J, ponds; K, log jams; L, meanders; M, channel instability.

types of punctuated transport processes deliver sediment and organic material to confluences. Debris flows episodically transport a chaotic mixture of sediment, including boulders and logs that may be too large to be moved by the receiving channel [*Johnson and Rodine*, 1984; *Hogan et al.*, 1998]. More frequently occurring floods and associated alluvial sediment transport create stratified deposits at confluences [*Harvey*, 1997]. Flash floods are generated by intense precipitation events, often following fires, and carry extremely high sediment loads creating deposits intermediate between debris flows and alluvial transport [*Costa*, 1988]. The frequency and magnitude of erosional and flood events that resupply confluence-specific fluvial landforms (i.e., fans bars, terraces, etc.) are predicted to scale with basin area [*Benda and Dunne*, 1997; *Church*, 1998], thereby influencing the age distribution of confluence-related landforms and their associated effects on channel morphology.

[5] The role of river network geometry on fluvial process and form also has relevance for riverine ecology. An early and influential conceptual framework, the River Continuum Concept [*Vannote et al.*, 1980], predicted gradual downstream adjustments of biota and ecosystem processes in rivers in accordance with the geomorphic perspective of gradual downstream changes in hydraulic and geomorphic properties averaged over many orders of magnitude in drainage area [*Leopold and Maddock*, 1953; *Leopold et al.*, 1964]. This spatially and temporally averaged and linear perspective of rivers has dominated much of river ecology [*Fisher*, 1997], despite the fact that downstream interruptions in channel and valley morphology (i.e., by confluences, canyons, etc.) are the rule, rather than the exception at the meter to kilometer scale [*Townsend*, 1989; *Grant and Swanson*, 1995; *Montgomery*, 1999; *McDowell*, 2001; *Rice et al.*, 2001]. Consequently, new conceptual frameworks have emerged in river ecology that focus on patchy heterogeneity and stochastic processes, including the patch dynamics concept [*Townsend*, 1989; *Poole*, 2002] and the perspective of "riverscapes" that emphasizes habitat development over multi kilometer scales, similar to the view of landscape ecology [*Fausch et al.*, 2002; *Wiens*, 2002].

[6] At the scale of whole river networks, the hierarchical and branched nature of channels emerges as a potentially important system property that can affect the types and spatial distribution of fluvial processes and related river habitats, yet the significance of river branching is poorly understood (in the sense of *Fisher* [1997]). Consequently, new concepts in the riverine sciences are hindered by the lack of a framework that views rivers as branching networks with ramifications for the nonuniform distribution of fluvial processes and habitats and the organization of disturbance regimes.

[7] Our objective here, and in a companion paper [*Benda et al.*, 2004], is to develop a framework to advance understanding about how river network geometry, coupled with dynamic watershed processes, structure fluvial processes and hence riverine habitats. Our interest is confluence effects over entire networks, where thousands of tributaries, from ephemeral rivulets to major rivers, intersect channels. Like others, we found evidence of a size threshold after examining 168 confluences from 14 studies that spanned 7 orders of magnitude in main stem drainage areas: large tributaries are more likely to affect channel morphology than small tributaries. This intuitive result has important implications when viewed at a scale of a network. The probability of confluence effects based on the size of the tributary relative to the main stem connects basin size, basin shape, network configuration, the power law distribution of channel sizes, local network geometry, and drainage density to the spatial distribution and abundance of physical heterogeneity and habitat diversity in a river basin. For example, the distance separating tributaries large enough to have morphological effects tends to increase nonlinearly downstream. This appears to be a general rule, but the actual patterns of confluence-related morphology are affected by network pattern, local network geometry, and drainage density. Finally, we use simulation modeling to illustrate how dynamic watershed processes influence the age distribution of confluence-related landforms that predicts a higher proportion of older features in headwater channels and increasing proportion of younger features downstream in larger channels.

## 2. Study Sites

[8] We reviewed 14 studies across western United States and Canada that documented localized effects of tributaries on the morphology of main stem rivers due to influxes of sediment and wood (Figure 1 and Table 1). In studies where sampling locations ranged over rivers of significantly different sizes, individual river systems were separated creating 21 sites. Across all study sites, a total of 167 confluences spanning 730 km of streams and rivers were evaluated. Study sites included both unregulated rivers (n = 119) and regulated rivers (i.e., dammed) (n = 48), because reduced floods in regulated rivers could cause smaller tributary basins to have significant confluence effects [*Melis et al.*, 1995]. Drainage areas of tributary basins ranged from 0.02 to 74,068 km$^2$ and drainage areas of main stem rivers ranged from 0.3 to 386,800 km$^2$.

[9] The study sites encompassed a range of depositional environments, including debris flow and alluvial processes in humid environments, debris flows and flash floods in semi arid and arid areas, and alluvial processes in semi arid environments (Table 1). By convention, humid areas correspond to the Pacific Coast, generally west of the north-south trending Cascade or Coast Ranges; semiarid refers to areas east of the humid zone and north of approximately 38° parallel; and arid areas are located south of the 38° parallel.

[10] The 168 confluences were separated into two climate zones reflecting variations in geomorphic processes that could influence depositional environments (i.e., at confluences) and their effects on main stem rivers. We distinguished between humid and semi arid basins (the only arid site was placed into the semi arid category) because flash floods occur predominantly in arid/semiarid areas and can originate from tributary basins significantly larger than basins from which debris flows originate in humid areas (Table 1). In the humid category, we distinguished between "debris flow" and "alluvial" processes, since debris flows are generally limited to headwater areas (i.e., confluences of first- and second-order channels [*Benda and Cundy*, 1990; *Grant and Swanson*, 1995]) and they transport much larger

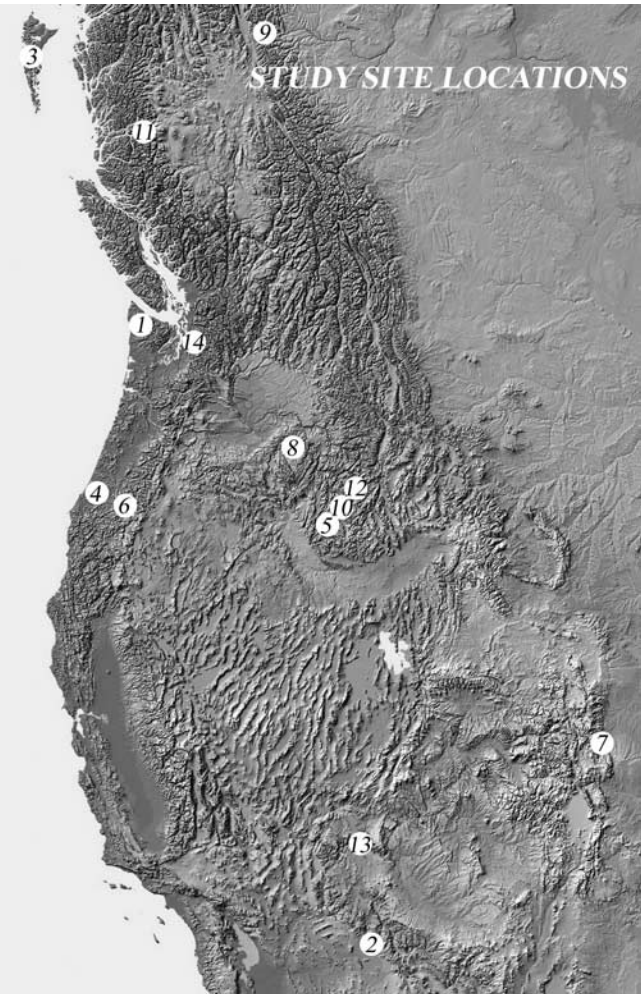

**Figure 1.** Fourteen studies documenting tributary confluence effects in rivers, including changes in substrate sizes, channel and floodplain widths, hydraulic geometry, and in sediment and wood storage, are located across western United States and Canada. 1, *Benda et al.* [2003a]; 2, *Wohl and Pearthree* [1991]; 3, *Hogan et al.*, 1998; 4, *Everest and Meehan* [1981] and *Benda* [1990]; 5, *Benda et al.* [2003b]; 6, *Grant and Swanson* [1995]; 7, *Grimm et al.* [1995]; 8, *Baxter* [2001]; 9, *Rice et al.* [2001]; 10, *Meyer and Pierce* [2003]; 11, *Church* [1983]; 12, *Meyer and Leidecker* [1999]; 13, *Melis et al.* [1995]; 14, *Booth et al.* [1991]. Refer to Table 1 for details.

materials (e.g., large boulders and logs) compared to alluvial processes, and therefore create deposits of different character. The term "flash floods" was limited to semiarid areas, and since flash floods are similar to debris flows in their ability to transport large clasts to fans during extreme runoff events, they were lumped with debris flows into a single category in the semiarid regions ("debris flow/flashflood").

[11] In this paper we concentrate on morphological effects at confluences related to tributary sources of sediment and wood, although our analysis of the influence of river network geometry should also apply to flow-related changes in morphology in less erosion prone and lower relief landscapes [e.g., *Best*, 1986; *Rhoads*, 1987]. We do not analyze confluence effects at river anabranches in braided river systems.

## 3. Methods

[12] By definition, a tributary is the smaller of two intersecting channels (i.e., and their drainage areas) and the larger is the main stem. Strictly speaking a tributary confluence is defined as the point where two streams meet. A broader definition is used in this paper, where a tributary confluence consists of the valley floor environment influenced by a tributary, including fans, terraces, secondary channels, and wider floodplains.

[13] On the basis of previous studies [*Roy and Woldenberg*, 1986; *Rhoads*, 1987] we postulate that sediment-related effects of tributary confluences on the morphology of main stem channels depend on the size of the tributary relative to the size of the main stem. For instance, larger basins typically produce larger quantities of sediment, so that larger tributaries generally create larger fans [*Bull*, 1964; *May and Gresswell*, 2003]. In addition, the size of main stem channels should influence the ability of tributary inputs of sediment to affect their morphology, a relationship identified in headwater areas with humid environments [*Benda et al.*, 2003a]. Since main stem channels increase in size and energy downstream, increasingly larger tributaries should be required to create significant confluence effects as river size increases.

[14] At each of the 21 study locations listed in Table 1 (with the exception of Canadian sites), 10-m digital elevation models were used to measure the drainage area of the tributary basin and the corresponding drainage area of the main stem river (i.e., drainage area is used as a surrogate for sediment and water discharge). Main stem drainage areas were measured immediately upstream of the intersecting tributary. For sites in western Canada, topographic maps (scale 1:50,000) were used to determine drainage area of tributary and receiving channels. In the analyses that follow, we refer to confluences that have observable morphological effects (see Table 1) as "geomorphically significant confluences".

[15] Along those river segments where field studies documented more than one confluence effect, we assumed that other tributaries did not have a significant morphological effect because of their lack of description in the studies. Observing confluence effects is probably related to a scale-dependent perception of environments, where the size of the feature that is noticed and measured scales with the size of the environment. Therefore tributaries that are assumed to have no effects actually may have had smaller effects that were not documented. Hence our distinction between "effects" and "no effects" in our analysis is more likely a distinction between noticeably large and imperceptivity small effects; however, it was not possible to assess this scale issue in our retrospective study. DEMs and topographic maps were then used to determine the drainage areas of those tributaries not having a significant confluence effect and of main stem rivers (Table 1).

[16] Using 10-m DEMs (and topographic maps for sites in Canada), we also calculated the distance separating individual tributaries reported to have morphological effects at those study sites that had more than one confluence. These data comprised 84 confluences (Table 1).

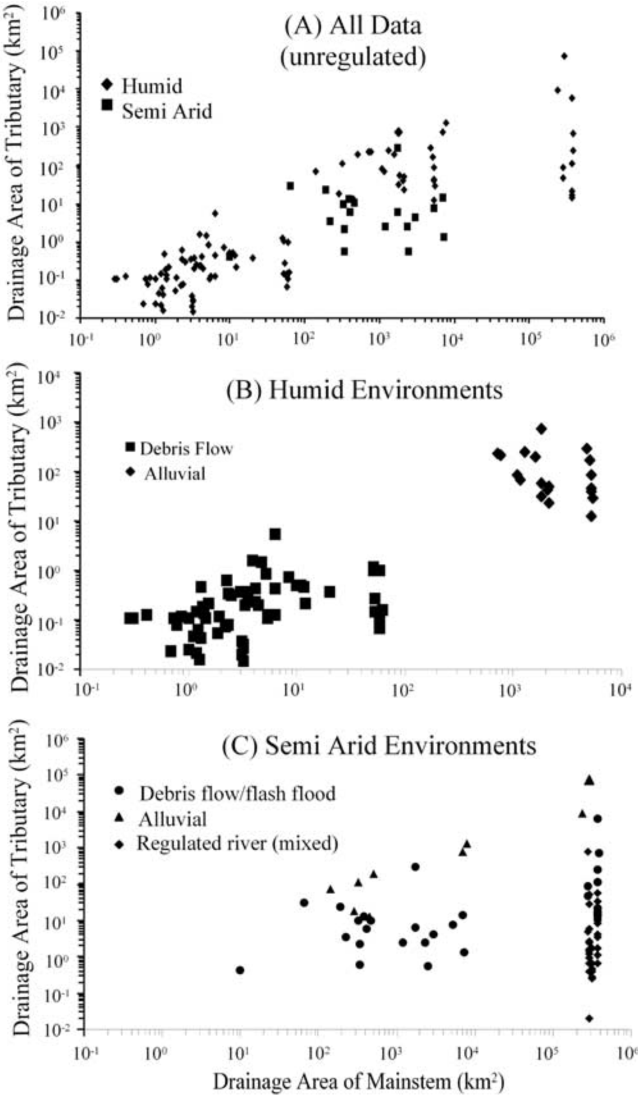

**Figure 2.** Comparison between drainage areas of tributaries and main stem channels for 168 geomorphically significant confluences: (a) all sites (regulated rivers only), (b) humid environments (unregulated rivers), and (c) semiarid environments, including data from a regulated river.

[17] The set of tributary–main stem pairs (i.e., the symmetry ratio of drainage area), divided between those with and without effects, were used to estimate the probability that a tributary will influence main stem channel attributes. We did not distinguish among sites based on either magnitude or type of confluence effect given the disparate data across the 14 studies and our retrospective approach. The cumulative distribution of tributary-to-main stem-area ratios for tributaries with effects was used to fit a logistic regression for both humid and semiarid sites.

[18] Finally, a stochastic simulation model was used [*Benda and Dunne*, 1997a, 1997b] to estimate the age distribution of fan landforms in one of the study landscapes (Oregon Coast Range) to infer how frequency and magnitude of erosion and sediment transport could influence the age distribution of confluence-related landforms, such as fans, terraces, and floodplains.

## 4. Results

### 4.1. Confluence Effects: Tributary Versus Main Stem Basin Size

[19] Comparison between tributaries and their respective main stems reveal a general pattern in which larger tributary basins are associated with confluence effects in larger rivers (Figure 2a). The relationship is particularly evident in humid areas for main stem drainage areas between 1 and 7000 km$^2$ (Figure 2b). In humid areas, effects of debris flows at confluences are restricted to main stem drainage areas of less than approximately 50 km$^2$, while alluvial effects are limited to main stem drainage areas greater than approximately 500 km$^2$. There is a gap in the data between approximately 50 and 500 km$^2$. Although data from semiarid areas could partially fill the gap (e.g., Figure 2c), the two climate types were separated in our analysis. Debris flow effects in humid areas are associated predominantly with tributaries of less than approximately 1 km$^2$. Hence debris flow effects occupy a distinct drainage area domain relative to alluvial effects, and collectively they demarcate an envelope in which larger tributaries are associated with confluence effects in larger rivers (Figure 2b).

[20] The relationship is less distinct in semiarid rivers, although it is helpful to consider alluvial and flash flood/debris flow sites separately in unregulated rivers only (Figure 2c). There are several interesting patterns evident in the semiarid data. First, there is little field data in main stem rivers below approximately 100 km$^2$. The reason for this is unclear. An absence of studies of fluvial morphology at small drainage areas in semiarid environments might be due to a lack of water flow, particularly in the summer that would reduce potential for aquatic life and other interesting aspects of aquatic ecosystems, thereby discouraging field studies. Although there is a general trend where larger tributaries are associated with confluence effects in larger rivers in unregulated fluvial systems, it is most apparent for the alluvial data set (Figure 2c). The relationship is less distinct for debris flow/flash flood sites. The large degree of scatter is due, in part, to the overlap between alluvial processes and debris flow/flash flood processes across the entire range of main stem drainage areas, from 100 to 400,000 km$^2$. Compared to larger alluvial tributaries, the ability of small tributaries to affect larger channels is likely due to the large boulders contained in debris flow and flash flood deposits in semiarid areas [*Melis et al.*, 1995]. The data suggest that both flash flood/debris flow and alluvial transport processes can occur in the same tributary basin size range, although for any given main stem drainage area, debris flow/flash floods generally originate from smaller tributary basins compared to basins categorized as alluvial (Figure 2c).

[21] Data on confluence effects from a regulated river (Colorado River located below Glen Canyon dam) are added to the semiarid data in Figure 2c. Tributary-main stem drainage area pairs for regulated rivers occupy a distinct domain in the plots. For example, tributary basins of between 0.25 and 50 km$^2$ create confluence effects in the

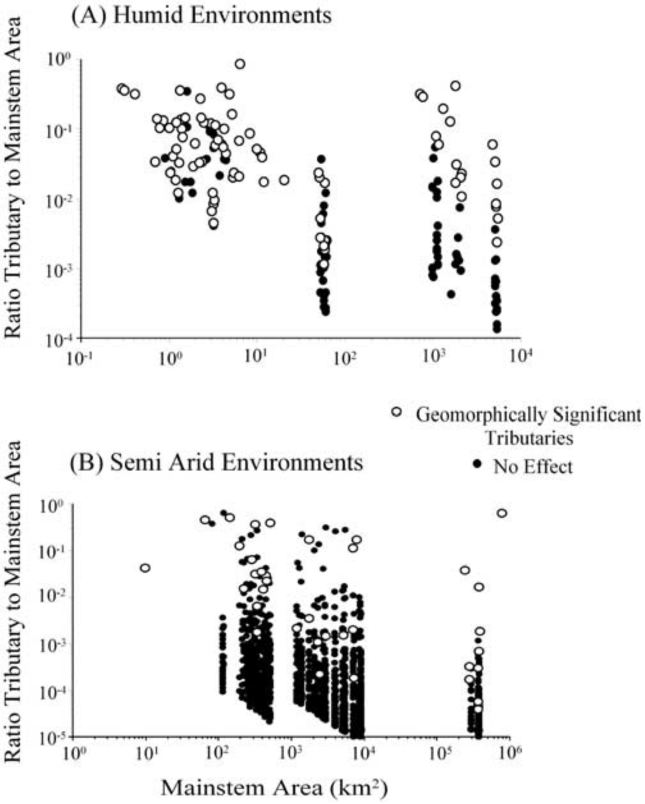

**Figure 3.** Ratio of tributary to main stem drainage area compared to main stem drainage area for geomorphically significant confluences and tributaries without effects for both (a) humid and (b) semiarid environments.

dammed Colorado River at a main stem drainage area of approximately 300,000 to 400,000 km$^2$. In contrast, tributary confluence effects documented in the predammed Colorado River are associated with tributaries ranging in area between 10 and 10,000 km$^2$. The data suggest that reduced floods in the dammed Colorado River resulted in smaller tributaries having confluence effects compared to predam flow conditions, a conclusion reached by others [*Melis et al.*, 1995].

[22] The data in Figure 2 also reveal a threshold in which tributary basins less than approximately 1 km$^2$ do not affect main stem rivers greater than approximately 50 km$^2$, a pattern particularly evident in the humid sites. Because approximately 80% of all channels (and their associated confluences) in a humid drainage networks have areas less than approximately 1 km$^2$ [*Benda and Dunne*, 1997a], reflecting the universal power law distribution of channel sizes [*Horton*, 1945], the threshold seen in Figure 2 indicates that only a small fraction of the third- and higher-order channels in a network can impact the morphology of rivers of drainage area greater than 50 km$^2$. This finding has important ramifications for the scale of morphological variability imposed on rivers by confluences, including the downstream spacing of confluence effects as main stem river size increases (discussed below).

### 4.2. Estimating the Probability of Confluence Effects

[23] We estimated the probability that a tributary would affect the morphology of a main stem river using the ratio of tributary to main stem drainage areas (symmetry ratio); this approach is different from the more deterministic approaches used previously to describe confluence effects [e.g., *Rhoads*, 1987]. Using data from unregulated rivers only (e.g., Figure 2a), the ratio of tributary to main stem drainage area for tributaries with confluence effects (i.e., geomorphically significant tributaries) and without effects is plotted in Figure 3. There are more data points for semi arid areas because of the longer stretches of river involved (Table 1). The data reveal that for any main stem drainage area, the proportion of geomorphically significant tributaries increases as tributary size increases (i.e., as the symmetry ratio increases). For instance in humid environments at a main stem drainage area of approximately 5000 km$^2$, most tributaries without effects have a drainage area of less than 1/500 of the main stem area (0.002), or less than 10 km$^2$ (Figure 3a). The majority of geomorphically significant tributaries have drainage areas between 1/140 (0.007) and 1/16 (0.06) of main stem drainage area, corresponding to tributary drainages between 35 and 300 km$^2$. The distinction between geomorphically significant tributaries and tributaries without effects is less for main stem areas less than 10 km$^2$, a channel size dominated by debris flows in humid environments (e.g., Figure 2b). This likely reflects the widespread ability of debris flows originating from a range of first- and second-order tributary sizes (but less than 1 km$^2$) to effect morphology of main stem channels of approximately less than 50 km$^2$.

[24] Data in Figure 3 are used to estimate the probability that a tributary will affect channel morphology, given any main stem drainage area. The data were binned by symmetry ratio and a logistic regression used to describe the proportion of tributaries having effects within each bin. The logistic model specifies the probability of geomorphically significant tributaries as:

$$P_e = \exp(g(x))/(1 + \exp(g(x))) \tag{1}$$

where $P_e$ is the probability that a tributary will affect the morphology of a main stem river and g(x) is fitted to the data in Figure 3. Effects in main stem channels are defined very generally as those listed in Table 1 and are not differentiated according to type or magnitude.

[25] Using data in Figure 3a for humid environments, the regression is:

$$g(x) = 3.79 + 1.96 \log(t_a/m_a) \tag{2}$$

where $t_a/m_a$ is symmetry ratio. On the basis of this equation, there is an 85% probability that a tributary with drainage areas 1/10 that of the main stem will create an observable effect (Figure 4a). The probability decreases to less than 10% for tributary basins less than 1/1000 (0.001) the size of the main stem.

[26] A logistic regression was also made using the data from semiarid areas (Figure 3b):

$$g(x) = 0.96 + 1.47 \log(t_a/m_a) \tag{3}$$

The regression for semiarid areas is more skewed, in part because of the lack of data at small main stem drainage

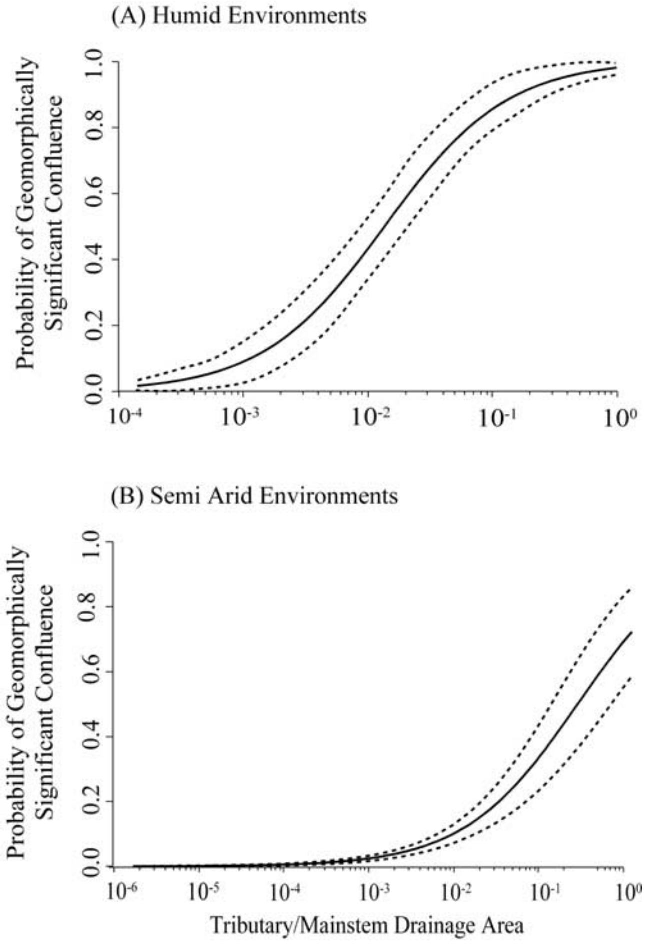

**Figure 4.** Logistic regression equations are created from the ratio of tributary to main stem drainage areas to predict the probability of geomorphically significant confluences (using data from Figure 3) for (a) humid environments and (b) semiarid environments. Dashed lines indicate 95% confidence intervals.

areas (i.e., <100 km$^2$), and attains a maximum of only P = 0.8, in part due to the few data points with high symmetry ratios at large main stem drainage areas (Figure 4b). This result suggests that a greater proportion of tributaries in semiarid climates are less likely to affect main stem channels than those in more humid climates (a potential consequence of regionally specific disturbance regimes, see section 5.5).

[27] The probabilities calculated likely do not simply reflect a dichotomous "effect" or "no effect," but rather, they likely pertain to the magnitude of morphological effects conditioned by the spatial scale of the environment. For example, in large rivers an observer's attention is drawn to tributary related features that create morphological effects of a scale similar to the river itself (i.e., large bars, meanders, terraces, etc.), while smaller effects (a few boulders at the base of a small tributary and a small patch of sediment) are probably ignored. Nevertheless, the relative magnitude of morphological effects (i.e., noticeably large, imperceptivity small) that is predicted by the probability functions has important physical and ecological ramifications. For example, large changes in fans, terraces, and bars, and hence in hydraulic geometry, have large implications for sediment transport and deposition compared to small changes in morphology, and likewise larger riverine habitats provide a larger niche space and habitat persistence in the face of various disturbances.

[28] The logistic regression predictions of how the symmetry ratio of drainage area affects confluence morphology apply to an undifferentiated range of channel changes (i.e., changes in substrate size, channel width, extent of floodplains and terraces, etc.), although effects can be broadly stratified according to upstream and downstream position relative to confluences (i.e., substrate fining upstream and coarsening downstream, etc. [see *Benda et al.*, 2004]). It is presently infeasible to develop quantitative predictions about specific morphological changes at confluences due to the resolution of data (e.g., Table 1) and the complex nature of riverine environments [*Rhoads*, 1987]. Changes in morphology at confluences may also represent local increases in physical heterogeneity [e.g., *Benda et al.*, 2003a] defined by the type, form, and age distribution of fluvial landforms, an attribute that has relevance for river ecological processes [*Huston*, 1994].

### 4.3. Spacing of Confluence Effects

[29] DEMs and topographic maps (for the Canadian sites) were used to measure the distance between geomorphically significant confluences in main stem rivers (Table 1). Eighty-four sites in unregulated rivers and 45 sites located in the Colorado River below Glen Canyon dam are plotted in Figure 5; humid and semiarid environments are combined. Two patterns are apparent. First, the distance between geomorphically significant confluences increases with increasing drainage area of main stem rivers. At drainage areas of less than 10 km$^2$, the distance separating tributaries with effects (typically debris flow effects in humid environments) is several hundred meters on average. For example, in upper portions of humid mountain drainage basins (e.g., drainage areas less than approximately 10 km$^2$ in the Oregon Coast Range, Queen Charlotte Islands, British Columbia, and Washington's

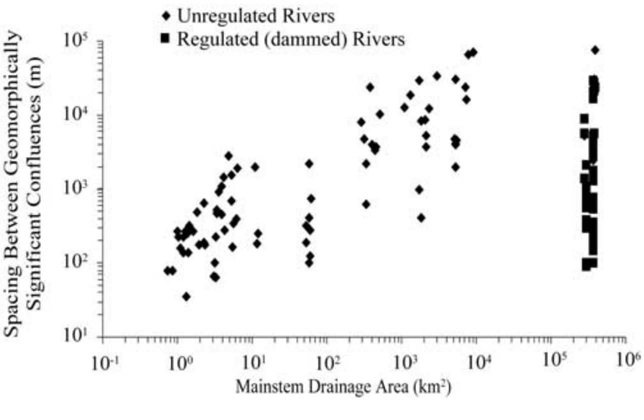

**Figure 5.** The distance separating geomorphically significant confluences for studies (listed in Table 1) recording more than one confluence. Note the altered pattern in the regulated Colorado River.

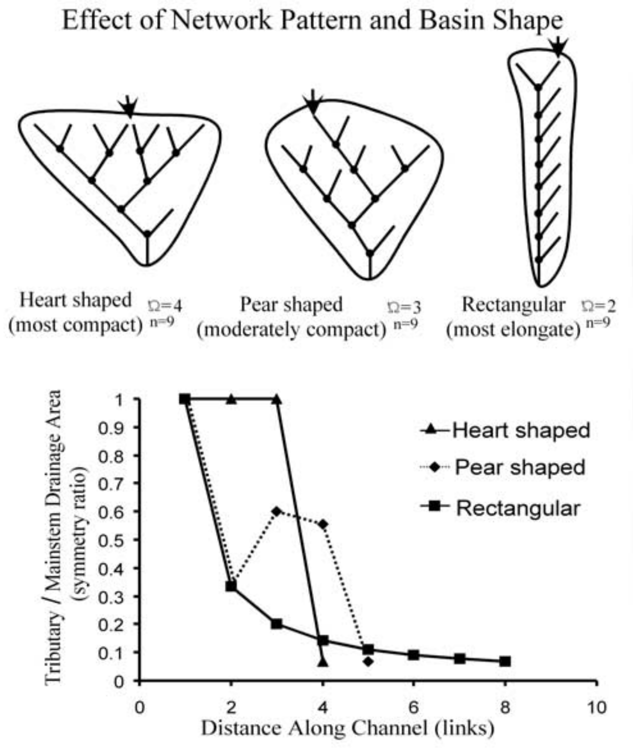

**Figure 6.** Basin shape and associated network patterns affects the downstream sequence of tributary-main stem drainage area ratios and hence the sequence of geomorphically significant confluences (each stream link in the networks shown has a drainage area of unity). Heart- and pear-shaped basins favor geomorphically significant confluences throughout the main stem channel. Rectangular basins do not support increasing tributary size downstream, and hence confluence effects should be limited. The arrows on the top of the basins indicate the head of the main stem channel that is plotted. Ω refers to Strahler stream order, and n refers to Shreve link magnitude.

Olympic Mountains, Table 1), debris flows that create boulder deposits, gravel accumulations, and log jams at confluences occur about every 200 m in third- and fourth-order channels, the average distance separating low-order tributaries [*Benda*, 1990; *Hogan et al.*, 1998; *Benda et al.*, 2003a]. In contrast, in midsize basins in semiarid areas (e.g., drainage areas of 350 to 520 km$^2$ in Oregon's Wenaha River and Idaho's Boise River, Table 1), the distances separating tributary confluence effects are between 10,000 and 600 m [*Baxter*, 2001; *Benda et al.*, 2003b]. Distances between confluences with effects pre-dam in the Colorado River ranged between 2.7 and 139 km (average 44 km) compared to 0.1 to 29 km (average 5.3 km) post dam.

## 5. Discussion

### 5.1. Role of Basin Shape and Network Configuration on Confluence Effects

[30] The scaling relationship between sizes of main stem rivers and sizes of tributaries (Figures 2–4) led us to consider the factors that affect the spatial distribution of tributary sizes in river networks. The shape of a drainage basin and the overall configuration of the channel network (i.e., dendritic, trellis, etc.) are related, since the channel network represents fluvial incision and erosion that ultimately sculpts the basin shape. Dendritic networks tend to be contained within heart- or pear-shaped basins (i.e., compact basins) while trellis networks tend to occupy rectangular-shaped or elongate basins (Figure 6). Increasing basin width downstream in heart- or pear-shaped basins creates the opportunity for the coalescing of hierarchical networks into larger channels of increasing order [*Strahler*, 1952] (although link magnitude [*Shreve*, 1966] may stay the same, see Figure 6). This creates tributary basins (those intersecting a main stem channel) of increasing size downstream, a requisite condition for maintaining a high probability of confluence effects downstream along main stem rivers (Figure 6). In contrast, basin width does not significantly increase downstream in rectangular-shaped basins and consequently there is little opportunity for the coalescing of larger channels and hence tributary sizes do not increase significantly downstream. This condition in rectangular-shaped basins containing trellis networks limits the downstream sequence of confluence effects (Figure 6).

[31] Since tributary basin area is related to main stem channel length ($L = 4.63A^{0.47}$, where L is catchment length and A is catchment drainage area [*Mueller*, 1972]), longer tributaries translate into larger tributary basin areas, and hence into catchments having larger widths. Tributaries of increasing width take up more space and hence geomorphically significant confluences are separated by an increasing distance, a pattern seen in the field data (Figure 5). Consequently, basin shape and network configuration relate to the distance between geomorphically significant confluences. For example, compact heart- and pear-shaped basins, in addition to favoring the occurrence of confluence effects, also favor an increasing, nonlinear separation distance between geomorphically significant confluences. In contrast, the more limited confluence effects in rectangular-shaped basins should be more closely spaced. These general inferences are illustrated using a computer model below. Other basin shapes may impose different patterns of tributary confluence effects.

### 5.2. Role of Drainage Density on Confluence Effects

[32] In addition to basin shape and network patterns, density of tributary confluences (i.e., number of confluences per unit area or per unit channel length) should provide an index of the potential net morphological effect of tributary confluences in river basins. Confluence density should positively correlate with drainage density (a relationship ill defined at this point), although it should also be conditioned by basin shape and network configuration, as described above (e.g., Figure 6). Drainage densities in semiarid to humid landscapes range from approximately 12 to 2 km/km$^2$, primarily reflecting variations in precipitation, age of landscapes, and bedrock porosity [*Abrahams*, 1972; *Grant*, 1997]. This large range in drainage density should translate to a corresponding large range in the density of geomorphically significant confluences, with implications for the degree of channel heterogeneity found in different landscapes. Highly dis-

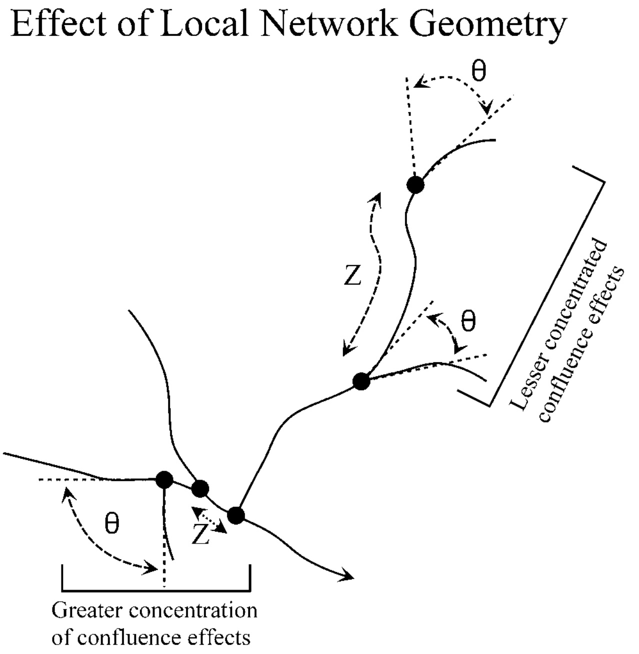

**Figure 7.** Confluence effects are affected by local (kilometer scale) network geometry, including the sequence of tributary sizes, their separation distance, and the confluence angles between tributaries and main stem rivers.

sected landscapes (i.e., high drainage density) are likely more topographically heterogeneous, pointing to a potential relationship between topographic complexity and riverine heterogeneity, via the size and abundance of tributaries. Little is known about how confluence density, and associated channel physical heterogeneity, varies across landscapes and regions.

### 5.3. Role of Network Geometry on Confluence Effects

[33] Local network geometry (kilometer scale) influenced by geologic structure and tectonic and erosional history of a basin should create departures from the general tendencies of confluence effects linked to basin shape, network patterns, and drainage density described above. For example, portions of networks may be characterized by a concentration of large tributaries that are closely spaced (Figure 7). Alternatively, tributaries may be separated by canyons, leading to clumped distributions of intersecting tributaries and isolated confluence-derived physical heterogeneity. In addition, confluence effects may be less pronounced in wide valley floors, where broad terraces or floodplains isolate alluvial or debris flow fans from main stem rivers.

[34] In addition to the size and spacing of tributaries, local network geometry pertains to the angle at which tributaries intersect main stem rivers (e.g., Figure 7). It has been shown by field and flume studies that confluence angle affects the type and degree of confluence effects. In general, as confluence angles approach 90° the likelihood of certain morphological effects due to confluences increases. For instance, *Mosley* [1976] and *Best* [1986] showed how bar size, bar location, and scour depth increased with increasing confluence angle. In addition in debris flow dominated headwater areas, confluence angles greater than 70° promote deposition and consequent confluence effects, while deposition is discouraged at confluences with more acute angles [*Benda and Cundy*, 1990]. Therefore the spatial sequence of sizes, locations, and confluence angles of tributaries in a watershed should influence the spatial distribution of confluence-related morphology.

### 5.4. Predicting the Effect of Network Structure on Confluence Effects

[35] To illustrate how confluence effects might vary across a single river network due to variations in basin shape, overall network patterns, and local network geometry, we applied the regression equation developed for humid environments (equation (2) and Figure 4a) to the Siuslaw River basin (1800 km$^2$) located in the central Oregon Coast Range (Figure 8). The impact of basin shape and network configuration can clearly be seen on the third- and higher-order portion of the network. The long rectangular-shaped subbasin located in the southeast corner of the Siuslaw River basin (i.e., river segment 1, Figure 8) is predicted to have confluence effects primarily near its headwaters with the probability of geomorphically significant confluences declining with distance downstream (Figure 8). This is due to the rectangular shaped basin that limits the sizes of tributaries downstream along the main stem river. In contrast, the more heart-shaped subbasin containing a dendritic network in the northern portion of the Siuslaw River basin (i.e., river segment 2, Figure 8) promotes a greater degree of confluence effects throughout that subbasin because of the larger tributaries that are formed within that basin shape. Significant confluence effects are also indicated for first- and second-order confluences (inset, Figure 8); a prediction in accordance with field evidence in the same area [*Everest and Meehan*, 1981; *Benda*, 1990].

[36] The differences in how basin shape and network configuration regulate confluence effects has ramifications for the spacing of those effects. The downstream increase in the spacing between geomorphically significant confluences shows up clearly throughout the Siuslaw basin (Figure 9a). However, along any specific river segment within the Siuslaw, there are deviations from this general trend because of variations in local network geometry (Figure 9b). In addition, the power law of stream sizes [e.g., *Horton*, 1945], and hence of confluences of those streams, creates a power distribution of distances between geomorphically significant confluences (Figure 9c); the vast majority of the predicted geomorphically significant confluences are separated by less than 500 m (even in the third- and higher-order portion of the network) and involve third- through fifth-order channels with drainage areas less than approximately 50 km$^2$. Hence the spatial scale of morphological variability linked to confluences in whole networks is defined by a power law reflecting the hierarchical branching of river networks.

[37] Predictions based on symmetry ratios alone (e.g., Figure 4) will be conditioned by other factors known to be important in regulating confluence effects, such as the caliber of transported sediment [see *Meyer et al.*, 2001]. For example, in the Oregon Coast Range mechanically weak sandstone bed load may lead to bed load-impoverished channels in some regions of networks [*Benda and Dunne*, 1997b]. Hence, by inference, confluence effects

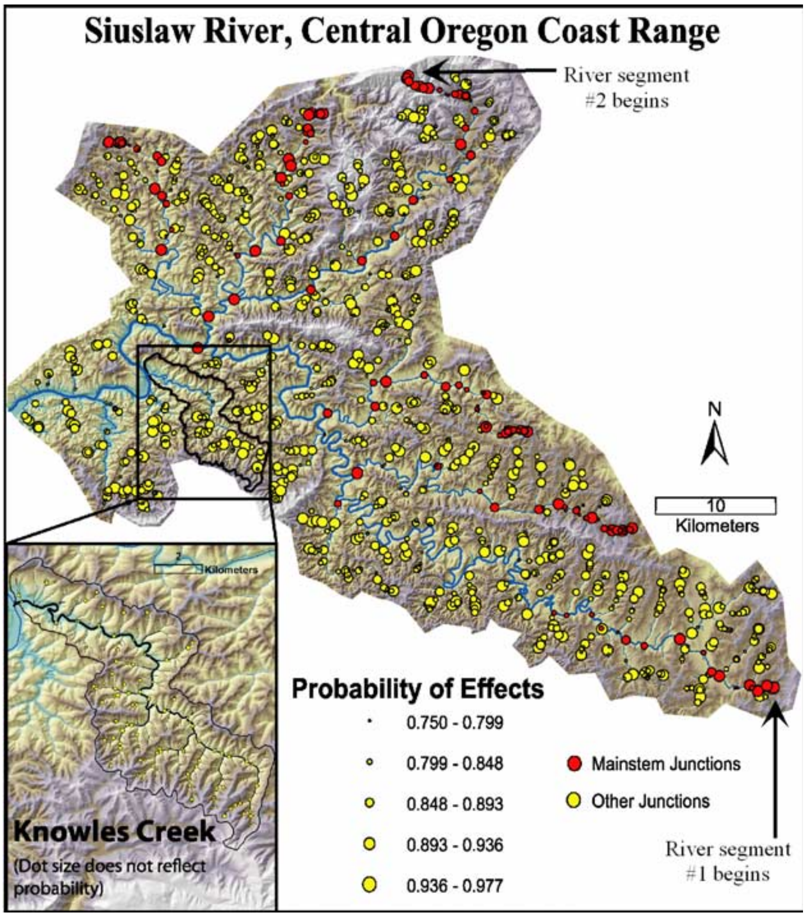

**Figure 8.** The logistic equation predicting tributary junction effects (e.g., Figure 4a) is applied to the Siuslaw River basin in the central Oregon Coast Range. A $P_e > 0.75$ is based on previous proposed thresholds [*Rhoads*, 1987] and for illustrative purposes. Only the third- and higher-order network is shown for the entire basin. The red dots indicate geomorphically significant confluences along the main stem rivers, while the yellow dots indicate geomorphically significant confluences within the tributaries; their diameter denotes the probability of confluence effects. The inset box shows the first- and second-order network; variation in probability represented by dot size is not shown. River segments 1 and 2 refer to Figure 9b.

may be limited in larger rivers in the sandstone terrain of the central Oregon Coast Range, an untested hypothesis at present.

### 5.5. Role of Watershed Disturbances in Regulating Confluence Effects

[38] Alluvial and debris fans and their associated depositional landforms near confluences are formed and rejuvenated during times characterized by accelerated sediment supply to rivers [*Bull*, 1964; *Meyer and Pierce*, 2003]. Consequently, fans and their up and downstream zone of influence expand and contract over time in response to fires, storms, and floods [*Benda et al.*, 2003b]. During periods of low watershed erosion, depositional areas at confluences become eroded and truncated by floods. Conversely, fans enlarge and expand during periods of heightened watershed erosion. Hence the size of a depositional area at a confluence observed at any snapshot in time, and the magnitude of its associated effects in main stem rivers, should vary depending on prior watershed disturbance history. The temporal expansion and contraction of confluence effects is undoubtedly one source of variability in the observed data set (Figure 2).

[39] Confluences are also zones of local disturbance amplification. First, the frequency and magnitude of sediment fluctuations are higher proximal and immediately downstream of confluences due to the punctuated inputs of sediment and water from the tributary. Secondly, areas upstream of confluences that have increased sediment storage may have associated reductions in channel gradients and increases in channel and valley floor widths. These zones may be more responsive to floods and accelerated sediment supply originating from upstream.

[40] The frequency and magnitude of sediment supply fluctuations should vary with tributary size, since the frequency and magnitude of erosion and transport are expected to change systematically with basin size (Figure 10). In theory, the episodic occurrence of accelerated sediment supply and transport should increase in frequency but decrease in magnitude with increasing drainage area. This is due to a suite of factors, including (1) the size distribution of storms whereby the most intense

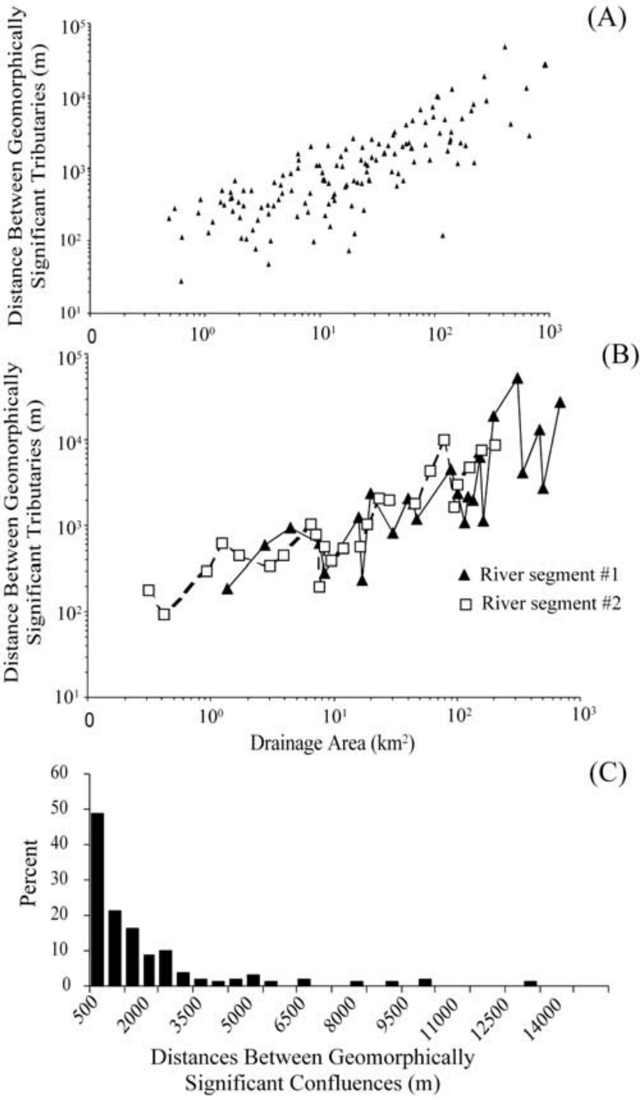

**Figure 9.** (a) Interconfluence spacing for geomorphically significant confluences ($P_e > 0.75$) is predicted to increase with increasing drainage area in the Siuslaw River basin (e.g., Figure 8). (b) Individual river segments (starting from headwaters) reveal large variability in spacing of tributaries (with effects) due to variations in network geometry in the Siuslaw basin; river segments 1 and 2 correspond to those indicated in Figure 8. (c) The frequency of interconfluence spacing of geomorphically significant confluences for the third- and higher-order network.

storms have small spatial extent and generally affect small sub basins rather than entire watersheds [*Church*, 1998]; (2) the number of subbasins increases with increasing drainage area, each potentially capable of generating independent pulses of sediment that then mix and interact downstream; (3) the diffusion and attrition of sediment pulses downstream due to selective transport, temporary sediment storage (e.g., behind bars, in log jams), and particle breakdown; and (4) an increasing store of sediment in larger and lower gradient channels that becomes increasingly more difficult to alter by lower magnitude sediment supply fluctuations. In total, these effects are predicted to lead to a systematically increasing frequency of sediment perturbations downstream but of a decreasing magnitude (Figure 10). The predicted evolution in the frequency and magnitude of sediment perturbations downstream is particularly evident in the probability distributions of sediment storage that varies from highly skewed in the headwaters to more a normal shape downstream (see *Benda and Dunne* [1997a, 1997b] for more detail and *U.S. Department of Agriculture* [2002] for visual simulations).

[41] The changing frequency and magnitude of sediment supply perturbations should have ramifications for the age distribution of confluence related landforms, including surfaces of fans and terraces, etc. For example, fans constructed by debris flows or flash floods at outlets of small basins are formed during periods of high-magnitude sediment supply having a frequency on the order of many decades to centuries [*Benda and Dunne*, 1997a; *Wohl and Pearthree*, 1991; *Meyer and Pierce*, 2003; *May and Gresswell*, 2003]. Hence, at any point in time, the observed age distribution of fans at mouths of small basins should be, by inference, skewed toward older, eroded features that may currently have only minor effects on main stem channels. A simulation model is used to illustrate this point in one of the study landscapes. The model [*Benda and Dunne*, 1997] employs a stochastic series of fires and storms overlaid upon a landscape characterized by landslide-prone bedrock hollows and debris flow-prone first- and second-order channels. The model predicts that in the Oregon Coast Range old fan surfaces (i.e., >160 yrs, Figure 11) dominate the age distribution at low-order tributary confluences because the low frequency of debris flows [see also *May and Gresswell*, 2003].

[42] Moving downstream in larger networks, the frequency of flooding-related sediment supply fluctuations that rejuvenate confluence effects is inferred to be higher based on the frequency and magnitude of sediment supply fluctuations (Figures 10b and 10c). Therefore, on average, the age distribution of fan surfaces and related fluvial landforms both upstream and downstream of confluences at mouths of larger basins should have a higher proportion of younger to middle-aged features (i.e., less than 50 to 100 years). These general patterns can be locally altered in time and space by very large storms or fires that trigger widespread basin erosion (e.g., during hurricanes [see *Hack and Goodlett*, 1960]). For instance, during periods of wildfires and large storms, the age distribution of fan surfaces can shift toward younger ages and a higher proportion of confluences can significantly impact main stem channel morphology. Likewise, climatic changes or changes in landslide rate associated with land use [e.g., *Montgomery et al.*, 2000] should alter the age distribution of fan deposits and hence the degree of physical heterogeneity linked to them.

### 5.6. Applications to Other Physiographic Regions

[43] The data and analysis presented in this paper pertain to mountainous, highly erosive watersheds throughout western United States and Canada (Figure 1 and Table 1). However, our analysis should also apply to other regions, particularly those with mountain terrain, such as the Appalachians where debris flows are a common occurrence in headwaters [e.g., *Hack and Goodlet*, 1960]. Confluence effects have also been documented in less erosion prone landscapes as illustrated by the work of *Mosley* [1976], *Best* [1986, 1988], *Rhoads* [1987], and *Pizzuto* [1992] among

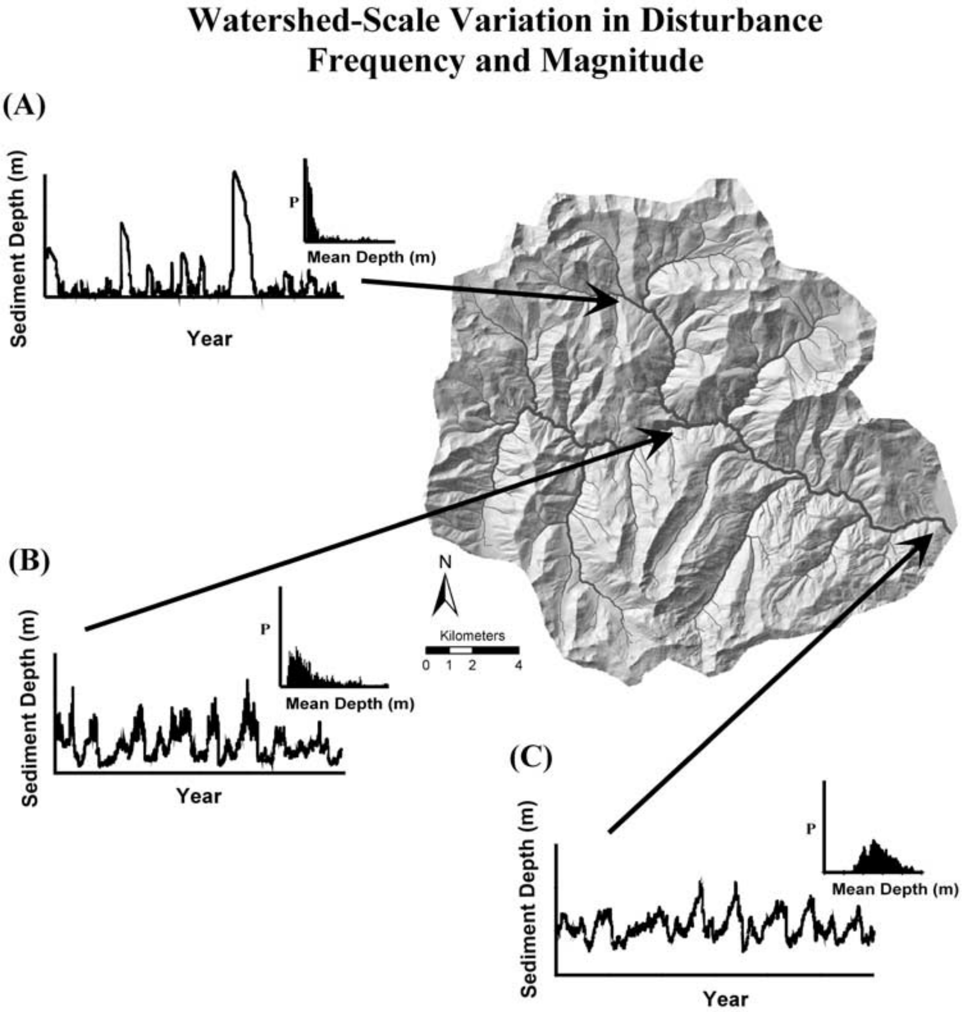

**Figure 10.** Frequency and magnitude of sediment-related disturbances (depth of channel stored sediment) are predicted to vary with basin size, which may influence the age distribution of fan surfaces and their effects in channels. (a) Disturbances are large but rare in headwaters leading to a higher proportion of older fan surfaces with potentially limited junction effects. (b and c) Sediment-related disturbances are more frequent but of lower magnitude farther downstream in a network, thereby creating a higher proportion of younger fan surfaces and more persistent junction effects. Time series of in-channel sediment depth and associated probability distributions are based on simulation modeling [*Benda and Dunne*, 1997a, 1997b]. Note the evolving shapes of the sediment storage PDFs from skewed to normal.

others. The changes at confluences in places such as the Brahmaputra River, Hunter Valley, Australia, and the River Fowey, Cornwall [*Rhoads*, 1987; *Bristow et al.*, 1993] take the form of changing sediment facies, mid channel and lateral bars, and scour holes that form because of the abrupt meeting of two different discharge regimes. These types of changes are in contrast with some of the morphology that develops in more highly erosive landscapes, such as wider valley floors, wider floodplains, more terraces, coarser substrates, including rapids, and log jams (see Table 1).

[44] Some of the relationships we have outlined in this paper should, nevertheless, apply to confluence effects in less erosive landscapes. For example, a relationship between the symmetry ratio and confluence effects outlined in this paper has been pointed out earlier by *Rhoads* [1987] for gentler types of land. From that apparently universal scaling principle, our analysis about how basin shape, network configuration, the power law distribution of channel sizes, and confluence density affect the spatial distribution of confluence effects should apply, in general, to all river systems. However, confluence effects in less erosion- and flood-prone landscapes should be more muted compared to some of the confluence morphology that develops in highly erosive landscapes. In addition, our analysis on the role of disturbance in creating confluence effects, including influencing the age distribution of fans and confluence-related landforms, would be less applicable in less erosive landscapes.

### 5.7. Implications For Riverine Ecology

[45] A linear perspective of river networks has dominated much of riverine ecology over the last 20 years [*Fisher*, 1997] despite the recognition that river networks are

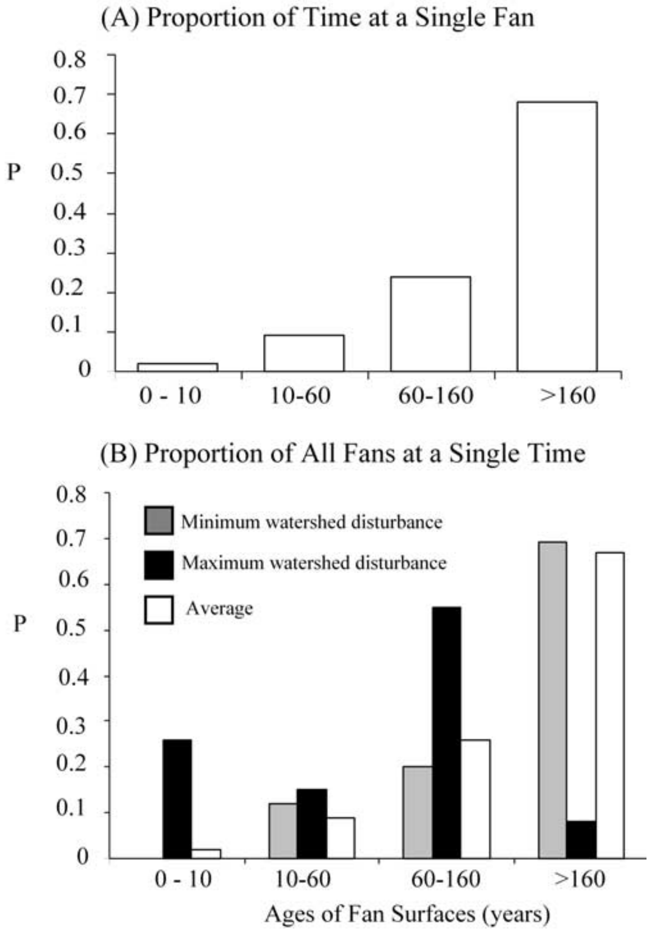

**Figure 11.** Predicted distributions of debris fan ages (i.e., age equivalent to time since last depositional event) for a 200-km$^2$ basin in the central Oregon Coast Range using a stochastic simulation model [*Benda and Dunne*, 1997a, 1997b]. (a) Predicted fan ages over time at a single low-order confluence (i.e., first- and second-order channel confluences). (b) Predicted fan ages for the entire population of low-order confluences at a single time for periods of low to high watershed disturbance (i.e., high watershed disturbance refers to numerous natural fires and storms and no land use).

branched with tributaries interrupting gradual downstream changes in channel and valley morphology [*Bruns et al.*, 1984]. Although the recognition of confluence effects and the role of networks in structuring disturbance regimes has led to new conceptual frameworks and field studies [*Benda et al.*, 1998; *Nakamura et al.*, 2000; *Rice et al.*, 2001; *Poole*, 2002; *Gomi et al.*, 2002], there is no general framework that defines the relationships between fluvial geomorphology and network attributes, including basin shape, network configurations, drainage density, local network geometry, and the stochastic flux of sediment. In this and in a companion paper [*Benda et al.*, 2004], we propose a general geomorphic framework (termed "network dynamics hypothesis (NDH)") that articulates the relationships among the key attributes of river networks and the patchy heterogeneity of fluvial processes and forms. NDH could underpin new conceptual advances in riverine ecology similar to how principles of average hydraulic geometry [e.g., *Leopold and Maddock*, 1953; *Leopold et al.*, 1964] created the physical foundation for the River Continuum Concept [*Vannote et al.*, 1980].

## 6. Conclusions

[46] Although geomorphologists and riverine ecologists recognize the importance of tributary confluences, the role of confluences as sources of morphological heterogeneity at the scale of entire networks is not well understood. Using data obtained from 14 studies covering 167 confluences spanning 7 orders of magnitude in drainage area, we find the probability that a tributary channel will locally alter main stem morphology scales with the size of the tributary relative to the main stem. This scaling relationship links confluence effects to basin shape, network patterns, drainage density, and local network geometry and hence to the spatial distribution of fluvial geomorphic processes and forms. For example, there is a higher probability of encountering geomorphically significant confluences in heart-shaped basins containing dendritic networks compared to rectangular-shaped basins containing trellis networks. Moreover, geomorphically significant confluences are separated nonlinearly by increasing distances downstream, indicating a systematic downstream scaling effect on physical heterogeneity in rivers driven by confluences. Our analysis of the effects of spatial scale and network geometry should also apply to more flow-related changes in morphology at confluences in less erosion prone landscapes [e.g., *Best*, 1986; *Rhoads*, 1987].

[47] Because of our retrospective approach and diversity of field studies reported in the literature, it was not feasible to differentiate among types, or magnitudes and frequencies of confluence effects. However, the probability functions we developed likely reflect magnitude of effects driven, in part, by scale-dependent perception of environments. Additionally there are numerous other factors in addition to those discussed in this paper that could control confluence effects. These include magnitudes of debris flow, flash flood, and flood flow events that construct fans, the history of flood events in a watershed (i.e., the age distribution of fan- and related landforms), the texture of the deposit (whether it contains large clasts, including boulders [see *Meyer et al.*, 2002]) and the width of the valley that would either promote (narrow) or discourage (wide) confluence effects. All of these factors, unknown for the most part in most of the studies, undoubtedly contribute to the variation exhibited in the data. Field studies aimed directly at evaluating confluence effects throughout large networks could conceivably account for these factors.

[48] Viewing rivers as networks and hence confluences as sources of physical heterogeneity has implications for the management of natural resources, including restoration of rivers. For example, maps of geomorphically significant confluences (e.g., Figure 8) could contribute to hazard assessments by identifying particularly vulnerable aquatic resources and could guide river restoration efforts by identifying probable biological "hot spots" (for a discussion of the ecological ramifications of confluences, see *Benda et al.* [2004]). Our analysis of effects of river network structure on the nonuniform distribution of channel confluences and their associated effects on channel attributes provide a geomorphic framework for underpinning new ideas in riverine ecology, including "riverscapes" [*Fausch

*et al.*, 2002; *Wiens*, 2002] and hierarchical patch dynamics [*Townsend*, 1989; *Poole*, 2002]. Other factors that influence river morphology, including alternating canyons and floodplains, landslides, bedrock outcrops, and log jams, can be overlaid upon fluvial geomorphic patterns imposed by river network structure.

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