JOURNAL OF THE AMERICAN WATER RESOURCES ASSOCIATION

Vol. 46, No. 5 AMERICAN WATER RESOURCES ASSOCIATION October 2010

EFFECTS OF GEOMORPHIC SETTING AND URBANIZATION ON WOOD, POOLS, SEDIMENT STORAGE, AND BANK EROSION IN PUGET SOUND STREAMS[1]

Catalina Segura and Derek B. Booth[2]

ABSTRACT: Interrelationships between urbanization, the near-riparian zone, and channel morphology were examined in 44 lowland stream reaches in the Puget Lowlands of western Washington, United States. Both the degree of urbanization and channel type control channel response to a range of instream and riparian conditions. Some of these relationships are not evident in lumped datasets (i.e., with all channel types and/or degrees of urbanization) and highlight the importance of fluvial geomorphology in determining channel response. We found that in low-urbanized watersheds dominated by forced pool-riffle and plane-bed morphologies, the frequency and distribution of large woody debris (LWD), pool spacing, sediment storage, and bank erosion have a strong relationship with channel confinement and characteristics of near-riparian vegetation. In contrast, high-urbanized reaches dominated by simplified morphologies are substantially less sensitive to the condition of the near-riparian zone (e.g., size of the near-riparian vegetation and the level of channel confinement), due to the common disconnection of stream and floodplain caused by the placement of stabilizing structures in the banks. These structures are typically placed to prevent erosion; however, they also result in fewer LWD and pools, less sediment storage, and higher potential for incision.

(KEY TERMS: urbanization; geomorphology; rivers/streams; near-riparian zone, erosion; riparian vegetation.)

Segura, Catalina and Derek B. Booth, 2010. Effects of Geomorphic Setting and Urbanization on Wood, Pools, Sediment Storage, and Bank Erosion in Puget Sound Streams. *Journal of the American Water Resources Association* (JAWRA) 46(5):972-986. DOI: 10.1111/j.1752-1688.2010.00470.x

INTRODUCTION

Urbanization has pervasively modified the physical, biological, and chemical character of freshwater systems. Physically, urbanization alters both the flow regime and the geomorphic state of channels. With urbanization, the once-forested land cover is replaced with impervious surfaces, altering both the magnitude of the discharges and the delivery of sediment to the stream network (Booth and Jackson, 1997). Other negative impacts of urbanization are the degradation of riparian ecosystems and the disconnection of stream channels from their floodplain. In general, urbanization results in simplified channels morphologies with uniform beds and few pools (Walsh *et al.*, 2005). These simplified conditions, triggered by alterations both across watersheds and within the near-riparian

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[1] Paper No. JAWRA-09-0143-P of the *Journal of the American Water Resources Association* (JAWRA). Received September 14, 2009; accepted June 21, 2010. © 2010 American Water Resources Association. **Discussions are open until six months from print publication**.

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zone, create low-quality habitat for fish and macroinvertebrates, with associated declines in diversity and population (Karr and Chu, 1999).

Over the past two decades, the effects of urbanization on streams in the Puget Sound lowlands have been intensely studied (Booth, 1990; Booth and Jackson, 1997; May *et al.*, 1997; Moscrip and Montgomery, 1997; Booth and Henshaw, 2001; Morley and Karr, 2002; Konrad *et al.*, 2005; McBride and Booth, 2005; Alberti *et al.*, 2007, among others). These studies have established relationships between land-cover change and alterations to streams, using a suite of metrics for physical, chemical, and biological conditions and quality. Although the cumulative effects of watershed land-cover change have been well studied, the specific effects of an altered near-riparian zone in urbanizing watersheds have received little detailed attention.

Physical habitat, reflected in channel morphology, is the result of the interaction of three major factors: sediment supply, sediment transport capacity, and vegetation (Montgomery and Buffington, 1998). Through the channel network of a given basin, different patterns and interactions of these driving factors give rise to spatial and temporal variation in channel morphology and response. Under urbanized conditions, however, additional factors are introduced that alter these drivers, in turn modifying the physical condition and response potential of stream channels. Channel morphology is influenced by both the cumulative effects of land-cover change on hydrology and the direct effects over the channel and the riparian area, such as channelization, large woody debris (LWD) removal, stream crossings, and so on. For example, May *et al.* (1997) found that both the prevalence and quantity of LWD declined with increasing basin urbanization, and Pizzuto *et al.* (2000) showed that urban streams are straighter and smoother than comparable streams in rural watersheds. A recent literature review demonstrates that urban streams ubiquitously display enlarged channel dimensions, decreased pool depth, increased scour, and reduced channel complexity (Walsh *et al.*, 2005).

The physical characteristics that can provide an assessment of channel condition and response in forested (or once-forested) mountain drainage basins are channel bed morphology, confinement, position in the channel network, and external influences such as riparian vegetation and in-channel woody debris (Montgomery and Buffington, 1998). Stream-channel condition reflects the capability of the channel to accommodate or resist change due to inputs of sediment, water, organic matter, or alterations of the riparian vegetation (Montgomery and MacDonald, 2002), and they are reflected in such indicators as channel pattern, bank conditions, gravel bars, pool characteristics, and bed material. These have therefore provided the primary variables for our study.

The focus of this study is to highlight how urbanization changes the nature and relative importance of watershed and near-riparian influences on channel morphology. The approach compares developed and undeveloped watershed conditions, looking at relationships between confinement, riparian vegetation, and channel morphology. These relations have been studied for pristine areas in the past (Harris, 1988; Fetherston *et al.*, 1995; Montgomery *et al.*, 1995; Hupp and Osterkamp, 1996; Millar, 2000; Rot *et al.*, 2000); however, the approaches and results are not necessarily transferable to urbanized watersheds.

METHODS

The influences of the near-riparian zone on channel morphology were evaluated for five Puget Sound Lowland watersheds (western Washington) across a wide gradient of urban development. Study sites were located in the Chico Creek watershed, a low-urbanized catchment west of Puget Sound on the Kitsap Peninsula, and at four highly developed watersheds east of Puget Sound near Seattle (Figure 1). Sites were selected for their similar climate and geology and their highly contrasting level of watershed urbanization.

Low- and high-urbanized sites were paired for comparability in terms of drainage area, underlying geology, location within the stream network, and channel gradient. These intrinsic watershed factors were targeted because they influence the geomorphic condition of a stream and its responsiveness to disturbance (Montgomery and Buffington, 1997; Montgomery and MacDonald, 2002) independent of variation in land cover. Controlling for these variables thus improves the likelihood of identifying differences in channel morphology that can be ascribed to differences in watershed urbanization or near- and instream alteration.

Site Selection

Twenty-two reaches with low levels of contributing watershed imperviousness, as defined by a total impervious area (TIA) of under 20% (Hill *et al.*, 2003), were selected in the Chico Creek watershed. An equal number of reaches draining watershed with high level of development (TIA >37%) but with similar geology, drainage areas, and slopes to those in Chico were chosen in the urban areas east of Seattle

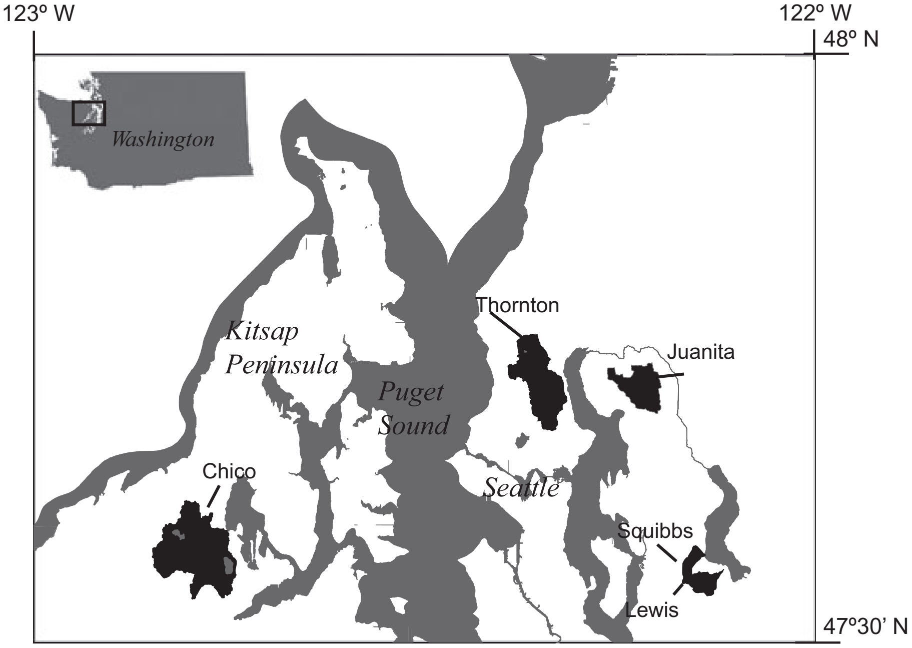

FIGURE 1. Location of the Study Watersheds.

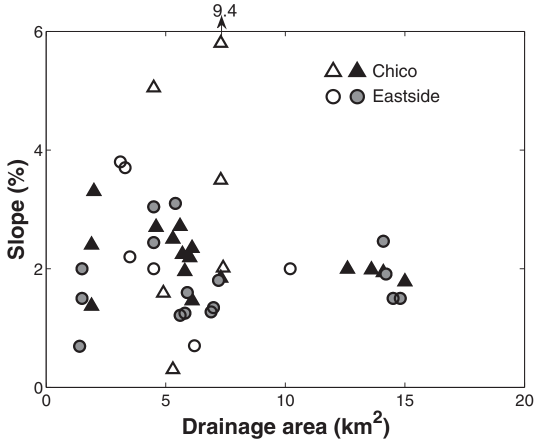

FIGURE 2. Drainage Area and Channel Gradient of the Surveyed Reaches. Filled symbols are members of the paired analysis.

(hereafter called the "Eastside" streams; Figure 2). All sites are underlined by glacial deposits such as advance and recessional outwash and glacial till. All sites receive between 1,000 and 1,500 mm of rain per year with mean annual temperatures of around 10.5°C. A minimum reach length of 20 times the channel bankfull width was used to represent repetitive patterns of the streams (MacDonald *et al.*, 1991; Montgomery and Buffington, 1997; Rot *et al.*, 2000; Martin, 2001). Of the 44 surveyed reaches, 16 pairs matched well in terms of drainage area, channel gradient, and channel profile (Figure 2). Six pairs were excluded from the pair analysis because of their high differences in slope and drainage area (Figure 2).

Before European settlement, vegetation in the study area was mainly covered by Western Hemlock old-growth forests, which are dominated by Douglas fir (*Pseudotsuga menziesii*), Western Hemlock (*Tsuga heterophylla*), and Red Cedar (*Thuja plicata*) (Franklin and Dyrness, 1988). Currently, there are still a few patches of mature second-growth Western Hemlock forest in the middle section of the Chico Creek. The remaining vegetation in this basin corresponds mainly to native deciduous trees of Red Alder (*Alnus rubra*) and Bigleaf Maple (*Acer macrophyllum*). The vegetation in Eastside basins is limited due to their high TIA. Riparian vegetation, where present, is dominated by deciduous species such as Red Alder (*Alnus rubra*), Willow (*Salix* spp.), Apple (*Prunus* spp.), and Poplar (*Populus* spp.), together with a collection of nonnative shrubs and vines.

Field Data

Detailed channel geomorphic surveys of the selected reaches were conducted during the summer of 2002. Channel and riparian features likely to be directly modified, or anticipated to be otherwise affected by urbanization in general, were measured. These geomorphic data included bankfull dimensions, streambank condition, sediment storage (frequency and volume of channel bars), and channel complexity

TABLE 1. Description of Field Measurements Taken at Each Surveyed Reach.

Variable Group	Measurement Taken
Bankfull dimensions	Bankfull width and bankfull depth
Reach condition	Confinement Channel type (Montgomery and Buffington, 1997)
LWD	LWD frequency (#/100 m channel length) LWD distribution (% LWD jams with >5 pieces and % single-piece LWD jams)
Pools	Pool spacing (channel widths/pool) % Pools per formation agent (LWD, free, or anthropogenic influence)
Sediment storage	Bar frequency (#/100 m) Bar volume (m^3/100 m)
Bank erosion	% Bank length eroded % Bank armored
Riparian vegetation	Number of trees (#/1,600 m^2) Basal area (m^2/1,600 m^2) % Trees isolated from the channel*

*Located above channel or hillslope or isolated from the channel by artificial structures.

as measured by the frequency of pools and LWD (Table 1). Bankfull dimensions were measured in an unconfined section of each reach taking into account field indicators such as the presence or absence of perennial vegetation, topographic breaks in the bank, and changes in sediment characteristics (Dunne and Leopold, 1978; Harrelson *et al.*, 1994).

Bed sediment accumulations (i.e., bars) of at least one channel width in longitudinal dimension were considered (Knighton, 1998; Montgomery and MacDonald, 2002). The bar-forming agent (e.g., behind LWD or by meandering) was recorded and the sediment volume in each bar was calculated from its height above the thalweg, its length, and its average width. A pool unit was defined as having a minimum residual depth of 25% the bankfull depth and a minimum pool length of 10% the bankfull width (Montgomery *et al.*, 1995). Recorded LWD were located in the wetted bankfull portion of the channel (Zones 1 and 2 as described by Schuett-Hames *et al.*, 1992) and had minimum dimensions of 1 m in length and 0.25 m in diameter (Montgomery *et al.*, 1995). The number of LWD pieces per jam was counted and the percentage of LWD jams with more than five pieces, between two and four pieces, and a single wood piece was reported. These observations aid the classification of the reaches into channel types (Montgomery and Buffington, 1997). All geomorphic observations were taken over the whole length of each reach; special attention was given to the banks to determine the existence of stabilizing structures and the extent of bank erosion. The location of each feature (e.g., bar, LWD, pool, bank-stabilizing structure) was recorded with a hip-chain.

The surveys included measurements of riparian vegetation and channel confinement at consecutive locations every 20-40 m over the length of each reach. Riparian vegetation per reach was characterized with four plots surveyed on each side of the channel for a total of eight plots per reach. Each vegetation plot was 20 m long and 10 m wide, located at the edge of the bankfull channel and perpendicular to it. The location of each tree relative to the channel was recorded (i.e., floodplain, terrace, hillslope, or in top of armoring structures) to determine the percentage of trees isolated from the channel (Table 1). We defined the near-riparian area as the region within 20 m of both sides of the channel.

Confinement was analyzed at the same locations as the vegetation plots. For the purpose of consistency, confinement followed the common definition of the ratio of the “floodprone” width to the bankfull width, where the floodprone width is the width of the valley at an elevation of two times the bankfull depth (e.g., Rosgen, 1994). Two broad confinement categories were recognized: “confined,” where the floodprone width is less than twice the bankfull width, and “unconfined,” where either the floodprone width is more than twice as wide as the bankfull width or where confining conditions are present but only on one side of the channel. The flow at such “unconfined” river sections can spread across the valley floor, dissipating much of its energy (Gregory *et al.*, 1991). In fully confined reaches, in contrast, when the flow increases above bankfull discharge the channel bed is subject to very high shear stresses because the channel depth continues to increase. Confinement was evaluated at four locations per reach, receiving scores of either zero (unconfined) or one (confined). The confinement score per reach was the simple average of the four measured confinement scores.

Data Analysis

Three different datasets were generated: sites from low-urbanized conditions (Chico Creek watershed, $n = 22$), sites from high-urbanized conditions (Eastside watersheds, $n = 22$), and 16 matched pairs of reaches from both the low- and high-urbanized groups with similar slope and drainage area ($n = 32$) (Figure 2). Datasets 1 and 2 were analyzed separately in order to identify particular functional relationships under each condition of urbanization (the Chico Creek watershed and Eastside watersheds). Dataset 3 is better suited for the identification of relationships only evident over a wide range of urbanization levels, such as those directly related to changes in channel configuration resulting from urbanization.

Our working hypotheses were that certain functional relationships common to forested watersheds, particularly those resulting from the interaction of the flow with a functional riparian area (e.g., commonly reported relationships between the size of the trees in the riparian area and the frequency and distribution of LWD, or the relationship between the frequency of LWD and the frequency of pools), would be absent at high-urbanized levels. Other relationships, however, might *only* be present in high-urbanized watersheds. We also expected to observe significant differences between artificially confined urbanized reaches, where bank armoring is present, and nonurban naturally confined reaches because the former might display differences triggered by recent disconnection from the floodplain and increased flow depths and shear stresses due to urbanization-induced incision.

All data variables within datasets were tested for normality with a Kolmogorov-Smirnov test, which was confirmed in most cases or achieved with a simple mathematical transformation. The only two exceptions were for the metrics of confinement and for the percentage of trees isolated from the channel. The difference between morphologic conditions between low- and high-urbanized reaches was evaluated with a two-sample t-test for all normally distributed variables and with the nonparametric Mann-Whitney test for the comparison of nonnormally distributed variables. In addition, we analyzed the relationship between the near-riparian zone variables and channel morphology for the three datasets by computing the coefficient of determination. This analysis was not intended to find predicting relations but rather to explore relationships between variables. In some instances, a simple data transformation was performed to improve linearity in the relation. Finally, we determined whether the distribution of residuals of the significant relations (i.e., with a p-value above 0.05) was normally distributed and found that all have normally distributed residuals. In the following section, unless specified, we refer to the paired-reaches dataset (Dataset 3).

RESULTS

Channel classification indicated that reaches in the Chico Creek watershed are mainly forced pool-riffle (FPR), followed by plane-bed (PB), step-pool (SP), and cascade (C). Channels in the Eastside watersheds are dominated by PB and SP morphologies (Figure 3). One group of channels with either PB or SP morphology was observed to have distinctly different attributes from the PB and SP channels originally defined by Montgomery and Buffington (1997). These chan-

FIGURE 3. Example Channel Types From the Chico Creek Watershed: (a) Plane-Bed (PB), Located in Chico Creek; (b) Forced Pool-Riffle (FPR), Located in Lost Creek; (c) Step-Pool (SP), Located in Kitsap Creek; (d) Plane-Bed Constrained (PBc), Located in Chico Creek.

nels have low frequency of LWD and wide pool spacing as a result of urban encroachment, limited or no hydraulic connection to the floodplain, and/or the absence of well-developed riparian vegetation. These reaches have lost most or all their self-forming alluvial character because lateral constraining structures (bank armoring, Figure 3) restrict them from interacting with the floodplain. The percentage of the bank length armored (i.e., constrained) for reaches surveyed in both areas (i.e., dataset with 32 reaches) varied between 0% and 76% (Figure 4). We defined these constrained morphologies, PBc and SPc, as having over 20% of their bank length armored (Figure 4). These channel types, which had an average confinement score of 0.63, dominated reaches surveyed in the Eastside (63%) but were rare in Chico Creek (6%). These constrained (i.e., armored) channels are highly confined and mainly unable to migrate into the floodplain. Other confined channel types have more chances to migrate into the floodplain over their longer sections of nonarmored banks.

A wide range of geomorphic conditions were observed (Table 2). The frequency of LWD varied from 0 to 64 pieces per 100 m. Pool spacing varied from 0.97 to 6.5 channel widths per pool, the frequency of channel bars varied between 0 and 7 per 100 m, and the extent of the channel bank with visible erosion ranged from 0 to 93%. We also found a wide range of conditions in the near-riparian area of the surveyed reaches, providing a good opportunity to study the relationships between the near-riparian vegetation zone and the geomorphic condition of the surveyed reaches. Basal area, a variable that incorporates both the abundance and size of the riparian vegetation, varied between 0.5 and 12.2 m^2 per 1,600 m. Confinement scores varied between 0 and 0.75.

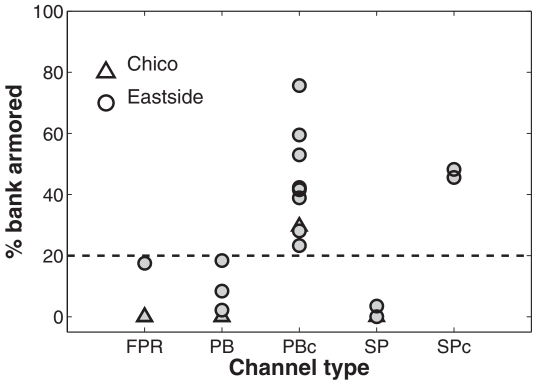

FIGURE 4. Percentage of the Bank Armored With Stabilizing Structures in the 16 Paired Reaches Surveyed in Chico and the Eastside (FPR, forced pool-riffle; PB, plane-bed; SP, step-pool). We defined constrained morphologies (PBc and SPc) as having more than 20% of their bank length armored.

Both the condition of the near-riparian vegetation and most geomorphic characteristics were significantly different between the Chico and Eastside reaches (Table 3). Basal area was significantly higher in Chico than in the Eastside ($p < 0.001$), whereas confinement was significantly lower in Chico than in the Eastside ($p = 0.002$). Eastside channels also had a significantly greater length of the bank cover with stabilizing structures ($p < 0.0001$). Reaches in Chico had significantly more LWD, more LWD jams with more than five pieces, and more pools formed behind LWD jams than reaches in the Eastside ($p < 0.001$ in all cases). There were significantly fewer single-piece LWD jams and less bank erosion in Chico than in the Eastside ($p < 0.0001$). No significant differences between the two datasets were observed with regards to pool spacing, bars, or the percentage of trees isolated from the channel. However, one-third of the pools in the Eastside were formed behind artificial structures (Table 3), the channel bars in the Eastside had significantly less sediment volume stored than those in Chico ($p < 0.001$, Table 3), and the trees isolated from the channel in the Eastside were mainly on top of armoring structures in residential backyards and so isolated from the channel, even during high-flow events.

Large Woody Debris Frequency

Instream LWD frequency is related with the size and abundance of the riparian vegetation, but only for certain channel types. Basal area was strongly related to in-channel LWD ($r^2 = 0.40$, $p = 0.0001$; Table 4, Figure 5a), particularly in FPR and PB reaches, which are mainly located in low-urbanized reaches within the Chico Creek watershed. Constrained morphologies (PBc and SPc), mainly located in high-urbanized reaches, had fewer LWD pieces regardless of the near-riparian vegetation basal area. As expected, FPR channels have significantly more LWD pieces than PB ($p = 0.001$) or constrained channels (PBc and SPc, $p < 0.0001$). The frequency of LWD in SP is highly variable and was unrelated to basal area over the small sample size (three reaches for this channel type) (Figures 5a and 6).

Confined reaches consistently have less LWD than unconfined channels (Figure 5b). High variability was observed at unconfined reaches (i.e., confinement score = 0; Figure 5b). FPR channels were mostly located at unconfined reaches with much instream wood. Conversely, PBc and SPc channels had few wood pieces and their frequency was unrelated to their (uniformly) high level of confinement. Figure 5b suggests a factor-ceiling distribution

TABLE 2. Characteristics of the Surveyed Reaches; Reaches 1 to 22 Are Located in the Chico Creek Watershed and Reaches 23 to 44 in the Eastside.

				Bankfull Dimensions					% Pools by Formative Agent				% LWD Events With			Sediment Storage/100 m		Bank Erosion			
No.	Type*	Slope (%)	DA (km^2)	Width (m)	Depth (m)	% TIA	Conf	Pool Spacing (BFW/pool)	LWD	Free	Anthr	LWD/100 m	>5 Pieces	2 to 5 Pieces	1 Piece	No. Bars	Vol. (m^3)	%	% B	BA (m^2/1,600 m^2)	Isol (%)
1**	PB	1.46	6.1	8.3	0.60	13.8	0.5	2.19	60.0	40.0	0.0	20.8	26.5	41.2	32.4	2.6	33.2	4.5	0.0	8.8	75.2
2**	FPR	2.34	6.1	9.8	0.45	13.7	0	1.28	83.3	16.7	0.0	63.9	37.0	33.3	29.6	0.9	43.6	4.3	0.0	9.6	72.5
3**	FPR	1.98	13.6	11.3	1.00	14.9	0	1.18	73.9	26.1	0.0	55.8	35.3	38.2	26.5	0.9	16.0	1.5	0.0	6.7	54.1
4**	FPR	1.94	14.1	11.8	0.60	14.7	0	0.97	73.3	26.7	0.0	37.8	23.8	19.0	57.1	1.7	55.8	5.2	0.0	7.0	52.2
5**	SP	2.71	5.6	8.2	0.75	9.3	0	2.91	65.0	35.0	0.0	59.2	45.5	13.6	40.9	5.1	165.6	20.6	0.0	4.7	83.7
6**	FPR	2.24	5.7	8.9	0.70	9.2	0	1.47	47.1	52.9	0.0	42.5	14.3	85.7	0.0	4.5	136.9	1.3	0.0	6.3	54.8
7**	FPR	1.96	5.8	8.4	0.60	9.1	0.5	1.74	69.2	30.8	0.0	25.3	30.8	46.2	23.1	3.4	125.0	0.0	0.0	7.1	42.5
8**	FPR	2.19	6.0	8.2	0.80	9.0	0	1.54	60.9	39.1	0.0	44.8	35.0	25.0	40.0	3.2	106.0	5.8	0.0	7.5	5.3
9	C	5.05	4.5	6.3	0.55	11.8	0.5	1.77	50.0	50.0	0.0	30.1	38.9	27.8	33.3	1.9	26.3	3.1	0.0	6.8	17.2
10**	FPR	2.70	4.6	8.6	0.60	11.7	0.5	1.28	47.8	52.2	0.0	46.5	28.0	32.0	40.0	0.4	6.2	2.0	0.0	8.4	60.5
11	FPR	1.59	4.9	8.5	0.50	11.5	0	1.28	40.0	60.0	0.0	28.3	13.0	39.1	47.8	2.3	67.9	11.9	0.0	2.9	66.7
12	PB	0.30	5.3	7.4	1.00	11.5	0.25	2.70	0.0	88.9	11.1	1.4	0.0	0.0	100.0	2.1	56.5	13.8	10.3	6.0	44.4
13**	PBc	2.50	5.3	7.8	1.00	11.5	0.5	6.49	25.0	75.0	0.0	7.3	10.0	30.0	60.0	2.2	54.7	46.9	29.6	7.1	78.1
14	C	9.35	7.3	5.6	1.00	19.5	1	1.71	16.7	62.5	20.8	18.3	8.3	25.0	66.7	0.8	15.8	17.1	11.7	7.1	100.0
15	FPR	3.49	7.3	8.5	1.00	19.5	0.75	1.37	54.2	41.7	4.2	42.4	21.7	34.8	43.5	0.6	16.7	34.8	20.0	8.5	100.0
16	SPc	2.01	7.4	5.9	0.60	19.4	0.75	5.26	35.7	35.7	28.6	7.5	16.7	50.0	33.3	0.9	11.3	42.2	38.9	3.1	92.6
17**	FPR	1.84	7.3	9.3	0.65	8.7	0	1.54	66.7	33.3	0.0	38.8	20.0	40.0	40.0	2.0	79.4	4.3	0.0	5.4	30.0
18***	PB	1.78	15.0	8.8	0.50	14.9	0	2.16	16.7	83.3	0.0	5.0	0.0	50.0	50.0	3.3	37.1	6.7	0.0	3.7	0.0
19**	FPR	1.99	12.6	9.8	0.50	15.0	0	1.44	94.1	5.9	0.0	51.4	30.8	30.8	38.5	1.0	16.2	5.3	0.0	12.2	59.6
20**	PB	1.37	1.9	5.4	0.60	9.7	0	2.63	25.0	75.0	0.0	28.6	27.8	27.8	44.4	6.7	60.8	0.0	0.0	10.9	18.2
21**	FPR	2.40	1.9	6.6	0.60	9.7	0	1.34	53.8	46.2	0.0	54.3	28.6	35.7	35.7	4.8	35.7	0.0	0.0	11.4	18.5
22**	FPR	3.30	2.0	6.1	0.60	10.1	0	1.83	50.0	50.0	0.0	49.1	26.7	26.7	46.7	5.5	38.9	0.0	0.0	7.8	0.0
23	SPc	2.00	10.2	5.1	0.60	54.0	0.75	3.64	0.0	55.6	44.4	4.2	0.0	16.7	83.3	1.2	4.4	92.7	74.2	4.0	46.2
24**	SPc	2.46	14.1	8.5	0.65	53.6	0.75	1.87	30.8	46.2	23.1	3.6	0.0	16.7	83.3	0.5	2.6	49.2	45.6	3.1	100.0
25**	PBc	1.91	14.2	8.8	0.80	53.6	0.25	1.87	7.7	76.9	15.4	4.1	0.0	14.3	85.7	2.1	7.6	31.7	28.1	3.5	40.0
26**	PBc	1.50	14.5	7.9	0.65	53.6	0.75	1.88	28.6	28.6	42.9	4.9	0.0	14.3	85.7	1.1	9.3	75.7	75.7	5.9	67.6
27**	FPR	1.50	14.8	8.1	0.80	53.5	0.75	1.37	25.0	65.0	10.0	11.4	0.0	35.3	64.7	4.5	39.9	25.0	17.5	3.5	85.7
28	PBc	0.70	6.2	4.6	0.65	55.8	0.75	3.33	13.3	60.0	26.7	0.0	0.0	100.0	0.0	1.5	5.5	54.0	51.8	0.5	100.0
29**	PBc	1.25	5.8	8.5	0.70	56.1	0.75	2.27	18.2	54.5	27.3	3.5	0.0	50.0	50.0	1.0	7.3	56.5	53.0	2.6	84.4
30**	SP	3.10	5.4	7.5	0.75	56.6	0.75	1.65	12.5	62.5	25.0	5.1	16.7	0.0	83.3	2.0	21.0	26.5	3.5	2.3	93.3
31**	PBc	1.21	5.6	5.3	1.00	56.3	0.75	3.08	16.7	50.0	33.3	2.7	0.0	25.0	75.0	0.5	3.2	63.2	59.5	0.5	100.0
32**	PB	0.69	1.4	5.2	0.55	39.5	0.75	2.90	28.6	57.1	14.3	20.8	9.1	27.3	63.6	5.0	10.4	17.3	8.4	1.4	100.0
33**	PB	1.50	1.5	4.8	0.60	39.7	0.25	2.40	9.1	72.7	18.2	7.5	0.0	40.0	60.0	5.7	12.4	37.3	18.4	1.6	79.3
34**	PBc	2.00	1.5	4.3	0.70	39.9	0.75	3.68	0.0	50.0	50.0	18.8	8.3	16.7	75.0	2.6	5.5	47.0	38.9	3.6	71.4
35**	PBc	1.27	6.9	5.5	0.70	44.5	0.75	2.25	26.7	40.0	33.3	15.4	22.2	22.2	55.6	4.1	17.5	49.7	42.3	9.1	95.2
36**	PB	1.34	7.0	7.7	0.75	44.4	0.75	2.67	37.5	62.5	0.0	25.0	13.3	13.3	73.3	5.0	31.1	14.1	2.2	7.2	100.0
37**	PBc	1.80	7.2	8.6	0.60	44.4	0.75	1.87	19.0	33.3	47.6	4.5	0.0	33.3	66.7	2.9	29.3	44.4	41.6	2.3	32.6
38**	PBc	1.60	5.9	5.3	0.65	53.9	0.75	4.65	28.6	42.9	28.6	6.1	0.0	0.0	100.0	2.5	9.7	30.7	23.3	2.9	91.3
39	SPc	2.20	3.5	4.7	0.80	42.1	0.75	7.58	25.0	75.0	0.0	0.8	0.0	0.0	100.0	0.0	0.0	72.5	72.5	0.9	100.0
40	SPc	3.80	3.1	1.8	0.50	42.5	0.75	4.31	0.0	83.3	16.7	0.0	0.0	100.0	0.0	0.0	0.0	70.2	70.2	3.8	94.4
41	SPc	3.70	3.3	4.7	0.70	42.5	0.75	5.68	85.7	0.0	14.3	6.3	0.0	11.1	88.9	0.0	0.0	26.3	26.3	2.1	100.0
42	PB	2.00	4.5	8.5	0.80	37.1	0.75	2.16	40.0	60.0	0.0	18.7	20.0	40.0	40.0	3.5	33.9	20.5	3.5	9.0	88.9
43**	SP	3.04	4.5	5.1	0.75	37.2	0.75	2.27	47.1	41.2	11.8	28.4	31.3	25.0	43.8	2.6	15.2	20.9	0.0	6.0	76.0
44**	SPc	2.44	4.5	7.2	0.70	37.3	0.75	2.23	25.0	31.3	43.8	8.0	11.1	66.7	22.2	2.8	14.7	51.8	48.2	7.7	94.3

Notes: DA, drainage area; TIA, total impervious area; Conf, confinement; LWD, large woody debris; free refers to pools formed by meandering; Anthr, anthropogenic; Vol., volume; B, bank armoring; BA, near-riparian area tree basal area; Isol, trees isolated from the channel.

*Montgomery and Buffington (1997).

**Paired reaches (Dataset 3) for analysis over the full range of urbanization.

TABLE 3. Comparison of the Near-Riparian Zone and of Geomorphic Conditions Between 16 Reaches Surveyed in Chico and 16 Reaches Surveyed in the Eastside.

Characteristic/Condition	Chico	Eastside	*p*-Value
Basal area (m^2/1,600 m)	7.8 ± 2.4	4.0 ± 4.5	0.00018
Confinement	0.1 ± 0.22	0.4 ± 0.26	<0.01[†]
Trees isolated from the channel (%)	44.1 ± 28.5	81.7 ± 20.4	0.064787
LWD/100 m	39.4 ± 17.7	10.6 ± 8.4	<0.00001
LWD jams with >5 pieces (%)	26.3 ± 11.1	7.0 ± 9.7	<0.00001
Single piece LWD jams (%)	37.8 ± 14.2	68.0 ± 19.1	0.000785
Pool spacing (channel width/pool)[*]	1.99 ± 1.31	4.43 ± 0.83	0.06
Pools formed by LWD (%)	57.0 ± 21.4	22.6 ± 11.9	<0.00001
Pools formed by anthropogenic structures (%)	0.0	26.5 ± 14.2	<0.00001
Bars/100 m	3.0 ± 1.9	2.8 ± 1.64	0.753176
Sediment storage in bars (m^3/100 m)	63.2 ± 46.9	14.8 ± 10.7	0.000918
Bank erosion (%)[**]	6.8 ± 11.8	40.1 ± 17.5	<0.00001
Bank armoring (%)	1.6 ± 4.7	31.9 ± 22.8	<0.01[†]

Notes: Values are means ± 1 SD. The *p*-value of a *t*-test comparing the means is also given.
[*] Logarithmic transformation of the data to improve normality.
[**] Square-root transformation of the data to improve normality.
[†] Using a nonparametric Mann-Whitney test.

(Thomson *et al.*, 1996), in which the upper bound represents the maximum LWD frequency per level of urbanization in the absence of other limiting factors, such as basal area (Figure 5a). This factor-ceiling relationship was also expressed by reaches at Chico but was absent among reaches in the Eastside (Table 4). Figure 5c indicates that confined urban channels still retain an appreciable amount of wood when bank armoring is less than ~20%, suggesting that lateral migration is an important factor in LWD loading.

The distribution of wood in LWD jams appears to be related to both the level of channel confinement and the basal area of the near-riparian vegetation. The frequency of single-piece wood jams increases with channel confinement ($r^2 = 0.28$, $p << 0.0001$; Figure 7b) and decreases with basal area of the near-riparian vegetation ($r^2 = 0.32$, $p = 0.0007$; Figure 7a). Conversely, the frequency of LWD jams with more than five pieces decreases with confinement ($r^2 = 0.21$, $p = 0.009$; Figure 7d, showing a factor-ceiling relation) and increases with basal area ($r^2 = 0.47$ $p < 0.0001$; Figure 7c), especially in FPR and PB channels. In these two channel types, stronger relations were found (Figure 7c). Single-piece LWD jams were more common in constrained morphologies than in FPR reaches ($p < 0.016$; Figure 7). The opposite pattern was observed for LWD jams with more than five pieces, which were more frequent in FPR channels ($p = 0.0117$; Figure 7) and were mainly absent in PBc and SPc reaches. The LWD distribution within both low- or high-urbanized reaches analyzed independently showed similar relations to basal area and confinement; however, they were not always significant (Table 4).

Pool Spacing

Pool spacing was positively related to confinement (Table 4). This relation was also present among high-urbanized channels (Table 4). More pools were formed by LWD in FPR than in PB ($p = 0.002$) or constrained channels (PBc and Spc) ($p = 0.0001$; Figure 6). Conversely, over one-third of the pools in constrained channels were found behind anthropogenic structures (Table 3). The percentage of pools formed by LWD in SP channels is more variable than in the other channel types (Figure 6), but again our sample size is small for this channel type. As previously reported for forested areas (e.g., Montgomery *et al.*, 1995), pool spacing decreases with increasing frequency of LWD ($r^2 = 0.16$, $p = 0.001$; Figure 8a), which in turn is influenced by basal area and the level of confinement (Figure 5). This relation is also better described by a factor-ceiling relation, unless only FPR and PB reaches from low-urbanized basins are considered ($r^2 = 0.46$, $p = 0.007$; Figure 8b).

Sediment Storage

The frequency of bars is related to the frequency of LWD only in constrained morphologies ($r^2 = 0.59$, $p = 0.006$; Figure 9 top), suggesting that a significant amount of sediment within these channels is stored behind wood pieces. In other channel types, sediment was also found as "free" point bars and mid-channel bars. High-urbanized reaches dominated by constrained morphologies had less sediment stored than low-urbanized channel types ($p < 0.0001$), indicating either low sediment supply and/or high transport

TABLE 4. Coefficient of Determination of Relationships Between Channel Morphology and the Near-Riparian Zone.

Channel Geomorphologic Feature	Chico and Eastside (n = 32)				Chico (n = 22)				Eastside (n = 22)			
	Basal Area (m^2/1,600 m)	**Channel Conf.**	**% Trees Isolated**	**LWD/ 100 m**	**Basal Area (m^2/1,600 m)**	**Channel Conf.**	**% Trees Isolated**	**LWD/ 100 m**	**Basal Area (m^2/1,600 m)**	**Channel Conf.**	**% Trees Isolated**	**LWD/ 100 m**
LWD/100 m	**0.4 (+)**	**0.46 (–)***	**0.13 (–)**		**0.2 (+)**	**0.22 (–)***	0.003		**0.29 (+)**	0.17	0.01	
Single-piece LWD jams (%)	**0.32 (–)**	**0.28 (+)**	0.11		0.01	0.03	0.001		0.04	0.003	0.04	
LWD jams >5 wood pieces (%)	**0.47 (+)**	**0.21 (–)***	0.07		0.16	0.06	0.006		**0.43 (+)**	0.01	0.03	
Pool spacing (channel widths/pool)	0.06	**0.16 (+)**	0.11	**0.16 (–)***	0.07	0.11	0.07	**0.33 (–)***	0.13	**0.25 (+)***	0.08	0.06
Bar/100 m	0.009	0.1	0.04	0.06†	0.01	**0.23 (–)**	**0.29 (–)**	0.01	0.11	**0.41 (–)**	0.002	**0.42 (+)**
Bar volume (m^3/100 m)	**0.16**** **(+)**	**0.31**** **(–)**	**0.22**** **(–)**	**0.32****† **(+)**	0.04**	**0.25**** **(–)**	0.08**	0.00**	**0.22 (+)**	**0.30 (–)***	0.01	**0.24 (+)**
Bank erosion (%)	**0.26(–)***	**0.50 (+)**	**0.29 (+)***	**0.53 (–)***	0.11	**0.3 (+)**	**0.4 (+)***	**0.19 (–)***	0.02	**0.33 (+)***	0.04	**0.4 (–)***

Note: Values in bold correspond to relationships with p-values <0.05, for which the direction of the relationship is shown (+ or –).

*Factor-ceiling relationship present.

**Using a logarithmic transformation of bar volume data.

†Using logarithmic transformation of LWD data.

capacity (Table 3). Sediment storage was negatively related to channel confinement (r^2 = 0.31, p = 0.0009; Table 4) and positively related to the frequency of LWD (r^2 = 0.32 p = 0.0008; Figure 9 bottom), independent of channel type. However, this relationship was stronger excluding FPR (r^2 = 0.35, p = 0.006), suggesting that sediment storage in this channel type is less dependent on the frequency of LWD.

Bank Erosion

Bank erosion was related to basal area (r^2 = –0.26, p = 0.003; Figure 10), the frequency of LWD (r^2 = –0.53, p << 0.0001; Figure 10), the percentage of trees isolated from the channel (r^2 = 0.29, p = 0.001; Figure 10), and channel confinement (r^2 = 0.50, p << 0.0001; Figure 10). These relations were stronger across the full range of urbanization than within similar urbanization levels (Table 4). Basal area was inversely related to erosion when reaches from all levels of urbanization are included in the analysis. This relationship was stronger when constrained morphologies (PBc and SPc) were excluded (r^2 = 0.53, p = 0.0002; Figure 10e), because these channels had consistently high percentages of bank erosion independent of basal area (Figure 10e). Three reaches (highlighted in Figure 10a) were observed with relatively high basal area (6-9 m^2) and unusually severe bank erosion (>47%); however, the effect of the riparian vegetation in these constrained channels is limited because they had more than 67% of the near-riparian trees isolated from the channel (Figure 10c).

The frequency of LWD was also found to be inversely related to bank erosion (Figures 10b and 10f), independent of channel type. Reaches with more than 40 instream wood pieces per 100 m had <5% of the bank length eroded. Conversely, reaches with <10 pieces of LWD/100 m had more than 20% of their bank length eroded (Figures 10b and 10f). This relationship was absent for low-urbanized unconstrained reaches, where bank erosion was well below 20% regardless of the LWD frequency. Extensive bank erosion was observed at reaches with high percentage of near-riparian vegetation isolated from the channel independent of channel type (Figure 10f). However, as for basal area, this relation was stronger when constrained morphologies (PBc and SPc) were excluded (r^2 = 0.41, p = 00017; Figure 10g). In these channels, the bank stabilizing effects of near-riparian vegetation are likely limited by the bank armoring structures.

Finally, there is a positive relation between confinement and bank erosion in all datasets (Table 4, Figures 10d and 10h); however, these relations disappear when constrained morphologies are excluded,

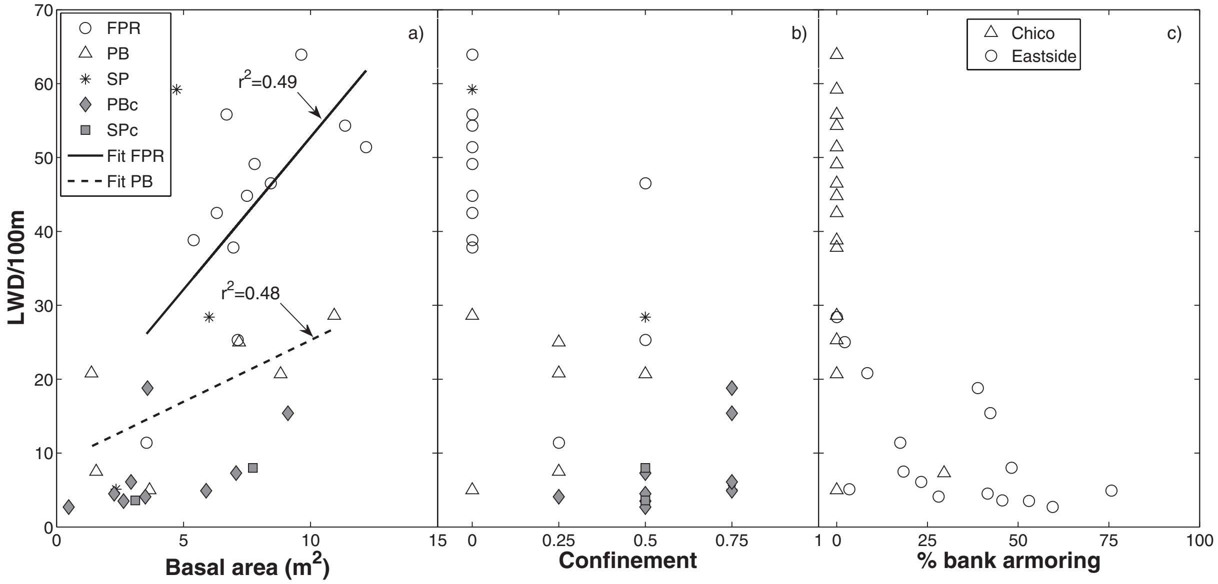

FIGURE 5. Scatter Plots of Riparian Vegetation Basal Area (a), Channel Confinement (b), and Bank Armoring (c) *vs.* In-Channel LWD Frequency in the 16 Paired Reaches Surveyed in Chico and the Eastside. Panel (b) suggests the upper bound of a negative factor-ceiling relationship as described by Thomson *et al.* (1996), where increasing confinement results in a declining maximum level of observed LWD.

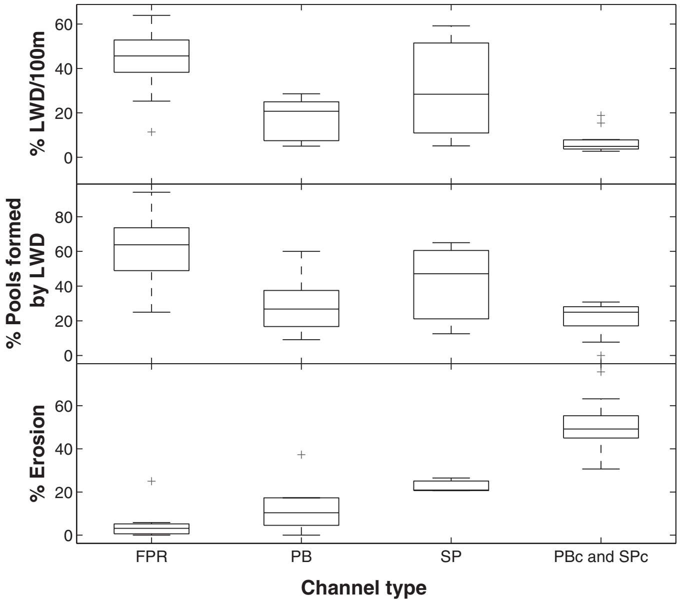

FIGURE 6. Variation in Channel Parameters by Channel Type (FPR, forced pool-riffle; PB, plane-bed; SP, step-pool; PBc, plane-bed constrained; SPc, step-pool constrained) in the 16 Paired Reaches Surveyed in Chico and the Eastside. Box and whiskers plots show the median (central mark) and the 25th and 75th percentiles (box edges). The whiskers extend to the most extreme data points excluding outliers, which are plotted individually.

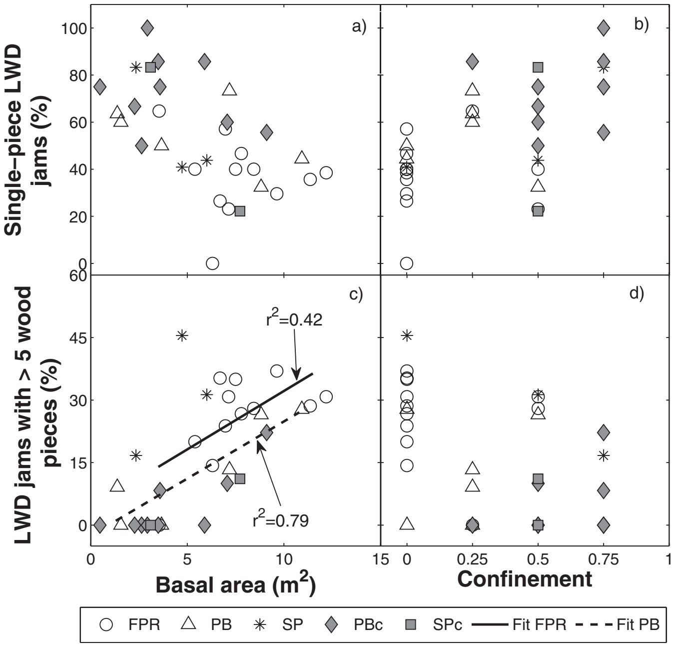

FIGURE 7. Relationship Between Basal Area and Confinement and the Percentage of LWD Jams With a Single Wood Piece (a and b) and More Than Five Wood Pieces (c and d) in the 16 Paired Reaches Surveyed in Chico and the Eastside. Note the channel-type-dependent relationship between basal area and LWD jams with more than five wood pieces (c).

suggesting that confinement has a minimal effect on bank erosion in the more natural channel types. The relationships in Figures 10a to 10c, like those in Figure 5b, are better described as factor-ceiling relationships. The upper edge of the data points suggest an upper bounding relationship between basal area, LWD frequency, and the percentage of trees isolated from the channel and bank erosion, absent other controlling factors.

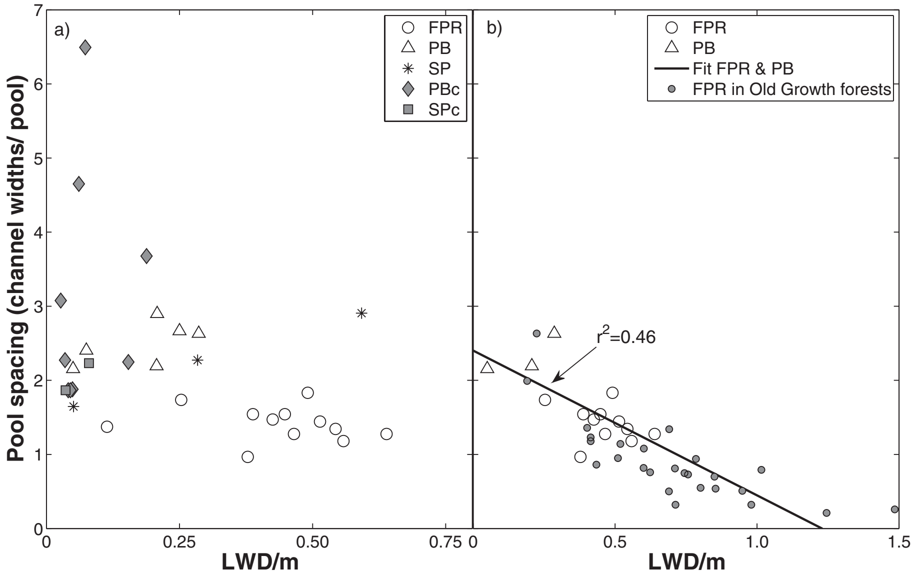

FIGURE 8. Relationship Between LWD Frequency and Pool Spacing in the 16 Paired Reaches Surveyed in Chico and the Eastside. Panel (a) presents all surveyed reaches and panel (b) presents the channel-type-dependent relation for low-urbanized FPR and PB reaches. Data from FPR channels draining through old-growth forests overlain for comparison (Montgomery *et al.*, 1995).

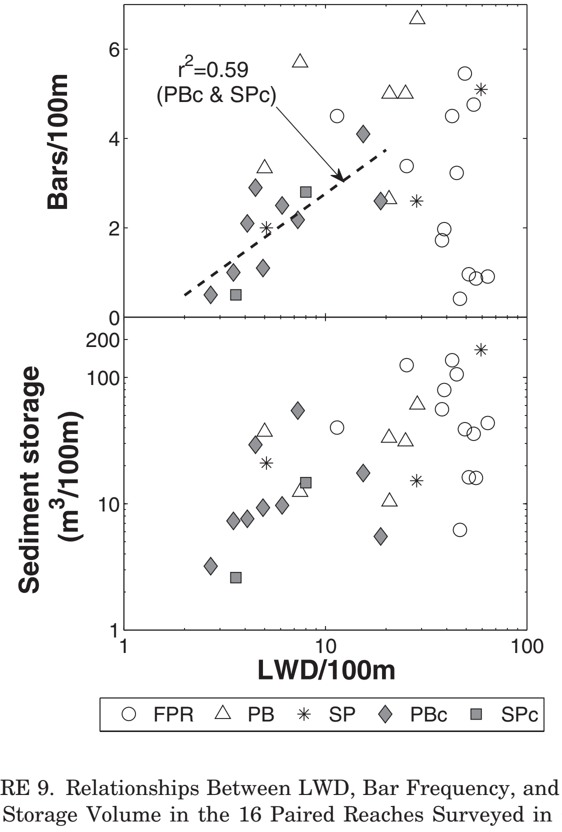

FIGURE 9. Relationships Between LWD, Bar Frequency, and Sediment Storage Volume in the 16 Paired Reaches Surveyed in Chico and the Eastside. The relationship shown in the top panel (with bar frequency) is only evident for constrained morphologies (PBc and SPc). Conversely, the relationship with sediment storage volume is independent of channel type but is stronger if FPR channels are excluded.

DISCUSSION

The goal of this study was to highlight how urbanization changes the nature and relative importance of watershed and near-riparian influences on channel morphology. We sought evidence by analyzing the influence of urbanization on relationships between channel morphology and near-riparian characteristics. As prior studies have shown, some channel features (such as LWD frequency and distribution, pool spacing, and bank erosion) relate to characteristics of the near-riparian zone across a wide range of watershed urbanization and regardless of channel type. However, other relationships are channel-type-specific due to differences in intrinsic channel sensitivity. These relationships would pass unrecognized if data from all channel types were lumped. Finally, some relationships are only evident within stratified levels of urbanization, analyzed independently.

Thus, both watershed urbanization and channel geomorphic setting are important to understand the interactions between the near-riparian zone and channel morphology. Previous studies (e.g., Roth *et al.*, 1996; Paul and Meyer, 2001; Morley and Karr, 2002; Alberti *et al.*, 2007), which generally focused solely on the condition of watershed or riparian land cover, have not recognized some of the relationships found here because they did not consider the overarching importance of fluvial geomorphology and the geomorphic setting.

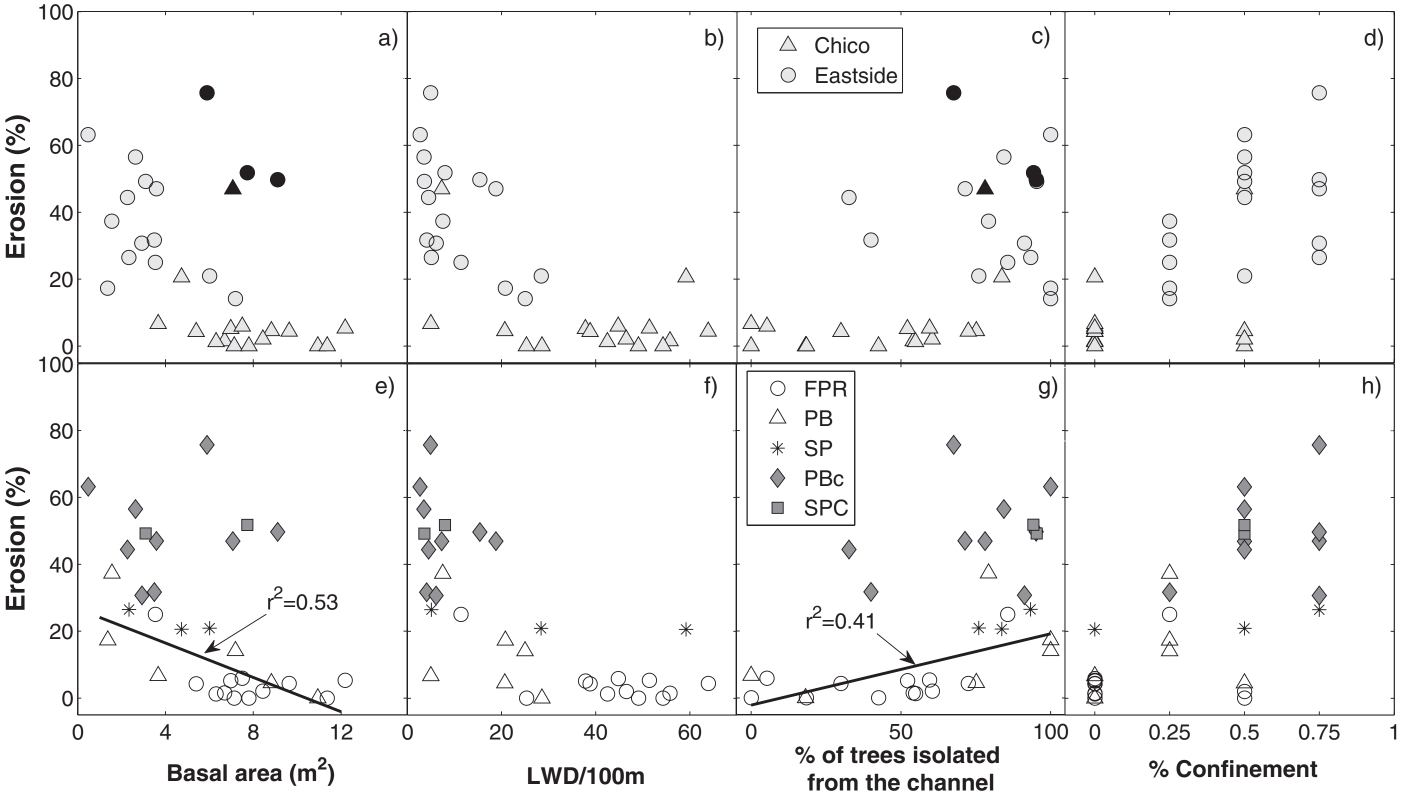

FIGURE 10. Relation of Bank Erosion With Several Near-Stream Parameters in the 16 Paired Reaches Surveyed in Chico and the Eastside. Panels (a to d) present the data with respect to urbanization level and panels (e to h) with respect to channel type. Highlighted points in (a) and (c) indicate the same sites, each with unusually high bank erosion despite the relatively large size of the near-riparian vegetation (a). These reaches, however, have nearly all of their riparian vegetation isolated from the channel (c). These relations are mainly channel-type-independent, except for nonconstrained types in which erosion decreases with increasing basal area (e) and increases with the percentage of trees isolated from the channel (panel g).

TABLE 5. Relative Sensitivity of Channel Morphology to Near-Stream Variables, by Channel Type and Urbanization Level.

Channel Type	LWD/100 m	LWD Distribution	Pool Spacing (channel widths/pool)	Sediment Storage	Bank Erosion
Relations by channel type					
FPR	BA	BA	LWD		BA, Isol
PB	BA	BA	LWD		BA, Isol
SP					BA, Isol
PBc and SPc				LWD	
Relations by urbanization level					
Basal area	1, 2, 3	3		1, 2, 3	3
Confinement	1, 3	3	2, 3	1, 2, 3	1, 2, 3
% Trees isolated	3			1, 2, 3	1, 3
LWD/100 m			1, 3	2, 3	1, 2, 3

Notes: BA, basal area; LWD, large woody debris; Isol, percentage of trees isolated from the channel. Dependency of observed relationship on urbanization is indicated by: 1, present only in low-urbanized reaches of the Chico Creek watershed; 2, present only in high-urbanized reaches in the Eastside; and 3, present across the full range of urbanization.

Strong channel-type-dependent relations exist in nonconstrained unconfined or naturally confined low-gradient reaches (FPR and PB). Other channel types, such as SP, SPc, and PBc, are less sensitive to the condition of the near-riparian zone (Table 5), indicating that the channel type must be explicitly considered in any analysis of relationships between channel condition and the near-riparian area. In FPR and PB reaches, pool spacing and the frequency and distribution of LWD are sensitive to the size and distribution of the near-riparian vegetation and to channel confinement because of their hydraulic connection with the near-riparian area. These relations express geomorphic processes that are not active in either steeper channels (SP) or high-urbanized constrained settings (PBc and SPc), where stabilizing structures (i.e., armoring) have isolated the channel from their near-riparian area.

There was only one relationship present exclusively in constrained morphologies: a relationship between LWD and bar frequency. This suggests an overriding dependency of sediment storage on LWD loading within these reaches. Based on our observations and results, we also infer that some of the high-urbanized Eastside channels are reflecting an evolution in type from FPR to PBc during the process of urbanization-induced incision.

All observed relationships were expressed across the full range of urbanization, but some were absent when analyzed within a more narrow range of urbanization (Table 5). The relationships between confinement and the frequency of LWD, between the percentage of trees isolated from the channel (i.e., located in the hillslope or on top of armoring structures) and bank erosion, and between LWD frequency and pool spacing were not expressed among high-urbanized reaches (Eastside) – most of which also have disconnected floodplains. Conversely, the relationships between the frequency of LWD and bar frequency, between basal area and LWD distribution, and between confinement and pool spacing were absent among the low-urbanized reaches of Chico. Other relationships, such as between basal area and bank erosion and between the percentage of trees isolated from the channel and LWD frequency, were only evident across the full range of urbanization (Table 5).

Large Woody Debris

The common relationships between LWD frequency and pool spacing, and the frequency of LWD and channel confinement found within undisturbed watersheds (Montgomery *et al.*,1995; Rot *et al.*, 2000; Fox *et al.*, 2003; Morris *et al.*, 2007), were also expressed among our low-urbanized reaches (specially in FPR and PB reaches). These relationships were absent within reaches in the Eastside, most likely because armoring structures along the banks of most of the surveyed reaches result in the total disconnection of the stream from the floodplain. This has led not only to limited interaction with existing vegetation (Finkenbine *et al.*, 2000) but also to more severe effects of hydrologic alteration (such as higher shear stresses at high flow) triggered by land-cover changes and impervious surfaces (Arnold and Gibbons, 1996) that limit LWD retention. In addition, these reaches run through populated areas (parks and near homes) in which the loading of LWD depends on the sense of esthetics of the landowner who may simply decide to remove them.

As in the case of confinement, the size of the near-riparian vegetation was only related to the frequency and distribution of instream LWD in FPR and PB channels. Constrained morphologies had low LWD recruitment regardless of the size and abundance of the near-riparian vegetation, not only because they had generally fewer and smaller trees but also presumably because they experience higher instream wood mobility. An exception was found for the relation between basal area and the frequency of single LWD pieces, which was evident across all channel types and among all levels of urbanization. The negative effects of bank armoring were recently reviewed by Florsheim *et al.* (2008), who found that these structures limited the supply of sediment into the stream and are associated with a loss of geomorphic processes (i.e., migration and widening) and connectivity with the riparian forest.

Sediment Storage

The formation of channel bars depends on the rate of sediment supply, the availability of suitable sites for their accumulation, and the energy environment of the river (Knighton, 1998). The frequency of channel bars in constrained morphologies (PBc and SPc) was directly related to the frequency of instream wood, suggesting that channel bars tend to form behind LWD structures in these reaches. Furthermore, sediment supply from channel banks, which in urbanizing watersheds can be a significant component of the overall sediment load (e.g., Trimbel, 1997; Nelson and Booth, 2002), is inhibited in constrained morphologies by the presence of bank-armoring structures, and these reaches are likely to experience even higher shear stresses than other urbanized reaches. This relationship was absent in all other channel types suggesting that the formation of channel bars in other morphologies does not depend solely on the availability of instream wood; these features also form as free point and mid-channel bars.

Bank Erosion

Relations with bank erosion were mainly independent of channel type and were only significant when evaluated across the full range of urbanization. The relationships between bank erosion and basal area and the percentage of trees isolated from the channel were stronger when constrained morphologies were excluded, and absent among high-urbanized reaches when analyzed independently. This suggests that the near-riparian vegetation has little stabilizing effect on the banks of constrained reaches (see also Finkenbine *et al.*, 2000). The riparian vegetation root system provides cohesion to the bank material (Simon and Collison, 2002; Docker and Hubble, 2008) in unconstrained reaches and is the source of LWD, which increases roughness, dissipating stream power and therefore limiting bank erosion (Booth, 1991; Booth and Jackson, 1997). LWD loading, however, was related to reduced bank erosion independent of channel and urbanization level, suggesting that it can mitigate for the effects of high stream power in all settings and channel types.

The results indicate that confined and armored channels (i.e., constrained morphologies) that dominated the high-urbanized dataset have more simplified morphologies, a universal symptom of the urban channels (Walsh *et al.*, 2005), than channels that are only confined. Confinement in high-urbanized channels is likely due (at least in part) to urbanization-induced incision (Hammer, 1972; Booth, 1990) due to the increase in channel depth, and therefore higher shear stresses and transport capacity, with increasing discharge. Because of the disconnection with their banks and floodplain, these constrained channels experience a severe reduction of sediment and wood supply, coupled with an increased transport capacity of both wood and sediment. Conversely, confinement in low-urbanized reaches is likely the result of natural valley setting and is typically not associated with bank armoring. These channels retain considerably higher amounts of wood and sediment than urban confined and constrained morphologies.

CONCLUSIONS

The determinants of channel morphology depend on the complex interaction between the level of urbanization and channel morphology. Previous studies, most of which have focused solely on the condition of watershed or riparian land cover, have been unable to recognize some of the relationships found here because such approaches do not consider the importance of fluvial geomorphology and the geomorphic setting. In channels draining both low- and high-urbanized basins, the condition of the riparian vegetation controls LWD loading; however, most of the high-urbanized basins have low LWD loading regardless of the condition of the near-riparian vegetation. Pool spacing in low-urbanized reaches depends on the frequency of LWD because most channels are FPR draining forested basins. In high-urbanized reaches, however, pool spacing is positively related with the degree of channel confinement, which in most cases is driven by anthropogenic structures. We also found that some relationships between near-riparian conditions and channel morphology are only expressed when evaluated across the full range of urbanization: the relationship between basal tree area and both distribution of LWD and bank erosion, channel confinement and the distribution of LWD, and the position of the near-riparian vegetation relative to the channel, and both LWD loading and pool spacing.

Stratified by channel morphology, FPR and PB channel types are most sensitive to the condition of the near-riparian area, whereas the constrained morphologies (PBc and SPc) were mainly simplified regardless of the size, abundance, and location of the near-riparian vegetation. In these channels, armoring structures in the banks have disconnected the stream from the floodplain. These structures were presumably placed to prevent erosion; however, they have also resulted in lower LWD and higher pool spacing, less sediment storage, and a higher potential for channel incision. In these reaches, the frequency and distribution of LWD, pool spacing, and the channel bank erosion do not depend on the size and location of the near-riparian vegetation, or on the level of channel confinement.

ACKNOWLEDGMENTS

This research was supported in part by the Fulbright Scholarship and the Center for Water and Watershed Studies (formerly the Center for Urban Water Resources Management) at the University of Washington. We also thank Christina Avolio and Mindy Roberts for helpful discussions, and Rachael Booth who helped with field work.

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