Reach-scale geomorphic and biological effects of localized stream bank armoring

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ABSTRACT

Armoring of stream banks is a common management response to perceived threats to adjacent infrastructure from flooding or erosion. Despite their pervasiveness, the effects of reach-scale bank armoring have received less attention than those of channelization or watershed-scale hydromodification. In this study we explored mechanistic ecosystem responses to armoring by comparing conditions upstream, within, and downstream of six stream reaches with bank armoring in Southern California. Assessments were based on four common stream-channel assessment methods: 1) traditional geomorphic measures, 2) the California Rapid Assessment Method (CRAM) for wetlands, 3) bioassessment with benthic macroinvertebrates, and 4) bioassessment with stream algae. Although physical responses varied among stream types (mountain, transitional, and lowland), armored segments generally had lower slopes, more and deeper pools and fewer riffles, and increased sediment deposition. Several armored segments exhibited channel incision and bank toe failure. All classes of biological indicators showed subtle, mechanistic responses to physical changes. However, extreme heterogeneity among sites, the presence of catchment-scale disturbances, and low sample size made it difficult to ascribe observed patterns solely to channel armoring. The data suggest that species-level or functional group-level metrics may be more sensitive tools than integrative indices of biotic integrity (IBIs) to local-scale effects.

INTRODUCTION

Urbanization and other land use changes can greatly alter watershed hydrology and sediment yield, causing a variety of morphologic adjustments in stream channels (e.g., Wolman 1967, Leopold 1968, Chin 2006). These hydrologic and geomorphic responses to urbanization have been termed *hydromodification* (USEPA 1973). Wolman (1967) outlined a conceptual model for hydromodification whereby, following an initial period of increased sediment yield and channel aggradation, increased impervious surfaces associated with urban development result in greater runoff, increased peak discharge, and channel incision and widening. In reviewing over 100 studies on the effects of urbanization on rivers, Chin (2006) found that, although channels exhibited considerable variation in the magnitude and timing of responses, Wolman's (1967) conceptual model was applicable worldwide.

A common management response to hydromodification is to attempt to physically stabilize channels that are actively adjusting. Eroding stream banks are often reinforced with hard structures such as concrete walls, boulders, or gabions. These bank armoring structures are intended to stabilize channels and protect infrastructure, but they often result in increased stream power and decreased channel roughness, exacerbating stream channel responses to urbanization (Riley 1998, Jacobson *et al*. 2001). For example, hardened banks can cause localized streambed erosion at the base of the banks, undercutting

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the very structures that were intended to stabilize the channel. Geomorphic and hydraulic channel responses can propagate upstream and downstream from hardened banks, depending on the shape and slope of the channel and the nature of the installed structure (Kassem and Chaudhry 2005, Labbe *et al*. 2010). Although few studies have examined it directly, it seems likely that channel adjustments to bank armoring can have negative impacts on aquatic biota. For example, habitat for salmonids is negatively impacted by the reduced overhead cover and woody debris recruitment associated with bank armoring (Schmetterling *et al.* 2001).

As the protection and restoration of urban streams becomes increasingly valued by society, watershed managers and fluvial scientists are challenged to accurately identify sources of environmental degradation. A general relationship between urbanization and biological responses in streams is well established (Paul and Meyer 2001, Roy *et al*. 2003, Brown et al., 2005, Alberti *et al*. 2007, Gurnell *et al*. 2007, Brown *et al*. 2009, Cuffney *et al.* 2010), but the relative importance of various mechanisms (e.g., altered hydrology, chemical pollutants, loss of riparian vegetation, etc.) in causing ecological degradation is debated (e.g., Walsh *et al.* 2005). In particular, the mechanisms and magnitude of aquatic ecosystem impairment by bank armoring have not been studied and are poorly understood. Watershed managers and regulators currently face tremendous uncertainty when contemplating the value of bank armoring projects. Under what scenarios or landscape settings should bank armoring projects be permitted? Is it possible to predict and mitigate the ecological effects of planned bank armoring projects? An improved understanding of the geomorphic and ecological impacts of bank armoring, particularly those associated with isolated, small-scale structures, would enhance our ability to protect and restore aquatic resources.

The objective of this study is to support improved stream corridor management practices by exploring the linkages among stream bank armoring, geomorphic changes to the streambed and channel form, and biological responses among aquatic macroinvertebrates, algae, and riparian habitats. We conducted a field study of alluvial streams in Southern California to explore the following questions: 1) What are the variety of mechanistic linkages between physical or hydrologic responses to bank armoring and community-level biological effects? 2) To what degree do landscape setting, channel form, and the nature and type of channel armoring affect the types and magnitudes of physical and biological responses to armoring? 3) How does the magnitude of physical and biological changes associated with bank armoring compare to endpoints indicative of stream condition and environmental quality? We are not aware of other studies that have specifically addressed these questions, so we designed this project as a pilot study to refine our understanding of possible mechanistic responses to bank armoring, rather than proposing specific hypotheses to test experimentally. Thus, this study represents a first step toward developing a general conceptual model of geomorphic and biological responses to bank armoring. Our approach was to use a wide variety of common stream monitoring protocols in order to maximize our ability to detect changes and to explore the potential benefits of different assessment methods for examining the effects of bank armoring.

METHODS

We investigated several geomorphic and biological effects of stream channel armoring by conducting a field study of six streams in the Los Angeles region, Southern California, USA (Table 1; Figure 1; selected site photos provided in Supplemental Information (SI) available at ftp://ftp.sccwrp.org/pub/download/DOCUMENTS/AnnualReports/2012AnnualReport/ar012_09SI.pdf). To insure that our study sites represented the range of stream types where bank armoring projects are typically constructed in our region, we selected study sites from three different watershed positions (mountain, transitional, lowland) with the following characteristics: watershed drainage areas of 50 to 300 km^2, channel slopes of 0.1 to 2%, pool-riffle morphologies, and discrete segments of bank armoring ranging from 100 to 200 m long (Table 1). The channel bottom at all sites consisted of natural substrates.

Each of the six study reaches comprised 1) a 150 m long, unarmored upstream segment (“A”), 2) a 100-200 m long segment with armoring on at least one bank (the “impact” segment, “B”), and 3) a 150 m long, unarmored downstream segment (“C”). Segment A was used as a control to examine effects in the armored segment (B), while segment C was used to investigate whether any observed effects propagated downstream. At one site (M1) we did not include a downstream segment because the impact

Table 1. Summary of study sites.

Watershed Position Category	Site Code	Site Name	Upstream Drainage Area (km^2)	Upstream Effects on Hydrology	Landscape Setting	Slope (%)	Q10[1] (cfs)	Predominant Land Use	Nature and Type of Bank Armoring
Mountainous/ Upper Watershed	M1	W. Fork San Gabriel River	215	Cogswell Dam; upstream fire in prior year	river gorge	1.68	8,667	forested	Concrete structure on right bank of outside bend of active channel, ~45 degree angle and ~5 m tall
	M2	E. Fork San Gabriel River	205	none	montane alluvial valley	1.59	8,218	forested	Gabions filled with riprap on left bank of outside bend of active channel, 90 degree angle and ~5 m tall
Transition Zone/ Foothills	T1	Big Tujunga	298	Big Tujunga Dam; upstream fire in prior year	proximal alluvial fan	1.39	5,119	mixed scrub-shrub + urban	Concrete structure on left bank of outside bend active channel, ~45 degree angle and ~5 m tall
	T2	Arroyo Seco	49	upstream fire in prior year	river gorge	2.64	3,342	mixed forested + urban	Concrete structure on right bank of inside bend of active channel, 90 degree angle and ~10 m tall
Lower watershed	L1	Arroyo Simi	215	none	montane alluvial valley	0.24	7,339	urban	Concrete structure on right bank of outside bend of active channel, ~45 degree angle and ~5 m tall, plus groins every ~25 m
	L2	Conejo Creek	197	none	alluvial valley	0.12	5,326	agriculture	Concrete structure on right bank of outside bend of active channel, ~45 degree angle and ~5 m tall

[1] Q10 is the adjusted long-term average 10-year flow, calculated by dividing Q10 from the closest stream gauge by the ratio of gauge drainage area to site drainage area

segment was located just upstream of a confluence with a major stream.

The type of bank armoring was fairly similar among the six study sites. For instance, at four of the sites, one bank was reinforced with concrete (either smooth or with embedded rip-rap) sloping at approximately a 45 degree angle and approximately 5 m in height (Table 1). Furthermore, armored segments (B) were most often located along the outside of meander bends. We believe that in all cases, the bank armoring structures (which severely constrained the lateral movement of the study streams) enhanced the forcing of pool scour and meander development by constraining channel migration. This position is supported by observations of historical planform photos of the study sites, which show that all of the channels had been quite dynamic, both upstream of, and within, the bank segments that were eventually armored. Thus, in most cases, we believe that the present-day channel planform patterns strongly reflect the influence of the bank armoring structures, and that physical differences between stream segments can justifiably be interpreted as resulting, at least in part, from bank armoring.

Channel Geomorphology

The physical effects of channel armoring were investigated using traditional stream channel geomorphic surveys (e.g., pebble counts, cross-sections, longitudinal profiles) as well as the Physical Habitat

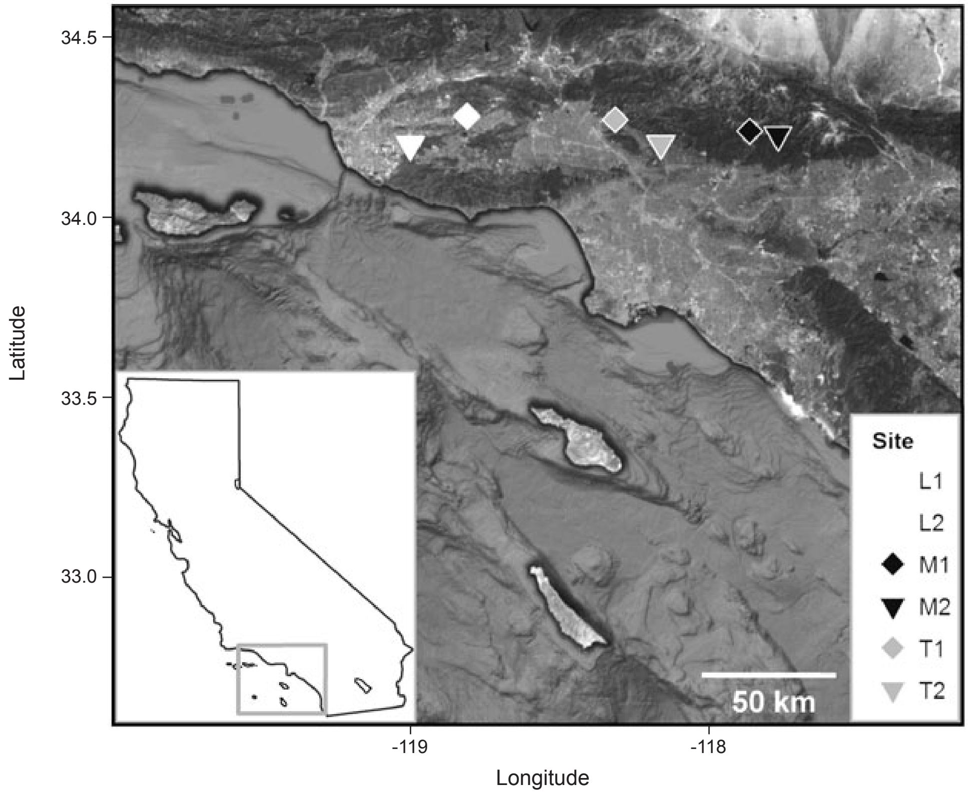

Figure 1. Map of study sites.

(PHAB) protocols associated with aquatic bioassessment surveys conducted by the State of California (Ode 2007). We measured channel geometry at each study site by surveying the channel's longitudinal profile and a representative channel cross-section with an auto-level, meter tapes, and a stadia rod. The longitudinal profile of each study reach was surveyed along the channel thalweg at approximately 10-m intervals, and/or at slope breaks, to capture information on channel gradient, riffle gradient, and pool depth. Within each segment we selected and surveyed a cross section representative of the segment's general topographic character.

We sampled bed surface particle size distributions by conducting pebble counts (Wolman 1954). Pebble counts were not conducted where the bed material was predominantly sand (Sites L1 and L2) or large boulders in deep water (M1). A minimum of 100 particles were measured in each study segment. Particles <4 mm in diameter were recorded as sand.

PHAB measurements were made at 11 evenly spaced transects in each segment, corresponding with sampling locations for benthic macroinvertebrates and algae (see below). At each transect, we measured the wetted width; flow habitats; water depth, particle size, coarse particulate organic matter; cobble embeddedness; slope; canopy cover; riparian vegetation; instream habitats; bank stability; and bankfull dimensions. Some of the PHAB measurements were also made at ten additional transects located between the main transects, to give a total of 21 transects per segment.

Biological Conditions

Biological effects of bank armoring were investigated using the California Rapid Assessment Method (CRAM) for wetlands (Collins *et al*. 2008) and standard protocols for bioassessment with benthic macroinvertebrates (Ode 2007) and algae assemblages (Fetscher *et al*. 2009). For this study, the "Riverine" version of CRAM for assessment of streams was employed.

CRAM is based on four attributes of wetland condition: landscape context, hydrology, physical structure, and biotic structure. Attributes are evaluated based on a set of metrics, or readily observable field indicators (Table 2) corresponding to a standardized set of mutually exclusive descriptions representing a full range of possible conditions. Metrics are scored according to narrative descriptions, quantitative measures, or diagrams (depending on the metric). Attribute and index scores can range from 25 (lowest possible) to a maximum of 100. The median CRAM overall index score for southern

California streams based on a recent probabilistic survey was 63 for sites in urban settings and 83 for sites in agricultural and undeveloped (open-space) settings (C. Solek, unpublished data).

Benthic macroinvertebrates (BMI) were sampled using the multihabitat method described in Ode (2007). Each 150 m segment was divided into 11 equidistant transects, and a 500 µm mesh D-frame net was used to collect macroinvertebrate from a 0.093 m^2 patch of substrate from an objectively chosen location along each transect (i.e., 25, 50, or 75% of the way across the stream). The 11 subsamples were composited into one container and specimens were preserved immediately using 100% ethanol, resulting in a final concentration of 70 to 80%. In the laboratory, a minimum of 550 macroinvertebrates were sorted and identified from every sample based on standard protocols and following the taxonomic standards of the Southwestern Association of Freshwater Invertebrate Taxonomists (SAFIT; Richards and Rogers 2006). Macroinvertebrate Index of Biotic Integrity (IBI) scores were calculated for each segment. The IBI consists of a set of metrics that are summed, and the overall score can range from 0 to 100 (Ode *et al*. 2005). The median IBI score for southern California streams based on a recent probabilistic survey was 16 in urban streams, 27 for agricultural streams, and 57 for streams in open-space settings (Mazor *et al*. 2011).

Stream algae were sampled using the standard protocol described by Fetscher *et al*. (2009). Benthic macro- and micro-algae (including diatom and soft-bodied taxa, as well as cyanobacteria) were concurrently sampled from a variety of stream substrata within the study segment. The same 11 transects used for the macroinvertebrate and PHAB sampling were used, spatially offset slightly, for sampling algae. At an objectively identified location along each transect, a sample of algal material was collected from whatever substrate type was present (e.g., cobble, gravel, sand, boulder, bedrock) using a device with a known sampling area. Specimens from all 11 transects were combined into a “composite” sample and mixed; the composite was then aliquoted into several subsamples for separate analysis of 1) diatom taxonomic identifications and enumeration, 2) soft-bodied algal and cyanobacterial taxonomic identifications and quantification, and 3) algal biomass analyses.

After diatom samples were cleaned of organic matter, they were mounted on permanent slides and 600 objectively selected diatom valves were identified to the lowest taxonomic category (species, variety, or form) possible, following the method of Van Der Werff (1955).

A total of 300 “counting entities” of soft-bodied algae and cyanobacteria were identified at 200 to1000x magnification (as needed) under a research-grade compound microscope. Entities could be multicellular taxa (colonies or filaments) or individual unicells. This procedure enabled objective characterization of algal assemblages that have a broad range of morphological forms and sizes. Volumetric measurements were used to estimate total biovolume of each taxon. All specimens were identified to the lowest taxonomic level possible (usually species or variety, except where sexual reproduction was necessary for identification to species level (*e.g.*, *Oedogoniales* and *Zygnematales*)).

Total soft-algal biomass was determined using a combination of water-displacement and volumetric measurements under a microscope in order to determine biovolume represented in the sample, as well as extrapolated to an estimate at the level of the stream segment. Ash-free dry mass (AFDM) of the entire algal assemblage was determined by homogenizing and filtering known volumes of composite sample, drying the filters to a constant weight, oxidizing them at 500°C, and reweighing them to determine the mass of organic carbon in the sample.

Data Analysis

The primary goal of this pilot study was to explore the range of possible linkages among bank armoring, physical responses, and biological effects in streams in our region. We did not develop specific hypotheses to statistically test because we anticipated that our sites would express a variety of mechanistic responses to localized armoring. Instead, our primary approach to data analysis was to look for consistent, mechanistic responses among all or a subset of our six sites. We used several statistical approaches as screening tools for general trends in our data.

First, we compared relative differences in physical and biological characteristics between upstream (A) and armored (B) segments and between the armored (B) and downstream (C) segments by performing the nonparametric equivalent of the paired t-test, the Wilcoxon signed-rank test, which ranks the absolute value of differences among pairs of data, sums the positive and negative values of signed ranks, and compares these sums to a critical value in order to test the null hypothesis that there are no differences between the segments. Unless otherwise stated, $\alpha = 0.05$ for all inferential analyses, and significance is based on two-tailed tests.

We also examined dissimilarity of the macroinvertebrate, diatom, and soft algal communities among sites and stream segments using non-metric multi-dimensional scaling (NMS) multivariate ordinations. Ordination is a statistical technique that reduces the dimensionality of information in a dataset in order to summarize its major gradients. The product of an NMS ordination conducted on community composition data (i.e., counts or proportions of the species recorded in the sample) is a series of axes, plots of which provide insight into similarity in species composition among samples. The closer two sample points are to one another within an NMS ordination plot, the more similar they are in terms of the types and proportions of species they contain. Relationships between NMS ordination scores and environmental gradients can also provide insight into potential controlling factors for species presence and abundance from site to site. NMS was run using PC-ORD software (McCune and Grace, 2002) with the Sorensen distance measure and "slow and thorough" autopilot mode, which runs initial ordinations to determine the best dimensionality (stability criterion of 0.00001, maximum of six axes, 40 runs with real data, and 50 randomized runs) and a second round of ordinations using the selected dimensionality (stability criterion of 0.00001, one run with real data, up to 400 iterations). We used untransformed taxa densities (individuals/m^2) for the macroinvertebrates, valve counts for diatoms, and cube-root transformed biovolume values for the soft algae community.

For macroinvertebrates, we examined the correlation of environmental variables with the biotic ordinations as well as the correlation coefficients between each taxon and the axes of the final ordination. We used a minimum correlation (r) value of 0.5 as the criterion for recognizing strong correlations.

Analysis of the biological data involved characterizing taxa in terms of features hypothesized to confer differential responses to hydromodification. For the macroinvertebrates, we examined traits including habitat (lotic or lentic), habit (burrower, clinger, swimmer, or sprawler), and functional trophic group (shredder, collector, scraper, predator, or parasite), using data from standard sources (Merritt *et al*.2008). For the diatoms, we examined traits relating to motility and growth form. Motility was classified as either "non motile", "moderately motile", or "highly motile". With respect to growth form, diatom taxa were classified based on whether they tend to be attached to substrata or not, and of the attached forms, whether they generally maintain low vertical profiles within the stream (prostrate), which presumably would render them more resilient to high-velocity flows, or extend more upwardly into the water column (stalked). Soft-bodied taxa were characterized according to their ability to tolerate sedimentation, and according to their tendency to prefer habitats with slower-moving water *vs*. faster. National databases (e.g., from the US Geological Survey's National Water Quality Assessment Program; Porter *et al.* 2008) and personal communications with the expert phycologists who identified the specimens were used to assign these characters to each taxon. A number of simple indices were created and applied across each of the sampling sites in order to look for consistent patterns relative to hydromodification. For some indices, this was done by assigning factors of varying magnitude to the different categories, then weighting the proportion of all taxa in each category by that factor, and summing the resulting products for each site. For example, for the "diatom motility index", the highly motile diatoms were weighted by a factor of 3, and the moderately motile were weighted by a factor of 2, such that a higher the overall score at a given site, the greater the inferred ability for the diatom community to tolerate sedimentation, and therefore the greater the likelihood that sedimentation had been occurring at that site. All of the indices were calculated using both relative abundance data and species richness data.

RESULTS

Physical Conditions

With the exception of site L2, measured bed slope was steepest in the upstream "natural" segments (A), less steep in the downstream segments (C), and least steep in the middle "impact" segments (B). Measures of cross sectional geometry, including wetted channel, primary channel, and floodplain widths, did not display consistent trends between upstream, impact, and downstream segments among study sites. However, we observed evidence of varying degrees of channel incision in the armored segments at all sites. We also observed bank toe failure (undercutting) in the armored segments at

Sites M1, M2, and L2, suggesting that bank hardening is contributing to localized incision at these sites.

The median grain size in armored segments was significantly smaller than in upstream segments (p = 0.039) and downstream segments (p = 0.047) based on the Wilcoxon signed-rank test. Although differences in the distribution of riffles and pools between upstream and armored segments were not statistically significant, trends in geomorphic relationships with armoring were similar between sites occupying similar positions within the watershed. For example, there was a substantial increase in pool area in the armored segments of the two mountain streams relative to the upstream segment, while streams in other landscape positions did not exhibit differences in pools. Similarly, armored segments had substantially greater riffle area than upstream segments in the four transitional and lowland streams (Figure 2). CRAM Physical Structure scores were higher in armored segments of mountain streams relative to the upstream areas (Figure 3).

Instream habitat complexity in upstream, armored, and downstream segments did not vary consistently among sites. Several sites exhibited reduced instream complexity in armored segments, but catchment processes, local disturbances, and/or natural features precluded attribution of these observations directly to the presence of a hardened bank (e.g., exposed bedrock in some segments can function similarly to an artificial bank-hardening structure).

Biological Conditions

There was a general trend toward lower CRAM index scores in the armored stream segments relative to the upstream segments. However, no statistically significant downstream effects were apparent, as CRAM index scores for downstream segments were comparable to those upstream of the armoring (Figure 3). At the individual attribute level, the most pronounced effect was that of consistently and significantly lower Biotic Structure in the armored segment relative to the upstream control segment. This result likely reflects loss of riparian vegetation and instream habitat as a result of bank armoring. The Hydrology attribute scores were slightly lower in armored segments than in upstream segments; however, the differences were generally within the 5% error range associated with CRAM attribute scores (Stein *et al.* 2009). There was a statistically significant difference between the armored and downstream segments in terms of the Buffer and Landscape Connectivity and Hydrology attributes, reflecting the differences in the landscape setting of the armored segments *vs*. the downstream segments.

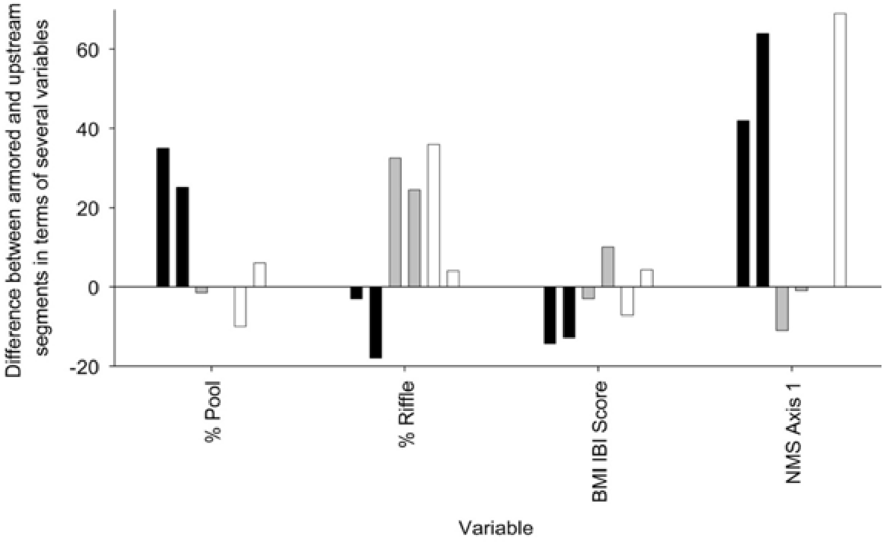

Figure 2. Differences in physical habitat and benthic macroinvertebrate (BMI) response variables between armored and upstream segments. Positive values indicate higher scores in the armored segment (B), while negative values indicate higher scores in the upstream segment (A). Zero values (i.e., where bars are not visible) indicate that there was no difference between the two segments. Note that the "mountain" sites (M1 and M2) often had different responses from the other sites. Black bars correspond to mountainous/upper watershed sites, grey to transition zone/foothill sites, and white to lower watershed sites. Each group of bars corresponds the following ordering of sites: M1, M2, T1, T2, L1, L2.

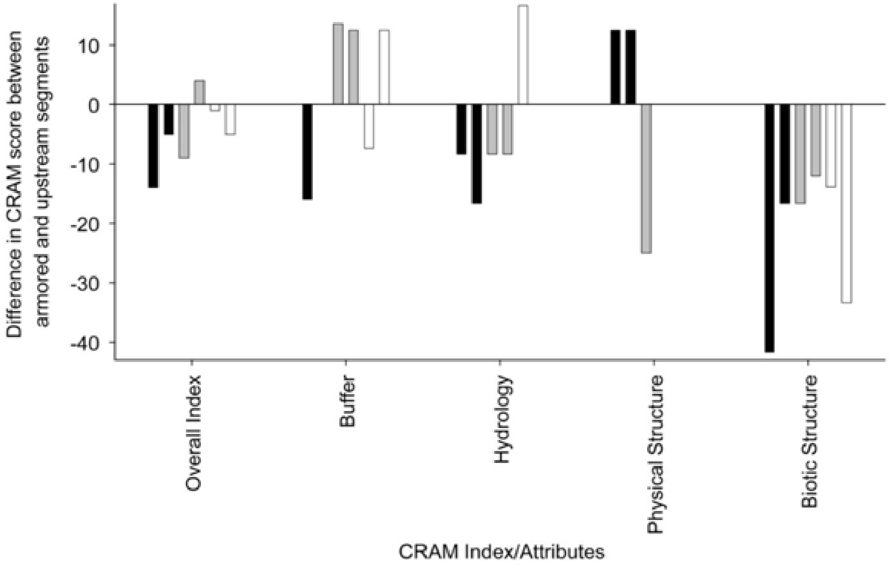

Figure 3. Differences in California Rapid Assessment Method (CRAM) index and attribute scores between armored and upstream segments. Positive values indicate higher scores in the armored segment (B), while negative values indicate higher scores in the upstream segment (A). Zero values (i.e., where bars are not visible) indicate that there was no difference between the two segments. Black bars correspond to mountainous/upper watershed sites, grey to transition zone/foothill sites, and white to lower watershed sites. Each group of bars corresponds the following ordering of sites: M1, M2, T1, T2, L1, L2.

There were no differences between the three segments (upstream *vs*. armored *vs*. downstream) in terms of macroinvertebrate IBI scores, constituent metrics, or functional traits. Impact segments had slightly lower mean IBI scores (36.4) than the upstream segments (40.2), but this difference was not statistically significant. Although strong, consistent responses to channel armoring in terms of macroinvertebrate metrics were not observed, a subset of individual sites did exhibit expected responses. For example, IBI scores decreased from upstream to armored segments at four of the six sites (Figure 2). The magnitude of change was the largest at the two mountainous sites (M1: 63.6 to 49.3; M2: 62.1 to 49.3), which were, in general, exposed to less anthropogenic stress than the other sites. The lower IBI scores in armored segments at these sites resulted from decreases in *Coleoptera* Taxa and increases in Percent Non-Insect Taxa and Percent Tolerant Taxa metrics.

The NMS analysis of macroinvertebrate community composition resulted in a stable, 3-dimensional solution, based on plots of stress *vs*. number of axes (Final stress, 7.8; final instability, 0.00001). Axes 1 and 2 were moderately correlated ($r^2 = 0.257$), while the other axes were essentially uncorrelated with one another ($r^2 <0.01$). Variation among sites was generally much greater than the variation among segments within sites, as evidenced by the generally close clustering of segments within sites. Generally, the mountainous sites (M1, M2) were more similar to one another, as were the lowland sites (L1, L2; Figure 4).

Several sites exhibited consistent differences in ordination values among segments. Axis 1 values increased by a mean of 0.29 (14% of total range of Axis 1) from upstream segments to armored segments, with the largest differences at L2 (0.69), M2 (0.64), and M1 (0.42) (Figure 4). Mean differences in ordination values between upstream and armored segments for Axis 2 and Axis 3 were near zero (Axis 2, -0.02; Axis 3, 0.05). Based on the known characteristics of the taxa associated with each ordination axis, Axes 1 and 3 are negatively correlated with cool, clean water or good habitat conditions, suggesting that higher Axis 1 scores in the armored segments represent more tolerant taxa. For example, only one taxon, the generalist and moderately tolerant midge *Tanytarsus*, was positively correlated (r = 0.601) with Axis 1; however, seven taxa exhibited moderate or strong negative correlations with Axis 1, including sensitive and cold-water taxa such as the perlid stonefly *Calineuria californica* (-0.628), the mayfly family Heptageniidae (-0.728), the riffle beetle *Narpus* (-0.624), and the ephemerellid mayfly *Ephemerella maculata* (-0.754).

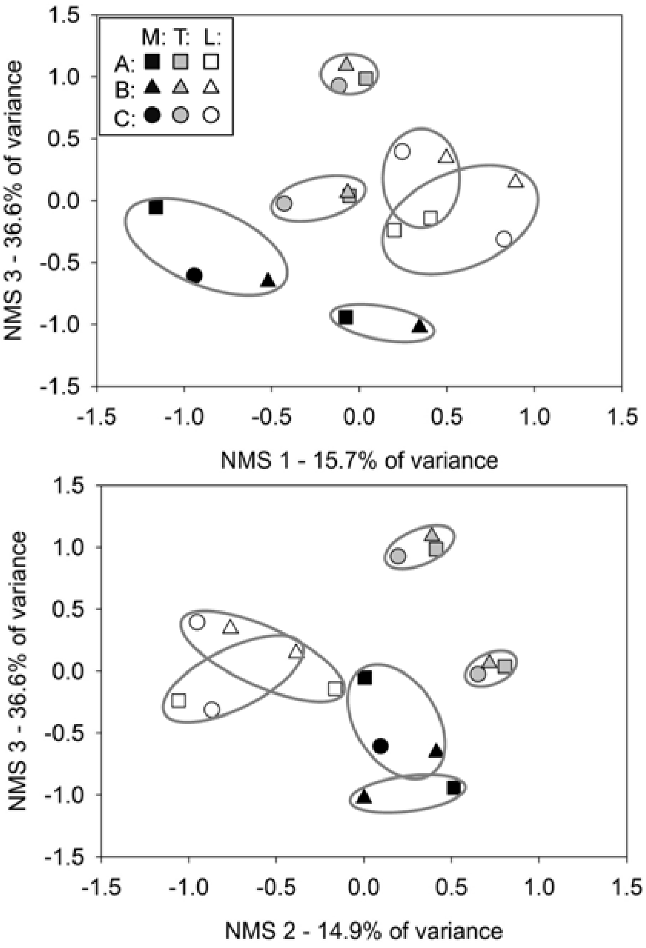

Figure 4. Nonmetric multidimensional scaling (NMS) ordination plots of benthic macroinvertebrate (BMI) raw taxa densities. Axis 1 vs. 3 is shown in the top graph, and Axis 2 vs. 3 in the bottom. Each point corresponds to a single stream segment. Black symbols correspond to mountainous/upper watershed sites, grey to transition zone/foothill sites, and white to lower watershed sites. Squares correspond to the upstream segment (A), triangles to the impact segment (B), and circles to the downstream segment (C). Points belonging to the same stream reach (i.e., site) are circled.

Several physical habitat variables were correlated with the macroinvertebrate NMS ordination axes. The correlations suggest that the armored segments were characterized by more pooling and correspondingly higher fine-grained substrate. Percent sand and fines on the streambed was negatively correlated with Axis 2 and positively correlated with Axis 1. Correspondingly, percent fast-flow habitats was negatively correlated with Axis 1. Total canopy density was negatively correlated with Axis 2, with the highest vegetation densities occurring at Site L1. Percent pool habitats and water depth were both negatively correlated with Axis 3, with the highest values for both variables occurring at Sites M1 and M2.

NMS ordinations of algae showed no consistent differences between the three sampling positions (upstream *vs.* armored *vs.* downstream; Figure 5), for diatoms or soft-bodied algae. However, with the exception of Site T1 for the soft-bodied assemblage, there were strong groupings of study segments by site based on community composition.

Mechanistic responses were also examined through relationships between bank armoring and groupings of taxa based on established or hypothesized flow and sedimentation tolerances. However, as with the NMS ordinations, most of the variance in index values was explained by site differences, and not by segments within each site (i.e., armored *vs.* upstream).

Diatom and soft-bodied algal communities aligned well in terms of sedimentation response, both between and within sites (Figure 6). Both diatom and soft-algal sediment-tolerant taxa were more prevalent in armored segments that had higher deposition of fine grained sediments. In addition, the two sites (M1 and M2) with the lowest sedimentation indices based on diatoms were also the lowest sites based on soft-bodied algae. Consistency between assemblages was also apparent at the higher sedimentation-response sites (i.e., L1 and L2). No relationship was apparent between assemblages in terms of flow response.

From the standpoint of biomass, neither soft-bodied algal total biovolume nor ash-free dry mass exhibited statistically significant relationships with channel armoring. However ash-free dry mass was highest at segment A (upstream of the armoring) in five of the six sites. As with most other types of analyses presented, variation between sites far exceeded that within sites.

DISCUSSION

The results of this study, albeit based on a small sample size, set a foundation in support of our conceptual model of geomorphic and biological responses to bank armoring. We found evidence that stream channel morphology responds to channel armoring and that such physical responses can in turn affect instream biological communities. Changes in flow and sedimentation patterns in armored segments can result in deposition of fine grained material and/or expansion of lower velocity pools or glides. These physical changes favor colonization by benthic

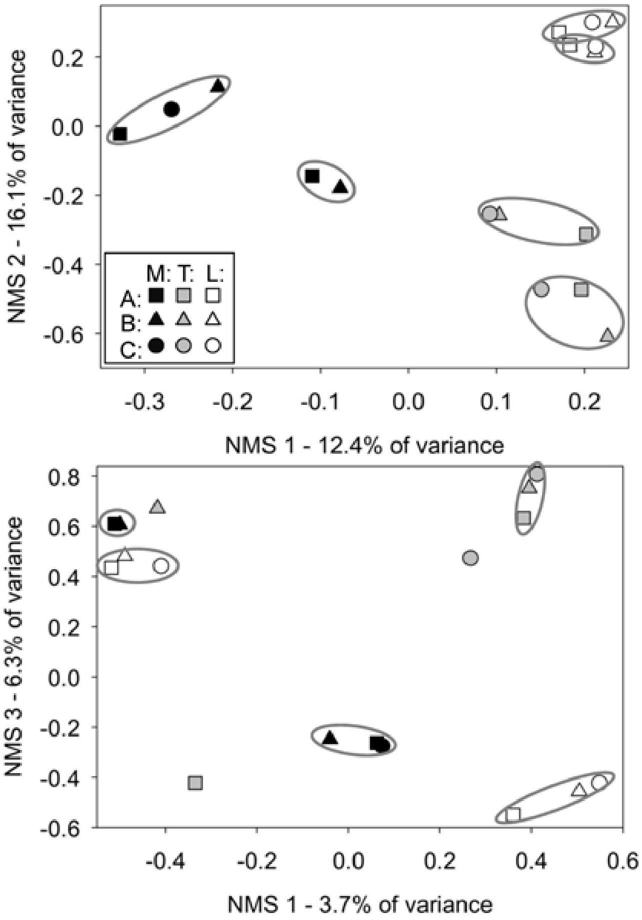

Figure 5. Relationships between Nonmetric multi-dimensional scaling (NMS) axis scores based on diatom community composition (top graph) and soft-bodied algal community composition (bottom). Each point corresponds to a single stream segment. Black symbols correspond to mountainous/upper watershed sites, grey to transition zone/foothill sites, and white to lower watershed sites. Squares correspond to the upstream segment (A), triangles to the impact segment (B), and circles to the downstream segment (C). Points belonging to the same stream reach (i.e., site) are circled (except for one site in the soft-bodied algae graph, for which the segments were too scattered to facilitate encircling them).

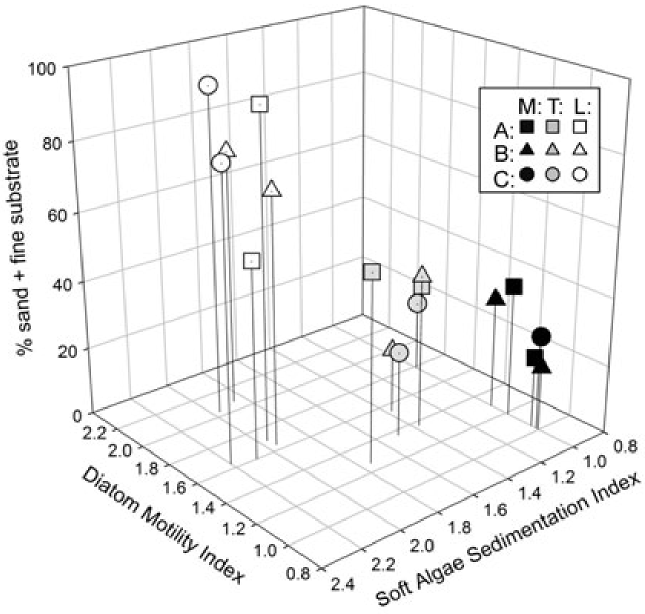

Figure 6. Relationship between stream percent sand + fine substrates and algal assemblages in terms of index scores for motility and sedimentation. Each point corresponds to a single stream segment. Black symbols correspond to mountainous/upper watershed sites, grey to transition zone/foothill sites, and white to lower watershed sites. Squares correspond to the upstream segment (A), triangles correspond to the impact segment (B), and circles correspond to the downstream segment (C).

macroinvertebrates and algae that are tolerant of these conditions. Although the exact patterns of response varied among the six sites sampled in this study, consistent, subtle patterns were observed that suggest channel response mechanisms may be occurring. However, these responses may be difficult to discern from other factors influencing the sites, such as upstream dams, anthropogenic discharges, or recent fires. Each of the study sites was distinct from the others in terms of both its physical and biological characteristics. NMS ordinations of taxonomic composition data for the three biotic assemblages (macroinvertebrates, diatoms, and soft-bodied algae) showed that between-site differences were much greater than differences between segments within the sites (and therefore relative to bank armoring). Therefore, the sites could not be considered as replicates, limiting the statistical power of our data set. In no cases did we observe any propagation of effects to the downstream segments.

Several of the effects of channel armoring were particularly evident at higher quality sites (i.e., those found in mountainous upper watershed areas). In particular, Sites M1 and M2 exhibited increased bed scouring and decreased instream habitat complexity within the armored segments relative to the upstream segments (as evidenced by the higher proportion of pools and lower proportion of riffles in the armored segments). This finding is in agreement with the conceptual model of river response to bank hardening. During high flows, water will move fastest along a hardened bank or bedrock surface where there is the least amount of friction, resulting in incision into the stream bed. Physical changes were accompanied by lower CRAM attribute scores for Biotic Structure at all sites, which is likely reflective of the direct effects of removing streamside vegetation to construct armoring. However, it is important to note that we cannot conclude that our observations and measurements can be solely attributed to the presence of a hardened bank. Site-specific conditions as well as natural and anthropogenic influences affect the extent to which hardened bank structures influence channel form and bed complexity as well as the ability to decipher these impacts. Channel incision observed in impact segments (specifically, toe failure), and in some downstream segments, can be partially attributed to catchment-scale processes and other upstream structures, such as dams, that may affect channel geometry and instream features at the study sites (Ligon *et al*. 1995, Gordon and Meentemeyer 2006). In addition, recent disturbances (such as the 2009 Station Fire) or recreational activities are likely affecting channel features. The assessments we employed provide a "snapshot" of impacts observed during summer when stream flow is low. Repeat cross section measurements following subsequent winter rains would help validate these findings and begin to discern the influence of local *vs*. watershed-scale influences.

Response of benthic macroinvertebrates to changes in flow and sedimentation is well documented (Moyle 1976, Poff and Ward 1989, Waters 1995). The ability of biological metrics or indices to detect physical change is a function of the severity of the impact and the spatial and temporal variability within the site (Milner *et al*. 2005, Bêche *et al*. 2006). Given the low number of sites in this study and the high variability among the study sites with regard to geomorphic setting and upstream land use, consistent, detectable responses to bank armoring of macroinvertebrate communities, as measured by the IBI and its constituent metrics, may be unlikely even if actual physical and biological responses are large. Nonetheless, at our high quality sites (M1 and M2), expected biological responses were observed and several of the measured physical effects were most pronounced. Response at high quality sites is often easier to detect with metrics and biotic indices that are anchored to least-impacted reference conditions. The depauperate or stress-tolerant biological communities generally observed at already impacted sites will be less likely than the communities of more sensitive taxa found at higher quality sites to change further in response to the additional effects of bank armoring. Moreover, historic land use, particularly agricultural (such as that characterizing sites L1 and L2) has been shown to be an important predictor of present-day low diversity of stream invertebrate assemblages (Harding *et al*. 1998). As such, legacy land-use effects may reduce the ability of our assessment tools to detect responses to bank armoring at these sites.

Overall biological indices are not always the most sensitive indicators of geomorphic responses to urbanization, possibly because the component metrics respond to factors (such as water quality) that are confounded with geomorphic processes (Booth and Jackson 1997, Paul and Meyer 2001, Rogers *et al*. 2002, Fitzpatrick *et al*. 2005). This suggests that more sensitive indicators, perhaps at the species or functional group level, may be necessary to detect effects of channel alteration (Poff *et al*. 2006, Chessman *et al*. 2007). This is particularly applicable to small, heterogeneous data sets where effects may be dampened at the metric level. Consistent with this phenomenon, increased Axis 1 values for the benthic macroinvertebrate NMS, as was observed at armored segments of Sites M1 and M2, is interpreted to represent a decrease in macroinvertebrate diversity and overall biological integrity, based on the negative correlations of this axis with pollution-sensitive taxa. In terms of changes to the physical environment, these biological shifts may be related to an increased extent of pools and less fast-water habitat resulting from channel armoring. Similarly, although there were no consistent differences in algal community composition or metrics between the armored and unarmored segments across sites, the diatom and soft-algae trait-based metrics reflecting sedimentation tolerance were found to be associated with percent fines and sand, supporting the ability of these assemblages to respond to at least some effects of hydromodification.

Specific aspects of stream algal communities have the potential to reflect flow regime and sediment transport, both of which are potentially altered by channel armoring. For example, some benthic diatom genera, such as *Nitzschia* and *Surirella*, are able to propel themselves, and this quality could render them less susceptible to burial by sedimentation. Indeed, some workers have found motile diatoms to be more frequent in stream segments subject to high levels of sedimentation, such that these taxa are sometimes considered sedimentation indicators (Pan *et al*. 1996, Fore and Grafe 2002).

With respect to flow, some taxa, such as *Lemanea fluviatilis* and *Hydrurus foetidus* (Wehr and Sheath 2003), have growth forms and/or preferred habitats that suggest that they are more tolerant of high flows than other forms that are only loosely attached to stream substrates and or have an extensive vertical profile, and therefore tend to be found in quiet pools or slow-moving waters.

Subtle shifts in algal species were observed at our study sites, suggesting a potential mechanistic response. The clearest outcome of this study was the relationship between the diatom and soft-bodied algal communities as indicators of sedimentation. With the exception of Site T1, there was a tendency for sites with high sedimentation based on diatom evidence to exhibit the same response in terms of soft algae. This same pattern was apparent using a variety of different sedimentation indices. Congruence between response of the diatom and soft-algae assemblages suggests that our assumptions about taxon-specific responses to bank armoring have merit.

The lack of observed downstream effects in either the physical or biological indices suggests that effects of armoring are localized and may not propagate downstream. This is consistent with the findings of other researchers who have similarly observed that benthic macroinvertebrates respond to local stream conditions by utilizing refugia with suitable flow requirements thereby allowing communities to recover quickly from the deleterious effects of habitat alteration (Negishi *et al*. 2002). Furthermore, macroinvertebrates can re-colonize over tens of meters from upstream by drifting (Waters 1972); therefore, once suitable conditions resume, indices often return to reference levels.

The overall weight of evidence of the biological indicators, and their concordance with the physical effects observed, suggest that the instream biological communities are responding to scour and sedimentation patterns associated with bank armoring. These effects appear to be more pronounced at higher quality sites, likely because there is more opportunity for degradation than at sites that have already been impacted by stressors associated with their surrounding landscape. This study should be considered a preliminary "pilot" that tests the ability of commonly used measures of instream physical and biological integrity to detect effects of channel bank armoring. The low sample size and extreme variability between sites makes it difficult to discern consistent patterns. Nevertheless, past studies have shown that local geomorphology and related physical parameters influence the structure of benthic macroinvertebrate functional group composition (Wohl *et al*. 1995, Suttle *et al*. 2004, Cover *et al.* 2008). While the small number of macroinvertebrate functional traits we examined in this study did not exhibit responses to bank armoring, we did observe some consistency in shifts in the macroinvertebrate assemblage in ordination space. As such, a functional trait approach, like that described by Poff *et al*. (2006) may be more sensitive to changes in local channel characteristics, such as those associated with bank armoring, while overall indices, such as IBIs, may be better applied to assessment of catchment-scale effects.

Future efforts should continue to elucidate mechanistic responses at the species and functional-group levels, with a goal of producing indicators more sensitive to local-scale effects. The universality of patterns observed in this study could be explored by replicating it in other areas and with streams of different sizes, geologic settings, dominant substrate types, and in different climatological settings. Results of such analyses will help determine whether trends we have seen with this pilot can be extrapolated broadly, or whether models for the effects of bank armoring must be customized for different systems.

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SUPPLEMENTAL INFORMATION

Supplemental Information is available at ftp://ftp.sccwrp.org/pub/download/DOCUMENTS/AnnualReports/2012AnnualReport/ar12_09SI.pdf