Regional impacts of urbanization on stream channel geometry: A case study in semiarid southern California

Kristine T. Taniguchi *, Trent W. Biggs

Department of Geography, San Diego State University, 5500 Campanile Dr., San Diego, CA 92182-4493, United States

A R T I C L E   I N F O

Article history:
Received 5 February 2015
Received in revised form 24 July 2015
Accepted 25 July 2015
Available online 1 August 2015

Keywords:
Regional hydraulic geometry curves
Urbanization
Fluvial geomorphology
Channel enlargement

A B S T R A C T

Urbanization often increases storm runoff, peak discharges and rates of stream channel erosion. Coastal California has experienced rapid urbanization over the past several decades and has the potential for stream channel degradation. Several counties in California have implemented Hydromodification Management Plans (HMPs) to protect channels from erosion, but few studies have quantified the impact of urbanization on channel geometry in diverse geological settings at the county scale. A synoptic survey of field sites (N = 56) by the California Environmental Data Exchange Network (CEDEN) and additional field surveys (N = 24) were used to develop regional hydraulic geometry curves relating bankfull cross-sectional area (A_w), width (w), mean depth (d), and discharge (Q_{bf}) to watershed area (A_w) in San Diego County. Regional curves were compared for urban and reference sites and to other regional curves developed for southern California. Multiple regression models were used to identify dominant watershed and channel controls on geometry, including A_w, percent impervious cover (I%), mean annual precipitation, underlying geology, longitudinal slope, hydrologic soil group, and channel particle size. For the reference streams, regional curves were statistically significant for w and A_w (p < 0.05). The regional curves for urban channels (I% > 20%) had significantly larger w, d, A_w, and Q_{bf} for a given watershed size. A majority (68%) of the urban channels and 78% of the small urban channels (A_w < 10 km^2) were enlarged. Enlargement of channels in small watersheds disrupted the correlation between A_w and bankfull dimensions, and I% was the only significant predictor of channel geometry in urban watersheds. Channel response differed by channel substrate: sand-bedded channels incised and experienced extreme enlargement of up to 115× the A_w of reference sites, while gravel-bedded channels widened and showed less enlargement (7× reference A_w). Diverse channel responses to urbanization were observed at the county scales with significant scatter about the regional curves and regression equations. Urban channels have a high probability of enlargement, with greater risk for sand-bedded streams, but the magnitude of enlargement was not predictable from watershed or channel characteristics.

© 2015 Elsevier B.V. All rights reserved.

1. Introduction

Urbanization can alter the hydrology and sediment supply of a watershed in ways that lead to physical and ecological damage to stream channels (Trimble, 1997). Impervious surfaces reduce infiltration rates and increase storm runoff (Dunne and Leopold, 1978; White and Greer, 2006). Urbanization also increases drainage density through the establishment of gutters and drainages and increases flow velocities of overland and channel flow (Dunne and Leopold, 1978; McBride and Booth, 2005). These changes increase the magnitude and frequency of peak flows, which are primary drivers of stream channel erosion (Hammer, 1972; Sauer et al., 1983; Trimble, 1997; Hawley and Bledsoe, 2011). Urban areas also alter the sediment supply, which increases during construction phase but decreases once the original surface is replaced by impervious cover and landscaped vegetation (Wolman, 1967), which can also result in channel erosion. The alteration in flow and sediment transport associated with urbanization, referred to as hydromodification, can induce stream channel erosion, often leading to infrastructure and property damage and degradation of water quality and aquatic ecosystems (Paul and Meyer, 2001; Walsh et al., 2005; Bledsoe et al., 2012).

Understanding the link between urbanization and stream morphology is vital for proper land use and stormwater management. Stream channel responses to urbanization can vary widely depending on geomorphic and watershed setting, making it necessary to avoid one size fits all management approaches and to develop improved management practices (Bernhardt and Palmer, 2007; Chin and Gregory, 2009; Bledsoe et al., 2012; Shoredits and Clayton, 2013). Most hydromodification management solutions consist of site-based runoff control rather than long-term management strategies that integrate a regional or watershed-scale approach (Stein et al., 2012). Managers, planners, and regulators

* Corresponding author at: Department of Geography, San Diego State University, 5500 Campanile Dr., San Diego, CA 92182-4493, United States.
E-mail addresses: taniguchi@rohan.sdsu.edu (K.T. Taniguchi), tbiggs@mail.sdsu.edu (T.W. Biggs).

http://dx.doi.org/10.1016/j.geomorph.2015.07.038
0169-555X/© 2015 Elsevier B.V. All rights reserved.
need a better regional understanding of where channel enlargement is occurring and the key variables driving channel susceptibility to hydromodification (Bledsoe et al., 2012). Predicting channel susceptibility using watershed or channel characteristics can ensure that management focuses on vulnerable streams and can more effectively prevent channel degradation.

Hydromodification is a prominent management issue in California. Many municipalities and counties—including Los Angeles, San Diego, Sacramento, Santa Margarita, and south Orange counties—have developed and implemented Hydromodification Management Plans (HMPs) to mitigate channel erosion by controlling runoff from new development sites. Stormwater permits issued in southern California under section 402 of the Clean Water Act have mandated that local municipalities require future development projects to prevent potential changes in channel morphology and to attempt to reverse past adverse effects on stream channels (San Diego, 2011). However, information is often lacking on the spatial frequency and magnitude of channel response to urbanization at the scale of management units, often the county level.

The majority of studies on hydromodification have focused on stream channels in humid environments (see reviews by Chin, 2006; Gregory, 2006), but recent studies on dryland streams have indicated that ephemeral stream channels are highly sensitive to increased impervious cover in watersheds draining to them (Chin and Gregory, 2001; Coleman et al., 2005; Hawley and Bledsoe, 2011, 2013; Hawley et al., 2012). In southern California, 20% imperviousness caused a sixfold increase in peak flows and resulted in substantially longer durations of geomorphically effective flows (Hawley and Bledsoe, 2011). With larger peak flows and longer durations of erosive flows, changes in channel form are accelerated and rivers adjust to establish a dynamic equilibrium (Bull, 1979; Chang, 2008; Hawley and Bledsoe, 2011). Regional channel evolution models (CEMs) on stream channel response to urbanization have been developed for semiarid regions and include evolutionary stages of incision, widening, aggradation, braiding, and quasi-equilibrium (Hawley et al., 2012). While CEMs provide a valuable conceptual framework, they may not account for the diversity of responses in regions with heterogeneous geology. The CEM developed for southern California by Hawley et al. (2012) is based on relatively few modeled systems (33 reaches) over a large area (6 counties from Ventura to San Diego), which may not capture the diversity and frequency of enlargement at the county level. The CEMs provide a conceptual framework for channel response to urbanization, but the actual spatial frequency and magnitude of enlargement in streams draining different rock types or with differing channel particle sizes are often not well documented. Stream channel responses to urbanization can vary greatly by geomorphic setting and climate and can be difficult to predict (Bledsoe et al., 2012), requiring a focus on a specific region of interest using a large sample size. Coastal California in particular has a variety of geology and channel substrates, with marine and fluvial sediments near the coast and igneous formations inland. In such regions with heterogeneous geology and channel characteristics, surveys are necessary to gain a regional understanding of the diversity of channel response to urbanization.

Watershed and channel characteristics can influence channel response to urbanization. Watershed characteristics have been used to estimate changes in sediment production pre- and post-urbanization, including geology, slope, and land cover (Booth et al., 2010; Splinter et al., 2010) or percent impervious cover (Hawley and Bledsoe, 2013). In wadeable streams throughout the conterminous United States, coarse-bedded streams (gravel/cobble/bedrock) were wider for a given watershed area ($A_w$) than fine-bedded streams (silt/sand) because of differences in erodibility of the banks and bed (Faustini et al., 2009), but the effect of bed material on channel response to urbanization has not been quantified. One of the most highly cited examples of channel enlargement following urbanization occurred on predominantly sand-bedded channels (Trimble, 1997), which may not be representative of the regional response. Pizzuto et al. (2000) investigated the impacts of urbanization on channel morphology for a range of watershed sizes in a humid climate (eastern U.S.) but only focused on gravel-bedded rivers. Significant uncertainty remains on the combined impacts of channel substrate, watershed size, and watershed characteristics on channel response to urbanization.

Bankfull channel dimensions are key geomorphological variables that may respond to urbanization. Bankfull discharge ($Q_{bf}$) occurs at the transition between the active channel and the floodplain, which defines bankfull width ($w$), depth ($d$), and cross-sectional area ($A_{bf}$) (Leopold et al., 1964). Watershed area ($A_w$) is one of the most reliable predictors of channel geometry, and is the basis for regional hydraulic geometry curves (regional curves) that predict bankfull dimensions and $Q_{bf}$ as a function of $A_w$ (Leopold and Maddock, 1953; Dunne and Leopold, 1978). Regional curves have been developed and compared from various regions and hydroclimates to better understand fluvial processes (Modrick and Georgakakos, 2014) and are often used in stream channel restoration and reconstruction (Chaplin, 2005; Brockman et al., 2012). Regional curves have also been used to identify the impact of urbanization on channel form along a single channel (Chin and Gregory, 2001) and have been used to document the impact of urbanization in multiple reaches in humid regions (Hammer, 1972; Navratil et al., 2013). Although previous studies have developed regional curves for southern California mountainous streams (Faustini et al., 2009; Modrick and Georgakakos, 2014), very little is known about the dynamics of urbanization and stream channel erosion in specific subregions that have diverse watershed and channel settings.

This paper develops regional hydraulic geometry curves in a rapidly urbanizing county in southern California that has diverse geology and channel particle sizes (San Diego County). The objectives are to quantify stream channel response to urbanization given different channel particle sizes and to evaluate whether channel response can be predicted from watershed characteristics. The research questions include:

- Do urbanized watersheds have a different regional hydraulic geometry curve than undisturbed reference sites?
- Where did channel enlargement occur and do the amount and type of enlargement (incision vs. widening) relate to channel particle size?
- What watershed characteristics govern stream channel response to urbanization?

The study will help understand stream channel response to urbanization in semiarid regions and will be useful for effective stream channel management, especially as more counties and states implement Hydromodification Management Plans.

2. Study area

San Diego County (southern California, USA) covers over 1.8 million acres and has ~3 million people and 18 cities (Project Clean Water, 2001). Most of the western part of the county is densely urbanized, while the northern and eastern parts are primarily undeveloped (Fig. 1). San Diego is located in a semiarid, Mediterranean climatic zone. Mean annual rainfall is ~256 mm near the coast (San Diego WSO Airport) and ~371 mm for the entire county (http://www.prism.oregonstate.edu/), with the majority falling between December and March and the highest amount of rainfall occurring in the eastern part of the county.

San Diego’s underlying geology is dominated by igneous rock, sedimentary rock, and alluvial and marine sediments with varying degrees of consolidation (Jennings et al., 1977). Tonalite, a plutonic igneous rock, comprises ~43% of the county’s underlying geology and is located in the eastern part of the county, but the majority of the current and projected urban development in the county occurs on alluvial and
marine terraces near the coast. Although only 25% of the total alluvium in the county is urbanized, 62% of the coastal alluvium is developed.

3. Methods

3.1. Data set description

Two data sets on channel morphology were used to answer the research questions: (i) an existing database of channel characteristics collected between 2001 and 2011 (N = 56) from the California Environmental Data Exchange Network (CEDEN) Physical Habitat data set; and (ii) field surveys conducted in 2013 and 2014 (N = 24) to supplement the CEDEN data with a focus on reference (undeveloped) channels on sedimentary formations, which were underrepresented in the CEDEN data set.

3.1.1. CEDEN Physical Habitat data set

CEDEN is a publically available, web-based data repository of California’s water resource monitoring data (http://www.ceden.org/). The CEDEN data set includes over 100 channel surveys in all major watersheds in San Diego County. A subset of the CEDEN data (N = 56) was utilized in this study and included only undammed stream reaches that are not channelized, are free of waterfalls, and are alluvial channels where the bed and banks are formed in unconsolidated sediment. Bedrock channels were excluded from this analysis. Pools, which may have larger cross-sectional areas than riffles or runs, were also excluded to ensure consistencies within the data set.

In the CEDEN methodology, the surveyed stream reach length is 150 m for streams that have an average active channel width ≤10 m and 250 m in length for streams with an average active channel width >10 m (Ode, 2007). Eleven equidistant main transects were arranged perpendicular to the direction of flow with 10 additional transects between each pair of adjacent main transects, to give a total of 21 transects per stream reach. The GPS coordinate for each site was only recorded at the downstream-most site (transect A) and was utilized as the pour point for watershed delineation. The cross sections surveyed at transect A were utilized in this analysis because (i) the reach-averaged cross-sectional area was not statistically different from the cross-sectional area surveyed at transect A; and (ii) for small watersheds, the drainage area was different by up to 18% between the downstream (transect A) and upstream sites. If transect A was located in a pool, the site was excluded from the analysis. The intermediate axis of 105 particles in each reach, including five particles from each of the 11 main transects and five from each of the 10 intertransects, was measured and recorded. Measurements of channel particle size were taken at five equidistant points across the channel at each transect.

The CEDEN data set included several surveys conducted between 2001 and 2011; the most recent survey for each reach was used in this analysis. Although some sites had repeat surveys, the repeat surveys occurred over a short period of time (<4 years and some within the same year). At each site, the bankfull stage was identified based on breaks in the slope and changes in the vegetation and sediment size distribution (Ode, 2007). Bankfull indicators can be difficult to consistently distinguish in the field (Hedman and Osterkamp, 1982; Wharton et al., 1989; Wharton, 1992, 1995), so evidence along the entire reach was utilized when attempting to identify bankfull. The bankfull depth to channel bed was measured at five equidistant locations along the transect and the derived cross-sectional area at bankfull (A⊥) was calculated as the sum of four trapezoidal areas below bankfull.

3.1.2. Supplementary survey data set

Most urbanized watersheds in San Diego County are on sedimentary formations near the coast, while the majority of CEDEN reference sites were located in central and eastern parts of the County on igneous rock (tonalite), so a survey of 24 additional reference and urban sites was conducted in 2013 and 2014 with a focus near the coast on sedimentary geology (Fig. 1). The field surveys were conducted on riffles or runs and not in pools. All sites were undammed, not channelized or artificially stabilized, free of waterfalls, and had a drainage area ranging from 0.3 to 1847 km².

![Fig. 1. The CEDEN Physical Habitat sites and supplementary sites located in San Diego County. Reference, intermediate, and urban sites have watersheds with <5%, 10–20%, and >20% impervious surfaces, respectively. CEDEN reference sites (white circles) are mainly in the eastern part of the county; white triangles represent the additional reference sites that supplement the CEDEN data set. Areas with >20% impervious cover are mapped as urban (gray) (Xian et al., 2011).](image-url)
At each supplementary site, bankfull stage was identified using the same methodology as the CEDEN data, based on morphologic evidence including changes in slope and vegetation (Leopold, 1994). Cross sections extended onto the floodplain, and the vertical distances from the channel bed to the reference datum were measured at breaks in the slope with an autolevel (Chin and Gregory, 2001; Galster et al., 2008). For sites that had ambiguous bankfull indicators, multiple cross-sectional surveys and plots of the cross sections were used to aid in identifying consistent estimates of bankfull channel metrics. Longitudinal slope of the channel thalweg was measured with an autolevel over a stream reach of 10 bankfull widths (Harrelson et al., 1994). Wolman pebble counts were performed on stream beds that were primarily composed of coarse particles (intermediate diameter > 4 mm) to quantify the median grain size of the channel bed (Wolman, 1954). To determine the size distribution of fine sediments, a soil sample from the bed (250–500 g if gravel is present and 40 to 50 g if no gravel) was taken in the field and a wet/dry sieve analysis was conducted in the lab based on the methodology presented by Guy (1969). Qualitative field notes on channel conditions, erosional features, and descriptions of the particle size of banks and bed were recorded at each site.

The CEDEN and supplemental data were combined for analysis, totaling 80 sites. A relatively stable, undeveloped site in the CEDEN database was resurveyed in May 2015 in order to verify consistency in the methods and channel measurements of the two data sets. Differences in channel measurements between the resurvey in 2015 and the CEDEN data from 2010 were small, including bankfull width (+4%), average depth (−8%), and cross-sectional area (−5%), suggesting that bankfull indicators were interpreted consistently for CEDEN and for the supplemental surveys and that the two data sets could be merged for analysis. Also, the parameters of the regional curves were not statistically different when excluding the supplemental survey points, suggesting that the results were not affected by merging of the data sets. Bankfull discharge was calculated for each site using Manning’s equation, bankfull cross-sectional measurements, longitudinal slope, and roughness values estimated from Table 1 of Aldridge and Garrett (1973). Watershed boundaries were digitized using a 10-m digital elevation model (DEM) derived from a USGS 7.5 minute quadrangle topographic map that has 6- and 12-m contour intervals. Geology from the U.S. Geological Survey (USGS) (Jennings et al., 2017) was aggregated into six groups (Eric Berntsen, State Water Resources Control Board, personal communication, 2013), including four sedimentary groups (fine-weak; coarse-weak; fine-competent; coarse-competent), an igneous group (crystalline), and water (Table 1 in Taniguchi, 2014). The hydrologic soil group was extracted from San Diego Association of Governments (SANDAG) 2002 soil layer for each channel location. The USGS National Land Cover Database 2011 (Xian et al., 2011) was used to calculate % for the watershed draining to each site. The range of % for the data set was 0.05 to 63%

All sites were classified as either reference, intermediate, or urban (Fig. 1; Table 1). Southern California streams show erosion when impermeable cover exceeds 5% and can experience extreme enlargement above 20% (Hawley and Bledsoe, 2013). Therefore, reference sites, or sites with watersheds that are minimally urbanized, were defined as watersheds with % < 5% (Hollis and Luckett, 1976; Morisawa and Lafleur, 1979; Navratil et al., 2013). Urban and intermediate sites were defined as those whose watersheds had % > 20% (urban) or between 5 and 20% (intermediate).

3.2. Statistical analysis

Ideally, studies on stream channel adjustment should be undertaken in the same reach before, during, and after urbanization (Leopold, 1973), but very little pre-urbanization data exists for streams in San Diego County. A space–time substitution technique was used to compare channels in urbanized watersheds to channels in undeveloped watersheds using regional hydraulic geometry curves (Wolman, 1967; Hammer, 1972; Chin and Gregory, 2001; Navratil et al., 2013). Regional hydraulic geometry curves (regional curves) relate bankfull channel geometry to A_ref:

\[ X = \alpha A_{ref}^{\beta} \]  

where X is a bankfull channel dimension (w, d, A_ref, or Q_{bf}), A_ref is in km², and \( \alpha \) and \( \beta \) are the coefficients (Dunne and Leopold, 1978).

The statistical analysis consisted of two components. First, regional curves for w, d, A_ref, and Q_{bf} were constructed for reference channels (% < 5%) and urban channels (% > 20%) using linear regressions on the log-transformed variables. Statistical significance of the difference in slopes (\( \beta \)) and intercepts (\( \alpha \)) of the reference and urban regional curves were tested using analysis of covariance (ANCOVA) (Chaplin, 2005; Johnson and Fecko, 2008). Sites whose bankfull characteristics were outside the upper bounds of the 95% confidence interval for the regional reference curves were considered enlarged. A channel enlargement ratio (ER) was calculated as the observed A_ref divided by the A_{ref} predicted from the regional curve for reference sites.

Multiple linear regressions were conducted to determine if mean annual P, %, longitudinal slope, median particle size (D_{50}), hydrologic soil group, and rock type were significant predictors of channel geometry (Faustini et al., 2009). A forward regression was conducted, starting with a simple regression model of A_{ref} as a function of A_ref and precipitation (Gotvald et al., 2012):

\[ A_{ref} = f(A_{ref}, P) \]

where P is long-term (30-year) mean annual precipitation in mm from gridded data that has 800-m resolution (http://www.prism.oregonstate.edu/). Explanatory variables were then added to the regression equation one at a time and the statistically significant variables (p < 0.05) were identified (Faustini et al., 2009).

4. Results

4.1. Regional curves for reference and urban streams

Regional hydraulic geometry curves relating A_{ref}, w, d, and Q_{bf} to A_ref were developed for reference and urban streams (Table 2). A majority of urban channels plotted above the regional curves for reference sites for all geometric variables (Fig. 2). Bankfull width and A_{ref} were highly correlated (R² = 0.72) and were significantly larger in urban channels compared to reference channels. The Q_{bf} and d were also strongly correlated (R² = 0.82), had slightly negative slopes in the urban curves, and exhibited the most scatter in the urban and reference regressions (R² < 0.08).

For reference sites, the regional curves had the least scatter and highest statistical significance for bankfull width (R² = 0.10; p < 0.05) and A_{ref} (R² = 0.09; p < 0.05). The \( \beta \) for Q_{bf} and d were statistically insignificant (p > 0.1). For the urban sites, none of the regional curves were statistically significant (p > 0.05), but width had the highest R² and lowest p-value (R² = 0.16; p = 0.06). The insignificance of \( \beta \) in the regional curve for the urban sites was caused by the large variability in bankfull characteristics, particularly in watersheds smaller than 10 km², one of

<table>
<thead>
<tr>
<th>Table 1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of sites from the CEDEN and supplementary data sets used in this study by disturbance class.</td>
</tr>
<tr>
<td>Data set</td>
</tr>
<tr>
<td>---------</td>
</tr>
<tr>
<td>CEDEN</td>
</tr>
<tr>
<td>Supplementary</td>
</tr>
<tr>
<td>Total sites</td>
</tr>
</tbody>
</table>
which was enlarged more than 115 times the reference dimensions (Fig. 2).

The \( \alpha \) values were significantly different between urban and reference regional curves for all channel geometry variables \( (p < 0.001) \), suggesting that \( A_w, w, d, \) and \( Q_bf \) are significantly larger in urban sites than in reference sites for a given \( A_w \). The \( \beta \) values were not significantly different between the urban and reference sites for all channel geometry variables \( (p > 0.1) \) (Fig. 2), indicating that the rate of increase in bankfull geometry \( (A_w, w, d, \) and \( Q_bf) \) with increasing \( A_w \) is not larger for urban streams compared to reference streams.

The parameters of the regional curves for width in southern California \( (\text{Faustini et al., 2009; Modrick and Georgakakos, 2014}) \) are in fairly good agreement with the parameters from the reference curve in San Diego, with a smaller \( \beta \) in San Diego (Table 2; Fig. 3). The intercept \( (\alpha) \) of the curve for urban sites in San Diego is 7.37, which is substantially larger than \( \alpha \) of the reference curve in San Diego \( (2.98) \) and at other sites in southern California. This indicates that urban channels in San Diego exhibit much larger bankfull widths compared to reference channels of San Diego and southern California (Fig. 3).

The reference curve for bankfull cross-sectional area from San Diego was in agreement with the curve of Modrick and Georgakakos (2014), which included mountain streams throughout southern California \( (\text{Faustini et al., 2009; Modrick and Georgakakos, 2014}) \). Overall, urban channels had larger width and cross-sectional areas for a given watershed area compared to reference channels.

### 4.2. Channel enlargement in San Diego County

A majority \((68\%)\) of the urban channels and \(42\%\) of the intermediate channels were enlarged, defined as plotting outside the upper 95% confidence interval of the regional curve for reference sites. Of the 14 urban sites with watersheds \(<10 \text{ km}^2\), 78\% were enlarged. Four sites downstream of a highly urbanized area of Escondido Creek and all of the urban sites on minor tributaries of Los Peñasquitos Creek were enlarged \((A \text{ and } B \text{ in Fig. 4})\). Some \((13\%)\) of the reference sites fell above the upper 95\% confidence interval and were also mapped as enlarged \((\text{Fig. 4})\).

The channel enlargement ratio \( (\text{ER}) \) was calculated for each site and plotted against percent impervious cover \( (\% ) \) \((\text{Fig. 5})\). The ER was modeled as a log-linear function of \( \% \). The ER values of up to 115 occurred on channels with sandy beds. The regression slope of the ER curve for sand-bedded channels was significantly larger than the ER slope for all other substrate types \( (p < 0.01) \), indicating that sand-bedded channels enlarge with a lower percentage of impervious cover. The enlargement curve in San Diego \( (\text{solid line}) \) matches the curve from Coleman et al. \( (2005) \) \((\text{dashed line}) \). Enlargement curve from Hawley and Bledsoe \( (2013) \) \((\text{dotted line}) \) has a larger coefficient and exponent compared to the enlargement curve from San Diego but is close to the observed ER in the sand-dominated channels \((\text{Fig. 5})\). Coarse gravel and cobble-bedded streams followed the more conservative enlargement curve of Coleman et al. \( (2005) \). On average, channels with \( \% \) of 20\% or greater had an ER of 15.

![Fig. 2](image2.png) Regional hydraulic geometry curves for width and depth for urban (black) and reference streams (gray). Different shapes represent the particle size class associated with the \( D_{50} \). Bankfull width curves show the most significant relationship.

![Fig. 3](image3.png) Regional hydraulic geometry curves for channel width from San Diego (urban and reference) and other regional curves from southern California \( (\text{Faustini et al., 2009; Modrick and Georgakakos, 2014}) \).
cobble-bedded channels were less enlarged (ER < 15) than sand-bedded channels (ER up to 115).

4.3. Explanatory variables on channel geometry

Multiple regressions predicted channel geometry as a function of watershed and channel attributes ($A_w$, $P$, $I\%$, $D_{50}$, geology, hydrologic soil group, and longitudinal slope). For the bankfull width equation, the coefficient for $A_w$ was statistically significant ($p < 0.01$), while the coefficient for $P$ was not ($p > 0.1$). Although precipitation is a driving factor in channel geometry in other regional assessments (Gotvald et al., 2012; Wilkerson et al., 2014), in San Diego the insignificance in $P$ could be from the insufficient regional variability in precipitation (274–726 mm). In addition to watershed area, $I\%$ was the only other statistically significant explanatory variable in the regression for $w$ ($p < 0.0001$). $D_{50}$, geology, hydrologic soil group, and longitudinal slope were not statistically significant predictors of $w$ ($p > 0.1$).

4.3.1. Effects of watershed area and channel particle size on enlargement

The relationship between $A_{xs}$ and $A_w$ was weak for urban channels from the varying degrees of incision for channels in different watershed sizes. Channels draining small watersheds may be more susceptible to urban-induced erosion compared to larger watersheds, but the critical sizes where urbanization effects decrease and the mechanisms behind the reduction in enlargement with increasing watershed size remain uncertain (Dunne and Leopold, 1978; Navratil et al., 2013). In this study, all urban sand-bedded channels with watershed areas $< 10$ km² experienced incision, falling well outside of the upper 95% confidence interval of the reference curve of bankfull depth, while all but one sand-bedded channel draining watersheds $> 10$ km² were not incised (Fig. 6), resulting in the unusual negative slope in the urban regional curve for bankfull depth (Table 2).

Channel particle size also impacted whether incision and/or widening occurred in urban channels. Sand-bedded channels tended to incise,
while cobble- or gravel-bedded channels tended to widen. This is reflected in the difference in the width-to-depth ratio between enlarged sand- and enlarged coarse gravel- or cobble-bedded channels in watersheds <10 km² (Fig. 7). Similarly, Faustini et al. (2009) found that streams with coarser bed material (gravel/cobble/boulder) were wider for a given watershed area compared to streams with fine bed material (sand/silt), but the effect of channel material has not been widely demonstrated in urban channels.

5. Discussion

5.1. Contribution of the current study

Most (68%) streams draining urbanized watersheds are enlarged, but the magnitude of the enlargement is highly variable and all regional curves have relatively low $R^2$ values (Table 2). Watershed characteristics like precipitation, geology, mean watershed slope, and hydrologic soil group are not statistically significant predictors of channel dimensions or enlargement. The lack of importance of geology may be from the low number of urban channels on igneous rock types, and geology has an indirect impact on channel size and enlargement through its impact on channel particle size. Impervious cover is the only watershed characteristic with a statistically significant coefficient in the regressions for bankfull width and cross-sectional area and is the only statistically significant predictor of cross-sectional area. Factors not accounted for in this study, such as connectivity of urban areas and drainage outfalls to the stream channels (Gregory et al., 1992), may account for the large variability in the magnitude of channel response. Road crossings and storm drains convey water directly into the channel, increasing peak discharge and channel erosion. Watershed area and percent impervious cover do not account for spatial variation in urban connectivity to the channel. Position in the channel network can also affect channel response to urbanization. Channel evolution models, including those modified for southern California, suggest that different parts of the stream network may be degrading or aggrading depending on local channel slope, upstream sediment supply, and time since urbanization (Hawley et al., 2012).

Channel response to urbanization differed by bed composition. Sand-bedded channels incised and enlarged more for a given percent impervious cover compared to gravel- and cobble-bedded channels, which widened but in general did not incise (Fig. 5). This is consistent with Coleman et al. (2005), who suggested that streams with highly resistant bed and bank materials are likely to have a larger threshold for stream channel change. All sand-bedded channels responded to urbanization, but channels draining small watersheds experienced the most incision. Channels draining larger watersheds may be less impacted by the factors that drive incision, although it was not verified in this study. Channels draining larger watersheds may be underlain by resista nt layers of coarse subsurface sediments that help prevent incision, and peak discharge may be attenuated in larger watersheds (Spellman and Whitting, 2014). Channels draining larger watersheds may also have more gradual longitudinal slopes, which reduce shear stress on the bed compared to streams draining small watersheds. Future studies should examine whether and why streams in smaller watersheds are more susceptible to incision compared to streams in larger watersheds.

Our results suggest that publically available data sets (CEDEN), supplemented by field surveys targeting channels with particle sizes that were not extensively sampled in the public data set, could be utilized to understand the effects of urbanization on stream channel geom etry. Such studies could be repeated in other locations that have similar public surveys (especially the thousands of CEDEN surveys throughout California) and integrated into Hydromodification Management Plans. Although this study did not look at stream channel changes over time, CEDEN surveys conducted from the early 2000s can be revisited to investigate potential channel changes over time. Care needs to be given to the identification of bankfull elevation to ensure consistencies in the field methods and comparability of different data sets.

5.2. Comparison of urban effects with other studies

One of the most cited studies of the impact of urbanization on stream channels in southern California documented extreme enlargement and was located near the coast on alluvial and marine sediments (Trimble, 1997). Our study also shows evidence of extreme channel enlargement (>115 ×) for sand-bedded channels, but much less incision and more widening in channels with coarse bed material, suggesting that the regional response to urbanization may be complex and spatially variable. Faustini et al. (2009) similarly found that channels with coarse bed material (gravel, cobble, boulder) were wider than channels with fine bed material (silt/sand) in undeveloped watersheds. Consistent with our observations in San Diego, Navratil et al. (2013) also concluded that channel change caused by increased impervious cover are largest in channels draining small watersheds. Streams draining watersheds <5 km² experienced the most enlargement caused by local factors such as close proximity to road crossings, urban areas, or storm drains (Navratil et al., 2013).

In addition to particle size and watershed area, the age of the urban areas (Hammer, 1972) and proximity to downstream grade control (Hawley and Bledsoe, 2013) can affect channel response to urbanization. Channels may experience deposition and narrowing during early stages of urbanization from increased sediment supply during the construction phase and may not experience channel enlargement until decades following urbanization (Wolman, 1967; Leopold, 1973). If
urbanization occurred fairly recently before the time of the survey, channel changes may not have occurred. In addition to the age of urban areas, downstream distance to channel hardpoints could affect channel enlargement with enlargement increasing upstream of a bedrock or artificial grade control (Chin and Gregory, 2001; Hawley and Bledsoe, 2013). Possible impacts of drainage density and proximity of channels to road crossings and urban storm drains should be examined in subsequent research.

6. Conclusion

Regional hydraulic geometry curves show that urbanization results in the enlargement of a majority of channels, but the magnitude of the enlargement varies widely.

Bankfull width and cross-sectional area had the most statistically significant response to urbanization, and the intercepts of the regional curves for width and cross-sectional area were substantially larger for urban sites compared to undisturbed reference curves, from this study and from other reference sites draining undisturbed watersheds in southern California. Watershed variables such as geology, hydrologic soil group, mean annual precipitation, and channel variables like longitudinal slope and D50 were not significant predictors of channel geometry, though geology impacted channel response to urbanization indirectly through its impact on channel particle size. Channel geometry and the enlargement ratio correlated with the percent impervious cover in the watershed, and significant differences by channel particle size were observed. Sand-bedded channels followed the enlargement curve of Hawley and Bledsoe (2013) and tended to have higher enlargement ratios (up to 115×) compared to coarse gravel- and cobble-bedded urban streams, which followed the enlargement curve of Coleman et al. (2005) and had enlargement ratios ~15. Urban sand-bedded channels draining small watersheds experienced more incision and enlargement compared to urban sand-bedded channels draining larger watersheds.

The regional survey of channel response to urbanization presented here supplements existing channel evolution models (Hawley et al., 2012), which provide a conceptual framework for anticipating the channel response to urbanization but are not predictive. Similar surveys using a combination of publically available data sets and additional field surveys can help identify channel types susceptible to enlargement. The survey suggests that channel response is variable but depends on watershed size and channel particle size, which will be useful for targeting management efforts. Future studies could investigate if and why smaller channels are more susceptible to erosion compared to larger channels in semiarid regions. Future research could also test if time since urbanization, distance to downstream grade control, and urban connectivity to the channel network are significant predictors of channel enlargement in San Diego County and in other semiarid regions.

Acknowledgments

The field research conducted in 2013 was funded by the County of San Diego through AMEC Environmental & Infrastructure, Inc. and the Southern California Coastal Water Research Project (SCCWRP) (Task Order #8895). Dr. Molly Costello and Dr. Thomas Rockwell provided in-field surveys can help identify channel types susceptible to enlargement. The survey suggests that channel response is variable but depends on watershed size and channel particle size, which will be useful for targeting management efforts. Future studies could investigate if and why smaller channels are more susceptible to erosion compared to larger channels in semiarid regions. Future research could also test if time since urbanization, distance to downstream grade control, and urban connectivity to the channel network are significant predictors of channel enlargement in San Diego County and in other semiarid regions.

References


