REGIONAL IMPACTS OF URBANIZATION ON STREAM CHANNEL GEOMETRY: IMPORTANCE OF WATERSHED AREA AND CHANNEL PARTICLE SIZE

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Kristine Teru Taniguchi
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The undersigned Faculty Committee approves the

Thesis of Kristine Teru Taniguchi:

REGIONAL IMPACTS OF URBANIZATION ON STREAM CHANNEL

GEOMETRY: IMPORTANCE OF WATERSHED AREA AND CHANNEL

PARTICLE SIZE

Trent Biggs, Chair
Department of Geography

Molly Costello
Department of Geography

Thomas Rockwell
Department of Geology

12/3/14
Approval Date
DEDICATION

This thesis is dedicated to Alfred R. Jay (1936 – 2014), who was the author’s grandfather, mentor, and best friend. He inspired the author to do her first science project on coastal erosion, which sparked her fascination with the movement of water and sediment. The author could not have completed this thesis without the love and support from her number one fan.
ABSTRACT OF THE THESIS

Regional Impacts of Urbanization on Stream Channel Geometry:
Importance of Watershed Area and Channel Particle Size
by
Kristine Teru Taniguchi
Master of Science in Geography (Watershed Science)
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Urbanization increases impervious surface cover, expands the drainage network, and increases flow velocity, which increases storm runoff, peak discharges and rates of stream channel erosion. Southern California has experienced rapid urbanization over the past several decades and has the potential for stream channel degradation. San Diego County has implemented a Hydromodification Management Plan to protect channels from erosion through monitoring new development projects and their increases in runoff, but no studies have identified the dominant controls and the impact of urbanization on channel geometry. A synoptic survey of 80 field sites by the California Environmental Data Exchange Network (CEDEN) and additional field surveys from 2013-2014 were used to develop regional curves relating bankfull cross sectional area (A_{xs}), width (w), mean depth (d), and discharge (Q_{bf}) to watershed area (A_w). Regional curves were compared for urban and reference sites and compared 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, and hydrologic soil group. For the reference streams, regional curves were most robust for w (p < 0.05) and A_{xs} (p < 0.05). The regional curves for urban streams had substantially larger coefficients in the regional curves, indicating that urban channels have larger w and A_{xs} for a given watershed size. The most predictive variables for w were A_w and I%. A_w is a predictor of A_{xs} only for reference sites; when all sites are included in a regression model, I% was the only predictive variable for all channel metrics, suggesting that urban-induced enlargement in smaller urban channels disrupted the natural A_{xs}-A_w relationship. A majority (68%) of the urban channels were enlarged, defined as a A_{xs} larger than the upper 95% confidence interval of the regional curve for reference sites. Of the enlarged channels, 73 percent were located in small watersheds (<10 km^2). Channel response differed by channel substrate. Sand-bedded channels incised, while gravel-bedded channels widened. Sand-bedded channels in small urban watersheds (<10 km^2) had much larger d compared to sand-bedded channels in larger urban watersheds (>10 km^2). Channels draining larger urban watersheds may be less susceptible to enlargement due to stabilization of channel banks through the establishment of riparian vegetation from increased urban baseflow. Management should focus on monitoring sand-bedded channels in watersheds smaller than 10 km^2.
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Introduction

Urbanization can alter the hydrology and sediment supply of a watershed in ways that lead to physical and biological damage to stream channels (Trimble, 1997). Impervious surfaces reduce infiltration rates and increase storm runoff (White and Greer, 2006). Urbanization also increases the drainage density through the establishment of gutters and drains, and increases flow velocities of both overland flow and channel flow (Dunne and Leopold, 1978). These changes increase the magnitude and frequency of peak flows, which is one of the primary drivers in stream channel erosion (Hammer, 1972; Trimble, 1997; Hawley and Bledsoe, 2011). 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 aquatic ecosystems (Bledsoe et al., 2012). Urban areas also alter the sediment supply, with increases during construction but potentially decreases once the original surface is replaced by impervious cover and landscaped vegetation (Wolman, 1967). The reduction in sediment supply can also result in channel erosion.

Channel erosion alters the physical stream channel and can detrimentally affect stream ecology (Gregory, 2006). Urban-induced channel erosion can be the main source of sediment that is harming estuarine ecosystems, as seen in San Diego Creek and Newport Bay, one of the few remaining estuarine habitats found in California (Trimble, 1997; Trimble, 2003). With excess sediment mobilized and transported downstream, estuarine vegetation can be buried and wetlands converted to uplands, negatively affecting the structure and function of aquatic ecosystems (Rogers, 1990).

Bankfull discharge, or the 1.5-year flow (Leopold, 1994), is typically defined as the dominant flow that maintains channel geometry. Bankfull stage occurs at the transition between the active channel and the floodplain (Leopold et al., 1964). The larger the contributing watershed area, the higher the bankfull discharge and subsequent bankfull channel geometry (Leopold and Maddox, 1953; Dunne and Leopold, 1978). Therefore, watershed area is one of the most reliable predictors of channel geometry, and is the basis for regional curves that predict bankfull channel width (w), depth (d), cross sectional area (A_{ss}), and bankfull discharge (Q_{bf}) as a function of watershed area (A_w) (Dunne and Leopold, 1978). Bankfull regional curves have been developed and compared from various regions.
and hydro-climates 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 been used to identify the impact of urbanization on channel form in a single channel (Chin and Gregory, 2001) and have been used to document the impact of urbanization from multiple reaches (Hammer, 1972; Navratil et al., 2013), but the authors are not aware of studies that have used a regional dataset to identify the spatial patterns and dominant controls on channel response to urbanization for a wide range of watershed sizes and channel materials.

The majority of studies on stream channel erosion and urbanization have focused mainly on those in humid environments, with less emphasis on semi-arid, ephemeral stream channels (see reviews by Chin, 2006; Gregory, 2006). Humid and semi-arid stream channels can have different responses to urbanization with infrequent large events in semi-arid regions causing channel enlargement, while comparable large events in humid areas exceed the channel capacity and flow over the floodplain (Gregory, 2006). This could be due to the fact that semi-arid, ephemeral streams are typically associated with a flashy flow regime (Wolman and Gerson, 1978) and infrequent large events could lead to episodic geomorphic responses in semi-arid environments (Nanson and Erskine, 1988). Additionally, stream adjustments and morphological responses to urbanization vary spatially depending on the hydroclimatic environment, lithology and stream composition, vegetation, slope, and urban structures such as road crossings and channelization (Chin, 2006).

Although much of the emphasis in research on hydromodification has been given to perennial stream channels, recent studies on dryland streams have indicated that ephemeral stream channels are highly sensitive to increases in flow rates associated with increased impervious surfaces (Chin and Gregory, 2001; Coleman et al., 2005). In southern California, 20% imperviousness caused a six-fold 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 (Hawley and Bledsoe, 2011). In response to changes in water and sediment, river channels adjust in order to establish a dynamic equilibrium (Bull, 1979; Chang, 2008). Hawley et al., (2012) developed a channel evolution model of semi-arid stream response to urbanization in southern California, including evolutionary stages of incision, widening, aggradation,
braiding, and quasi-equilibrium (Hawley et al., 2012). Although studies on southern California streams provide valuable information on stream channel response, they may not be representative of conditions in smaller areas, such as San Diego County. This could be due to the large geographic area covered in the studies, large heterogeneity in controlling mechanisms, and/or micro-scale or site-specific controls on stream channel response to urbanization (Bledsoe et al., 2012). It may be necessary to focus on a specific region of interest because stream channel responses to urbanization can vary greatly among geomorphic settings and climate and can be difficult to predict (Bledsoe et al., 2012).

Southern California has experienced significant urbanization over the last several decades and urbanization is forecast to continue, which has the potential to cause severe damage to the stream channels in this semi-arid region (Coleman et al., 2005). In response to this concern, stormwater permits issued in southern California under section 402 of the Clean Water Act have mandated that local municipalities require future development projects to address potential changes in channel morphology and attempt to reverse past adverse effects on stream channels (County of San Diego, 2011). In San Diego County, a Hydromodification Management Plan (HMP) was implemented in order to mitigate erosion impacts by controlling runoff from new development sites (County of San Diego, 2011).

Although there has been research on regional bankfull geometry relationships on southern California mountainous streams (Faustini et al., 2009; Modrick and Georgakakos, 2014) and the effects of urbanization on peak flows, sediment transport, and channel change in southern California (Coleman et al., 2005; Hawley and Bledsoe, 2011; Hawley et al., 2012; Hawley and Bledsoe, 2013) very little is known about the dynamics of urbanization and stream channel erosion in San Diego County.

Additionally, there is significant uncertainty about the impacts of channel substrate and watershed size on urban channel response to erosion. Although landscape metrics have been used to estimate changes in sediment production pre-and post-urbanization, including geology, slope, and land cover (Splinter et al., 2010; Booth et al., 2010) and percent impervious cover (Hawley and Bledsoe, 2013), the impact of channel particle size on urban channel response has yet to be investigated. In wadeable streams throughout the conterminous United States, coarse-bedded streams (gravel/cobble/boulder) were wider for a given A_w than fine-bedded streams (silt/sand) given differences in erodibility of the banks
and bed (Faustini et al., 2009), but these effects have not been quantified to incorporate the effects of urbanization. One of the most highly cited examples of channel enlargement following urbanization occurred on predominantly sand-bedded channels (Trimble, 1997). The response of channels to urbanization in heterogeneous regions that have a variety of watershed sizes and channel materials has not been fully documented.

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 typical “one size fits all” management approaches and to develop improved management practices (Bledsoe et al., 2012). City managers, planners, and regulators need a better understanding of where channel enlargement is occurring and the key variables driving channel susceptibility, such as dominant bed material, grade control, channel planform, proximity to geomorphic thresholds, and channel bed and bank conditions to assess specific stream reaches and their susceptibility to hydromodification (Bledsoe et al., 2012). By focusing management efforts on development projects located near highly vulnerable streams, a considerable amount of time and money could be saved and more attention could be given to the improvement of water quality and the survival of biological ecosystems downstream.

This thesis develops regional bankfull geometry curves for streams in San Diego County to better understand stream channel response to urbanization and to evaluate whether channel response can be predicted from watershed characteristics. This investigation will provide both an understanding on the channel response to urbanization, as well as provide a valuable screening tool to focus management efforts.

**Research Questions/Objectives**

**Question 1. Where has stream channel enlargement occurred in San Diego County, and does the amount of enlargement correlate with channel characteristics?**

Answering this question will help identify if there are any “hotspots” of enlargement and how stream enlargement is spatially distributed throughout the county. Because historical channel dimensions have rarely been recorded in the county, channel enlargement will be measured as a change in the $A_{sc}$ to $A_w$ relationship compared to undeveloped watersheds (Chin and Gregory, 2001). It is hypothesized that channel enlargement will be more evident
in sand-bedded, urban channels near the coast, also referred to as urban sand channels, whereas channels armored by larger particles (i.e. cobbles and coarse gravel) will be more stable.

**Question 2. What are the primary watershed and landscape characteristics that govern stream channel erosion in San Diego County?**

Multiple linear regression will be used to predict channel geometry based with independent variables including $A_w$ and watershed characteristics such as mean annual precipitation ($P$), impervious cover percentage ($I\%$), median particle size of the channel bed ($D_{50}$), underlying geology, hydrologic soil group, and longitudinal slope. It is hypothesized that $D_{50}$ and $I\%$, which aren’t typically included in geomorphic landscape models, may be important predicting variables in stream channel response to urbanization. Grain size in stream channel beds depends on local conditions such as geology, climate and weathering regime, and hillslope stability, and is a large component of erosional resistance within the channel (Wohl and Achyuthan, 2004).

**Study Area**

San Diego County covers over 1.8 million acres, with approximately 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 areas are primarily undeveloped (Figure 1). San Diego is located in a semi-arid, Mediterranean climatic zone. Mean annual rainfall is approximately 256 mm near the coast (San Diego WSO Airport) and approximately 371 mm for the entire county (PRISM), with the majority of the rainfall occurring between December and March (NOAA NWS).

The geology is dominated by plutonic rock, alluvium, and sandstone (Table 1; Jennings, 1977). Tonalite, a plutonic rock, comprises approximately 43% of the county’s underlying geology and is located in the eastern region of the county, but the majority of the current and projected 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.
Table 1. Percent of geology types throughout San Diego County and percent of the given geology type that is urbanized.

<table>
<thead>
<tr>
<th>Aggregated Rock Type</th>
<th>Units Within</th>
<th>Percent in County</th>
<th>Percent Urbanized</th>
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<tr>
<td>Coarse-Competent</td>
<td>Marine and Non-Marine Sedimentary Rocks:</td>
<td>7</td>
<td>14</td>
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<tr>
<td></td>
<td>conglomerate; mudstone; sandstone</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Coarse-Weak</td>
<td>Alluvium; Loosely consolidated Pliocene and/or</td>
<td>22</td>
<td>22</td>
</tr>
<tr>
<td></td>
<td>Pleistocene sandstone, shale, and gravel deposits</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Crystalline</td>
<td>Plutonic Rocks: tonalite; gabbro; granitic and</td>
<td>57</td>
<td>45</td>
</tr>
<tr>
<td></td>
<td>metamorphic rocks</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fine-Competent</td>
<td>Felsic Volcanic rocks, Pelitic Schist; others</td>
<td>12</td>
<td>17</td>
</tr>
<tr>
<td>Fine-Weak</td>
<td>Argillite; Older alluvium, lake, playa, and</td>
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<td>1</td>
</tr>
<tr>
<td></td>
<td>terrace deposits</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Water</td>
<td></td>
<td>1</td>
<td>0</td>
</tr>
</tbody>
</table>

Source: San Diego Aggregated Geology by Eric Berntsen 2013 based on USGS, CA Geology (Jennings, 1977); SANDAG Land Use 2009

Methods

1. Datasets

Two datasets on channel morphology were used to answer the research questions: 1) an existing database of channel characteristics collected from 2001 to 2011 (N = 56) from the California Environmental Data Exchange Network (CEDEN) Physical Habitat Dataset; and 2) field surveys conducted in 2013-2014 to supplement the CEDEN data, with a focus on reference (undeveloped) channels on sedimentary rock types, which were underrepresented in the CEDEN dataset.
CEDEN Physical Habitat Dataset

CEDEN is a publicly available, web-based data warehouse of California’s water resource monitoring data. The CEDEN dataset includes channel surveys (N=56) in all major watersheds in San Diego County (Figure 1). The drainage area of the surveyed channels ranges from 0.3 – 195 km². Reference sites were defined as those whose watersheds had less than 5 percent I% (N=36), urban sites as having watersheds with I% greater than 20 percent (N=10), and intermediate sites as those whose watersheds had I% between 5 and 20 percent (N=10). The reference I% threshold was based on previous studies (Hollis and Luckett, 1976; Morisawa and Laflure, 1979; Navratil et al., 2013).

The CEDEN Physical Habitat datasets includes undammed stream reaches that are not channelized and are free of waterfalls. The surveyed stream reaches are alluvial channels where the bed and banks are formed in unconsolidated sediment. Bedrock channels were excluded from this analysis. The surveyed stream reach length is 150 meters for streams with an average wetted width less than or equal to 10 meters, and 250 meters in length for streams with an average wetted width greater than 10 meters. Eleven equidistant main transects are arranged perpendicular to the direction of flow (transects A-K) with 10 additional transects (“inter-transects”) between each pair of adjacent main transects (AB, BC, CD…etc.), to give a total of 21 transects per stream reach (Appendix A). Because the GPS coordinates were only recorded at transect A, only the cross sections surveyed at transect A were selected and utilized in this analysis. If transect A was located in a pool, the site was excluded from the analysis. Pools, which may have larger cross sectional areas than riffles or runs, were excluded to ensure consistencies within the dataset.
Figure 1. The CEDEN Physical Habitat sites and field sites located in San Diego County. CEDEN reference sites (green circles) are mainly in the east county; Green triangles represent the 11 additional reference sites that supplement the CEDEN dataset. Urban areas, or areas with >20% impervious cover, were mapped in grey (NLCD, 2011).

The attributes used in this analysis include year surveyed, location, bankfull height from the water surface, bankfull width, wetted water depth, wetted width, substrate size class, and longitudinal slope. Since the dataset had a variety of surveys from 2001 to 2011, the most recent survey for each reach was used in this analysis. $A_{ss}$ was calculated based on the available attributes, and $Q_{bf}$ was calculated from the CEDEN data using Manning’s equation (Appendix B and C). For the substrate size class in CEDEN, the intermediate axis of 105 particles in each reach were measured and recorded, and comprised five particles from each of the 11 main transects and five from each of the 10 inter-transects. Substrate measurements were taken at five equidistant points along each transect (Appendix B). The substrate size class and the derived median particle size for each reach were used as predictor variables in Question 2. Fine particle distribution of the channel bed and bank resistance were not quantified in the CEDEN database.
Field Survey Dataset

In order to supplement the CEDEN database, a survey of 24 field sites were conducted in 2013 and 2014: 10 reference sites, 12 urban sites, and 2 intermediate site. Most urban channels in San Diego County are on sedimentary rock types near the coast, and the majority of CEDEN reference sites were located in central/east County (tonalite rock type), so the additional reference sites were near the coast (Figure 1). Field surveys were of riffles or runs and did not include pools. Additionally, all sites were on undammed stream reaches that were not channelized, free of waterfalls, and had a drainage area ranging from 0.3 – 1847 km².

At each field site, bankfull stage was identified based on morphologic evidence including changes in slope (i.e. the boundary of the channel bank to the floodplain) and changes in vegetation (Leopold, 1994). $A_{xs}$ and longitudinal slope were surveyed, and samples of the channel bed were collected for particle size analysis. $A_{xs}$ was measured with an autolevel. Cross sections extended onto the floodplain, and the vertical distance from the channel bed to the reference datum were measured at breaks in the slope (Galster et al., 2008; Chin and Gregory, 2001). Three representative cross-sectional profiles were surveyed per site (upper, mid, and lower reach) over a 150 to 200 meter stream reach, and the averaged measurements were used in the analysis (Stein and Bledsoe, 2013). At some sites, three cross sections could not be surveyed due to vegetation obstruction, so one to two representative cross sections were surveyed. Longitudinal slope of the channel bank was measured with an autolevel over a stream reach of 10 bankfull widths (Stein and Bledsoe, 2013). Qualitative field notes on channel conditions, erosional features, and descriptions of the channel composition of banks and bed were also recorded at each site.

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 the finer sediments, a soil sample from the bed between 40 to 500 g (250 to 500 g if gravel is present; 40 to 50 g if no gravel is present) was taken in the field and a dry sieve analysis was conducted in the lab (Guy, 1969). Sand and gravel were separated from the silt-clay fraction by wet-sieving using water and a 62.5 μm sieve. The sand-gravel and the silt-clay content were placed in separate drying pans and went into a drying oven at 100 °C for 1 hour. Once
cooled, the dried samples were weighed and recorded. The dried sand and gravel were spread out on a large sheet of paper and disaggregated by gently using fingers to crush the aggregates without breaking individual grains. The disaggregated sample was dry sieved in a standard U.S. sieving set for 10 minutes and each sieve phi class was weighed and recorded to the nearest 0.01 g. The sediment that passed through the 62.5 μm sieve was added to the silt-clay material that was obtained during the initial wet-sieve procedure.

The CEDEN and field data were combined, totaling 80 sites: 46 reference (I% < 5%), 22 urban (I% > 20%), and 12 intermediate sites (5% < I% < 20%) (Figure 1). Watershed boundaries were digitized using a 10-m digital elevation model (DEM) derived from a USGS 7.5 minute quadrangle elevation contour lines with 20-foot and 40-foot contour intervals. USGS’s National Land Cover Database 2011 (NLCD 2011) was used to calculate I% for the watershed draining to each site. The range of I% for the dataset was 0.05 to 63 percent. Geology types from the United States Geological Survey’s (USGS) Jennings (1977) geology layer were aggregated into 6 groups based on expert knowledge by Eric Berntsen in 2013: fine-weak; coarse-weak; fine-competent; coarse-competent; crystalline; and water (Table 1). The hydrologic soil group was extracted from San Diego Association of Governments’ (SANDAG) 2002 soil layer for each channel location.

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 (Wolman, 1967; Hammer, 1972; Chin and Gregory, 2001; Navratil et al., 2013). Regional hydraulic geometry curves, which relate bankfull channel geometry (w, d, Axs) and \( Q_{bf} \) to \( A_w \) in the form of:

\[
X = \alpha A_w^{\beta} \quad \text{Equation 1}
\]

where X is bankfull channel dimensions (w, d, Axs, or \( Q_{bf} \)), \( A_w \) is the watershed area (km²) and \( \alpha \) and \( \beta \) are coefficients (Dunne and Leopold, 1978), were developed for non-urban watersheds to serve as a natural baseline and were then compared to the regional curves for urban watersheds (Chin and Gregory, 2001). \( Q_{bf} \) is commonly used to detect channel
response to urbanization, but in some cases w has a more robust relationship with A_w and urbanization (Chin and Gregory, 2001).

This analysis focuses on determining: 1) where channel enlargement has occurred (Question 1); and 2) whether the regional channel geometry curves and channel response to urbanization can be predicted by a combination of climate (P), I%, rock type in the channel, longitudinal slope, hydrologic soil group, and/or D_50 of the channel bed (Question 2).

The statistical analysis consisted of two components. First, regional curves of channel bankfull characteristics (w, d, Axs, and Q_bf) versus A_w were constructed for reference channels (I% < 5%) and urban channels (I% > 20%). Statistical significance of the difference in slopes and intercepts of the regional curves were tested using Analysis of Covariance (ANCOVA) (Chaplin, 2005; Johnson and Fecko, 2008). Regional curves for natural stream channels were developed by conducting a linear regression of the channel Axs to the A_w (Equation 1) for natural streams (Hammer, 1972; Chin and Gregory, 2001; Mulvihill and Baldigo, 2007; Navratil et al., 2013). The same was done for urban streams to create regional curves for urbanized channels. The natural and urban regional curves for all bankfull characteristics were compared and tested to see if there were statistical differences in the slopes and/or intercepts (Chin and Gregory, 2001).

Sites whose bankfull characteristics were outside the upper bounds of the 95% confidence interval for the regional reference curves were considered “enlarged”. Enlarged sites were mapped to help identify hotspots of enlargement. A channel enlargement ratio (ER) was calculated, which is the Axs of each urban stream divided by the expected Axs in absence of urbanization (Hammer, 1972; Navratil et al., 2013). The expected Axs was predicted from the regional regression curves for reference stream channels found above and based on the A_w. I%, including 5-20% impervious, was plotted against ER and compared to other I-ER curves for southern California developed by Coleman et al. (2005) and Hawley and Bledsoe (2013).

Second, multiple linear regressions were conducted to determine if mean annual P, I%, longitudinal slope, D_50, hydrologic soil group, and rock type were significant predictors of channel geometry (Faustini et al., 2009). Watershed area alone may not be sufficient to control for the natural variability in channel geometry, which may also be influenced by P (Gotvald et al., 2012; Wilkerson et al., 2014) and geology (Chaplin, 2005). A forward
regression was conducted, starting with a simple regression model of $A_{xs}$ being a function of watershed area and precipitation (Gotvald et al., 2012):

$$A_{xs} = f(A_w, P)$$

Equation 2

where $A_w$ is watershed area (km$^2$) and $P$ is long-term mean annual precipitation in mm derived from the 30 year annual mean 1:800 meter PRISM data.

Following the development of the $A$ and $P$ model, the explanatory variables were added to the regression equation one at a time and the statistically significant variables ($p < 0.05$) were considered significant predictors of channel geometry (Faustini et al., 2009). The hypothesized multivariate regression equation is:

$$A_{xs} = f(A_w, P, I\%_c, D_{50})$$

Equation 3

where cross sectional area is a function of watershed area, mean annual precipitation, percent impervious cover, and $D_{50}$ median particle size of the channel bed.

**Results**

1. **Regional Curves for Reference and Urban Streams**

   Regional bankfull curves relating $A_{xs}$, $w$, $d$, and $Q_{bf}$ to $A_w$ were developed for both reference and urban streams (Figure 2; Table 2). A majority of urban channels (grey points) fell above regional reference curves for all geometric variables (solid black lines). The most statistically robust $\beta$, in terms of coefficient of determination ($R^2$) and the p-value of the regression, were bankfull width ($R^2 = 0.10; p < 0.05$) and $A_{xs}$ ($R^2 = 0.09; p < 0.05$). $\beta$ for $Q_{bf}$ and $d$ were statistically insignificant ($R^2 < 0.05; p > 0.1$ for both).

   For the urban sites, none of the regional curves were statistically significant based on $R^2$ and p-value, but width had the highest $R^2$ ($R^2 = 0.16; p = 0.06$). The insignificance of $\beta$ for the urban sites was due to the large variability in bankfull characteristics in urban channels with watersheds smaller than 10 km$^2$. Of sites in urban watersheds and sandy channel beds, those with $A_w$ less than 10 km$^2$ tended to have larger $d$ compared to those with $A_w$ larger than 10 km$^2$, creating a negative slope in the urban regional curve for $d$ (Figure 2). This will be discussed further in the third section of the results.

   There was a significant difference in $\alpha$ values between urban and reference curves for all channel geometry variables ($p < 0.001$), suggesting that $A_{xs}$, $w$, $d$, and $Q_{bf}$ are significantly larger in urban sites than reference sites for a given $A_w$. $\beta$ values were not significantly different between the urban and reference sites for all bankfull curves ($p > 0.1$) (Figure 2),
indicating that the rate of increase in bankfull geometry ($A_{xs}$, $w$, $d$, and $Q_{bf}$) per $A_w$ is not larger for urban streams compared to reference streams.

Figure 2. Regional bankfull curves ($A_{xs}$, $w$, $d$, $Q_{bf}$) developed for urban and reference streams. CB is cobble, FN is fines, GC is coarse gravel, GF is fine gravel, and SA is sand-bedded channels. $A_{xs}$ and $w$ curves show the most robust relationship.
Table 2. Regional curve equations for San Diego County (this study) with associated $R^2$ and p-values for each curve and southern California curves with $R^2$.

<table>
<thead>
<tr>
<th>Location/Source</th>
<th>Equation</th>
<th>$R^2$</th>
<th>p-value</th>
<th>n</th>
</tr>
</thead>
<tbody>
<tr>
<td>Urban San Diego (this paper)</td>
<td>$A_{xs} = 4.67 A_w^{0.17}$</td>
<td>0.05</td>
<td>0.31</td>
<td>22</td>
</tr>
<tr>
<td>Reference San Diego (this paper)</td>
<td>$A_{xs} = 0.75 A_w^{0.17}$</td>
<td>0.09</td>
<td>&lt;0.05</td>
<td>46</td>
</tr>
<tr>
<td>Southern California (Modrick and Georgakakos, 2014)</td>
<td>$A_{xs} = 0.53 A_w^{0.39}$</td>
<td>0.29</td>
<td>54</td>
<td></td>
</tr>
<tr>
<td>Urban San Diego (this paper)</td>
<td>$w = 7.34 A_w^{0.21}$</td>
<td>0.16</td>
<td>0.06</td>
<td>22</td>
</tr>
<tr>
<td>Reference San Diego (this paper)</td>
<td>$w = 3.01 A_w^{0.12}$</td>
<td>0.10</td>
<td>&lt;0.05</td>
<td>46</td>
</tr>
<tr>
<td>Southern California (Faustini, 2009)</td>
<td>$w = 2.17 A_w^{0.24}$</td>
<td>0.45</td>
<td>37</td>
<td></td>
</tr>
<tr>
<td>Southern California (Modrick and Georgakakos, 2014)</td>
<td>$w = 2.06 A_w^{0.27}$</td>
<td>0.45</td>
<td>54</td>
<td></td>
</tr>
<tr>
<td>Urban San Diego (this paper)</td>
<td>$d = 0.87 A_w^{-0.02}$</td>
<td>0.002</td>
<td>0.84</td>
<td>22</td>
</tr>
<tr>
<td>Reference San Diego (this paper)</td>
<td>$d = 0.32 A_w^{0.06}$</td>
<td>0.04</td>
<td>0.17</td>
<td>46</td>
</tr>
<tr>
<td>Southern California (Modrick and Georgakakos, 2014)</td>
<td>$d = 0.26 A_w^{0.12}$</td>
<td>0.07</td>
<td>54</td>
<td></td>
</tr>
<tr>
<td>Urban San Diego (this paper)</td>
<td>$Q_{bf} = 26.54 A_w^{-0.11}$</td>
<td>0.008</td>
<td>0.75</td>
<td>22</td>
</tr>
<tr>
<td>Reference San Diego (this paper)</td>
<td>$Q_{bf} = 1.38 A_w^{0.20}$</td>
<td>0.06</td>
<td>0.10</td>
<td>46</td>
</tr>
</tbody>
</table>

The parameters of the regional curves for urban and reference channels in this study ($\alpha$, $\beta$) were compared to other studies in southern California. The bankfull width regression parameters for southern California (Faustini, 2009; Modrick and Georgakakos, 2014) and the reference curve from this study are in fairly good agreement, with a slightly smaller $\beta$ in this study (Table 2; Figure 3). The urban bankfull width curve in this study has an $\alpha$ of 7.34, which is substantially larger than the reference curves. This indicates that urban channels in
San Diego exhibit much larger bankfull widths compared to reference channels of San Diego and southern California (Figure 3).

Similarly, the reference bankfull cross sectional area curve from this study was in agreement with the curve of Modrick and Georgakakos (2014) (Table 2; Figure 3). The urban cross sectional area curve also had a much higher $\alpha$ (4.67) compared to the reference curve and Modrick and Georgakakos’s (2014) curve. In addition to urban regional curves yielding wider channels compared to reference curves, they also yield larger cross sectional areas compared to reference relationships.

![Figure 3. Regional $A_{xs}$ and $w$ curves from this study (urban and reference) compared to other regional curves for southern California (Faustini, 2009; Modrick and Georgakakos, 2014).](image)

2. **Channel Enlargement in San Diego County**

Channels were defined as enlarged if their $A_{xs}$ fell outside the upper 95% confidence interval of the regional curve for reference sites (Figure 4). A majority (68%) of the urban channels and 42% of the intermediate sites were enlarged. Of the 15 enlarged urban sites, 11 sites were in watersheds less than 10 km$^2$. Some (13%) of the reference sites fell above the upper 95% confidence interval and were also mapped as “enlarged” (Figure 4).
Figure 4. Map showing the urban, intermediate, and reference sites that are enlarged (red). Enlargement is defined by having a cross sectional area that falls above the 95% confidence interval of the reference $A_{xs}$ curve. Urban areas, or areas with >20% impervious cover, are mapped in grey (NLCD, 2011).

The channel enlargement ratio (ER) was calculated for each site and plotted against percent impervious cover (I%) (Figure 5). ER was modelled as a log-linear function of I%.

Regional enlargement curves developed in this study were compared to curves developed for southern California (Coleman et al., 2005; Hawley and Bledsoe, 2013) and are as follows:

\[
ER \text{ (This study, 2014)} = 1.05 \, e^{0.046 \, I}\% \\
ER \text{ (Hawley and Bledsoe, 2013)} = 1.18 \, e^{0.11 \, I}\% \\
ER \text{ (Coleman et al., 2013)} = 1.12 \, e^{0.049 \, I}\%
\]

Equation 4
Equation 5
Equation 6

The coefficients of the enlargement curves for San Diego are slightly smaller than the curves previously developed for southern California (Coleman et al., 2005; Hawley and Bledsoe, 2013). The enlargement curve developed in this study (solid line) matches the curve from Coleman et al. (2005) (dashed line; Figure 5). Hawley and Bledsoe’s (2013) enlargement curve (dotted line) has a larger coefficient and exponent and does not match the data well.
Some sand-dominated channels fell on or above the enlargement curve developed by Hawley and Bledsoe (2013), while coarse gravel and cobble streams followed the trends of Coleman et al.’s (2005) more conservative enlargement curve.

Figure 5. Enlargement curve for San Diego County (this study) compared to curves developed for southern California. Different shapes represent the particle size class associated with the D50.

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 there may not be sufficient regional variability in precipitation for it to show as a significant explanatory variable. In addition to watershed area, $I\%$ was the only other statistically significant explanatory variable in the regression for $w$ ($p < 0.0001$). $D_{50}$ ($p > 0.1$), geology ($p > 0.1$), hydrologic soil group ($p > 0.1$), and longitudinal slope ($p > 0.1$) were not statistically significant predictors of $w$. 
In contrast, the only independent variable with a statistically significant regression parameter for $A_{xs}$ was I\% ($p < 0.01$). The parameter for $A_w$, although significant for the reference data alone ($p < 0.05$), was insignificant with the addition of urban and intermediate sites ($p > 0.5$). The lack of a relationship between $A_{xs}$ and $A_w$ when including both urban and reference sites was due to significant enlargement of urban channels in small watersheds (Figure 6). The enlarged urban channels had bankfull dimensions that were similar to channels in watersheds an order of magnitude larger. We conclude that urbanization results in a disruption of the classic regional relationships between watershed area and channel geometry due to significant enlargement in channels in small watersheds.

![Figure 6](image)

**Figure 6.** Bankfull mean depth to watershed area relationship for channels in urban watersheds (I\%>20\%). Solid line represents the reference bankfull depth curve and the dotted lines are the 95\% confidence intervals. Urban sand channels with watershed areas less than 10 km$^2$ are incised (black oval) while urban sand channels larger than 10 km$^2$ had much shallower channels (grey oval).

### 3.1 Differences due to watershed area and channel particle size

The relationship between $A_{xs}$ and $A_w$ could weaken due to the varying degrees of incision for channels in different watershed sizes, as mentioned in section 1 of the results. Urbanization can cause a higher degree of erosion in channels draining smaller watersheds.
compared to larger watersheds but this process, including critical sizes where urbanization effects decrease and the mechanisms behind the reduction in impact with increasing watershed size, remains uncertain (Dunne and Leopold, 1978; Navartil et al., 2013). In this study, sand-bedded channels with watershed areas smaller than 10 km$^2$ experienced high amounts of incision and widening in urban areas, falling well outside of the upper 95% confidence interval of the reference bankfull depth curve, while sand-bedded channels with watersheds larger than 10 km$^2$ had much shallower and smaller cross sections (Figure 6), resulting in the unusual negative slope in the urban regional mean bankfull depth curve (Table 2).

Channel particle size impacted the relative importance of incision and widening in urban channels. Sand-bedded channels tended to incise, while cobble- or gravel-bedded channels tended to widen (Figure 7). 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 less than 10 km$^2$ (Figure 8). 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 demonstrated in urban channels.

Figure 7. An urban sand channel (watershed area = 0.8 km$^2$; black) and urban coarse gravel/cobble channel (watershed area = 1.1 km$^2$; grey). Urban sand channels tend towards incision, while coarser bedded channels promote widening.
Figure 8. Width to Depth (w:d) ratio for enlarged urban channels. The highly enlarged sand-bedded channels with watersheds less than 10 km\(^2\) tended to have lower w:d ratios compared to channels with coarser beds (CB, GC).

Of the enlarged urban sites, 11 out of 15 were channels whose watersheds drain < 10 km\(^2\). Sand-bedded channels in large urban watersheds may be less susceptible to erosion compared to sand-bedded channels in small urban watersheds due to a substantial amount of urban baseflow that sustains riparian vegetation growth on or near the channel banks year-round. During field reconnaissance, substantial amounts of baseflow were observed in urban channels draining larger watersheds compared to little or no baseflow in urban channels draining smaller watersheds. In Los Penasquitos Creek in San Diego County, for example, urbanization has caused an increase in dry season baseflow due to lawn irrigation and urban runoff, which doubled the area of riparian vegetation following urbanization (White and Greer, 2006). This urban-induced vegetation growth on larger watersheds could serve to protect the channels from erosion, while the sub-tributary channels are left susceptible to erosion. Anderson et al. (2004) found that the effects of riparian vegetation on channel width differed between streams draining small watersheds (<100 km\(^2\)) compared to large
watersheds (>100 km²) in undeveloped areas. For channels with watersheds greater than 100 km², widths were narrower with the presence of thick woody bank vegetation than in grass lined or non-forested banks, while for channels with smaller watersheds, vegetated banks had larger widths compared to bare banks (Anderson et al., 2004). Anderson et al. (2004) suggest that riparian vegetation on large streams can serve as bank protection against widening, while small streams do not experience the same protection. Therefore, future development near these vulnerable minor tributaries could cause even more degradation to the stream channel. Management should consider focusing their efforts on sand-bedded channels that are less than 10 km² in drainage area (on sub-tributaries).

**Discussion: Comparison of urban effects with other studies**

The regional study presented here suggests that a majority of urban channels respond to urbanization, but the magnitude of the response varies with watershed size and channel particle size. Previous studies on the impact of urbanization on stream channel geometry in southern California documented enlargement and were located near the coast on alluvial and marine sediments (Trimble, 1997). The San Diego streams also show evidence of extreme channel enlargement for sand-bedded channels. In contrast, we see much less incision and more widening in channels with coarse bed material, suggesting that the regional response to urbanization may be less severe than highlighted in Trimble (1997). Faustini et al. (2009) similarly found that streams with coarse bed material (gravel/cobble/boulder) had much wider channels compared to streams with fine bed material (silt/sand).

Additionally, previous studies concluded that hydromodification from changes in percent impervious cover are most prominent in channels in watersheds smaller than 50 km² for southern California streams (Coleman et al., 2005) and for watersheds less than 5 km² in France (Navratil et al., 2013). The results from the San Diego channels suggests that channels with watersheds smaller than 10 km² were most vulnerable to enlargement, though the exact value is not precisely determined. Coleman et al. (2005) suggested that the threshold of ephemeral channel response to urbanization affects channels of larger watershed sizes, but their study was conducted on a smaller number of sites (N=11) and over a larger, more heterogeneous region (Los Angeles, Orange, and Ventura Counties) compared to this study (N=80; San Diego County). Navratil et al. (2013) suggested that streams with watersheds smaller than 5 km² experienced the highest enlargement due to local factors such
as close proximity to road crossings, urban areas, or storm drains. Channel enlargement can also vary by stream bed and bank resistance. Streams with highly resistant bed and bank materials are likely to have a larger threshold for stream channel change (Coleman et al., 2005), which is confirmed by our observation of greatest enlargement in sand-bedded channels.

Hawley and Bledsoe (2013) used a duration density function (DDF) and an equation for bedload transport to estimate long term sediment transport pre- and post-development to test if sediment imbalances between pre-development and post-development predict enlargement better than percent impervious cover in southern California. The sediment transport equation did not significantly improve the R² values for the enlargement curve compared to using percent impervious cover alone; both were significant predictors of enlargement and explained nearly 60% of the variance in enlargement. Additionally, channels can start to enlarge with as little as 2% (Coleman et al., 2005) to 5% (Hawley and Bledsoe, 2013) increase in impervious cover. Hawley and Bledsoe’s (2013) ER curve predicted higher responses of enlargement compared to Coleman et al. (2005) and this study (Figure 5). Hawley and Bledsoe’s (2013) pre-urban Axs estimation, which was determined by estimating width from historical aerial imagery and depth from field indications (i.e. depth from an artificially hardened cross section with little signs of incision), may be a more realistic historical Axs estimation for a given site compared to using the Axs reference regional curve. Therefore, enlargement due to increases in impervious cover in this study could be underestimated compared to actual enlargement following urbanization in San Diego County.

In addition to watershed size and particle size of the channel, urban age (Hammer, 1972) and proximity to downstream grade control (Hawley and Bledsoe, 2013) could have a significant effect on channel response to urbanization. A decade of urbanization in Maryland (Leopold, 1973) did not change the frequency of high flows, but thereafter the number of high flows increased rapidly and massively (Dunne and Leopold, 1978). In-bank channel deposition gradually narrowed the channels in the first decade following urbanization, while the second decade was characterized by overbank deposition that increased the height of the banks (Dunne and Leopold, 1978). In addition to urban age, downstream distance to channel hardpoints could affect channel enlargement with cross sectional areas increasing moving
upstream of a bedrock or artificial grade control (Hawley and Bledsoe, 2013). Hardpoints and subsequent headcutting could cause an increase in cross sectional area with decreasing watershed area. Possible impacts of spatial location of urbanization within the watershed, in addition to I%, should be examined in subsequent research, as well. Future research needs to be conducted to test if urban age, distance to downstream grade control, and spatial arrangement of urban areas within each watershed are significant indicators of channel enlargement in San Diego County and in other semi-arid regions.

This study utilizes publically-available habitat datasets complemented by field surveys and has the utility to be repeated in other locations that have similar habitat surveys. Given that the CEDEN database has thousands of habitat surveys throughout California, subsequent studies comparing different regions could be made (i.e. northern California compared to southern California streams). As more states start implementing hydromodification management plans, publicly-available datasets could be useful in understanding the effects of urbanization on stream channel geometry and utilized for effective stream channel management.

**Conclusion**

Regional bankfull curves relating bankfull cross sectional area, width, mean depth, and discharge to watershed area were developed from a total of 80 survey sites throughout San Diego County (reference, intermediate, and urban). Regional curves for bankfull width and bankfull cross sectional area have the most statistically significant parameters and highest $R^2$ values. Intercepts in the bankfull width and cross sectional area curves were substantially larger for urban sites than for reference curves in this study and compared to other regional curves for southern California, indicating that urban channels tend to have larger bankfull widths and cross sectional areas for a given watershed size.

Based on a forward multiple regression, watershed/landscape variables such as geology, hydrologic soil group, longitudinal slope, mean annual precipitation, and $D_{50}$ were not significant indicators of channel geometry in the heterogeneous area of San Diego County. Bankfull width of alluvial channels in San Diego County was explained by both watershed area and percent impervious cover in the watershed. Urbanization has caused sufficient incision and widening of urban channels in small watersheds such that percent
impervious cover was the only significant predictor of channel cross sectional area, completely disrupting the relationship between watershed area and channel dimensions.

Sand-bedded channels followed the enlargement curve of Hawley and Bledsoe (2013) and tended to have higher enlargement ratios compared to that of coarse gravel- and cobble-bedded urban streams. Additionally, urban sand channels whose watersheds drained less than 10 km² had much higher mean bankfull depths compared to urban sand channels larger than 10 km² in watershed size. Sand-bedded channels with watershed areas greater than 10 km² may be less susceptible to erosion due to stabilization of channel banks through the growth and maintenance of riparian vegetation through increased urban baseflow. Baseflow was observed during field reconnaissance in channels of large urban watersheds and non-existent in channels of small urban watersheds. Management should focus their efforts on monitoring development projects located near urban sand channels of less than 10 km² drainage areas.
REFERENCES


APPENDIX
Appendix A. CEDEN Physical Habitat stream reach with 10 main transects (A-K) and 11 inter-transects (Ode, 2007).

Appendix B. CEDEN Bankfull measurements and equations used to calculate bankfull cross sectional area. Five equidistant points where the substrate size was measured are also shown (left bank, left center, center, right center, and right bank).

Bankfull Cross Sectional Area = Dry Bankfull Area + Wetted Area
Dry Bankfull Area = 0.5 * (bankfull width + wetted width) * bankfull height (treated as a trapezoid)

Wetted Area = Area 1 + Area 2 + Area 3 + Area 4, where
- Area 1 = (ww/4) * wd.lctr (rectangle)
- Area 2 = (ww/4) * (wd.lctr + wd.ctr)*0.5 (trapezoid)
- Area 3 = (ww/4) * (wd.ctr + wd.rctr)*0.5 (trapezoid)
- Area 4 = (ww/4) * wd.rctr (rectangle)

Where ww is wetted width, wd.lctr is wetted depth left center, wd.ctr is wetted depth center, and wd.rctr is wetted depth right center.

**Appendix C.** Manning’s Equation to estimate bankfull discharge from the cross sectional area. Manning’s roughness was estimated using a generated lookup table.

\[
Q = VA = \left( \frac{1.49}{n} \right) AR^{\frac{2}{3}} \sqrt{S} \quad [\text{U.S.}]
\]

\[
Q = VA = \left( \frac{1.00}{n} \right) AR^{\frac{2}{3}} \sqrt{S} \quad [\text{SI}]
\]

Where \( Q \) = Flow Rate (ft\(^3\)/s), v = Velocity (ft/s), A = Flow Area, (ft\(^2\)) n = Manning’s Roughness Coefficient, R = Hydraulic Radius (ft), S = Channel Slope (ft/ft).

For Manning’s roughness coefficient, a simple lookup table was generated and used with the D50 particle size of each reach:

<table>
<thead>
<tr>
<th>D50 Substrate Size Class</th>
<th>Manning’s Roughness</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cobble (CB)</td>
<td>0.0245</td>
</tr>
<tr>
<td>Coarse Gravel (GC)</td>
<td>0.03</td>
</tr>
<tr>
<td>Fine Gravel (GF)</td>
<td>0.0275</td>
</tr>
<tr>
<td>Sand (SA)</td>
<td>0.085</td>
</tr>
<tr>
<td>Fines (FN)</td>
<td>0.01</td>
</tr>
</tbody>
</table>