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Channel enlargement in semiarid suburbanizing watersheds: A southern California case study

R.J. Hawley [a,b,1], B.P. Bledsoe [a,*]

[a] Dept. of Civil and Environmental Engineering, Colorado State University, Fort Collins, CO 80523-1372, United States
[b] Sustainable Streams, LLC, 1948 Deer Park Avenue, Louisville, KY 40205, United States

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SUMMARY

Semiarid channels exhibit an extreme sensitivity to upstream urban development, particularly in unconfined valleys with unprotected grades. For example, one of our study streams in southern California has increased its cross-sectional area by nearly 14-fold relative to its pre-developed channel form in a watershed that has been only lightly developed (10.4% imperviousness). Multivariate regression models of cross-sectional channel enlargement at 61 sites were highly dependent on the ratio of post- to pre-urban sediment-transport capacity over cumulative duration simulations of 25 yrs (Lr), which explained nearly 60% of the variance. The proximity of a channel hard point such as bedrock or artificial grade control was also significant, indicating that channel enlargement increased moving upstream from grade control. The enlargement models point to the importance of balancing the post-developed sediment transport to the pre-developed setting over an entire range of flows rather than a single flow in order to reduce the risk of adverse channel responses to hydromodification. The need for controlling a wide range of flows was underscored by logistic-regression analyses that indicated a high risk of instability in systems with $Lr > 1$, especially for fine-grained systems (i.e., $d_{50} < 16$ mm).

1. Introduction

Watershed urbanization can be a primary driver of hydrologic and geomorphic change in stream channels (i.e., 'hydromodification;' Hammer, 1972; MacRae, 1993) and semiarid systems seem to exhibit an increased sensitivity to this phenomenon (Trimble, 1997; Coleman et al., 2005; Hawley et al., 2012). Previous work in humid temperate systems has linked watershed urbanization to channel enlargement (Hammer, 1972), incision (Booth, 1990), and widening (Galster et al., 2008); however, there is an urgent need for improved understanding of channel response potential in semiarid settings due to the combination of rapid development rates across these regions and stream systems that are inherently dynamic. With sporadic sediment movements (Graf, 1981), extended aggradation/degradation phases (Wolman and Gerson, 1978), and infrequent periods of equilibrium (Bull, 1997), semiarid streams have little natural resistance against unmitigated urbanization. Southern California channels offer a valuable case study because the region includes additional risk factors such as high-relief watersheds with relatively fine-grained bed materials, particularly in unconfined valleys at intermediate and lower portions of the stream network. Moreover, and in contrast to much of the rest of the nation, stormwater controls at the development scale are largely lacking in southern California (based on an extensive field reconnaissance and data-collection campaign). This lack of flow mitigation has consequently amplified flows and durations (Hawley and Bledsoe, 2011), and resulted in rapid and extensive channel enlargement that may be one of the most extreme examples of morphologic channel responses induced by land-use dynamics. For example, an unnamed tributary to the Santa Clara River in north-central Los Angeles County near Acton, California (i.e., 'Acton') has enlarged on the order of 100–1000% over the reach since becoming only lightly developed during the last few years (2.5% impervious area in 2001, 11% in 2006).

1.1. Beyond single-flow analyses: can channel enlargement be predicted using cumulative sediment transport?

The use of single-flow analyses for assessing and managing channel stability has increasingly been brought into question (Graf, 1988; Bull, 1997) because all flows capable of moving sediment

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* Corresponding author. Tel.: +1 970 4918410.
E-mail addresses: bob.hawley@sustainablestreams.com (R.J. Hawley), brian.bledsoe@colostate.edu (B.P. Bledsoe).
[1] Tel.: +1 502 7182912.

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have the potential to affect channel form, and it is the combination of both frequency and magnitude that leads to geomorphic effectiveness (Wolman and Miller, 1960). One of the earliest process-based approaches to managing hydromodification considers the cumulative excess shear stress over all flows capable of transporting the channel-bed material (Santa Clara Valley Urban Runoff Pollution Prevention Program, 2004). The so-called 'effective work index' is computed using binned flows from long-term rainfall runoff simulations in the Hydrologic Engineering Center–Hydrologic Modeling System (HEC–HMS) over cumulative flow durations of 50 yrs.

As an alternative to rainfall–runoff models, Hawley and Bledsoe (2011) developed a regional scaling procedure to model long-term cumulative flow durations and magnitudes as functions of watershed characteristics, such as drainage area, precipitation, and imperviousness. Duration Density Functions (DDFs) estimate cumulative durations for all geomorphically-effective flows in a logarithmically-binned histogram format such that long-term sediment transport can be subsequently estimated.

This paper focuses on applying DDFs and other tools to develop an improved, process-based understanding of channel-response magnitude associated with watershed urbanization. That is, increased flows and durations result in higher sediment-transport potential, culminating in large surpluses of excess energy relative to the pre-developed regime. Models of the corresponding channel enlargement provide managers with tools for predicting changes in channel form in urbanizing watersheds, but more importantly, will lead to informed evaluations of various mitigation strategies to minimize the risk of such channel degradation.

In summary, the objectives of this paper are to address the following questions:

1. Are sediment-transport imbalances between post-developed and pre-developed flow regimes significant in predicting observed channel enlargement, and if so, do sediment imbalances predict enlargement better than previously used surrogates for watershed urbanization such as imperviousness?
2. At what level of sediment imbalance and/or development extent does the risk of channel instability become apparent in semiarid southern California systems?

Resolving these questions could provide watershed managers with a much needed empirical basis for anticipating channel response to varying degrees of development and identifying policies that reduce the risk that channels will cross unacceptable thresholds of enlargement and instability.

2. Methods

Extensive field data were collected and analyzed for this project, guided by independent reviews and state-approved quality-assurance/quality-control (QA/QC) procedures. In general, the modeling approaches used and developed in this paper are designed for broad application in semiarid regions as opposed to high precision along a single reach. Although process-based, the empirical models presented here are more appropriate for quantifying relative extents of change than absolute magnitudes.

In the following sub-sections, we outline the site-selection process and describe how data were collected. We discuss how channel enlargement was quantified based on departures from reference channel form using field measurements coupled with historic aerial photography. Next, computational methods for hydrologic, hydraulic, and sediment-transport processes are covered. Lastly, the analytical and statistical methods are presented, describing how results from the preceding steps were used to develop final models.

2.1. Site selection and channel stability

Pre-developed, developing, and heavily-developed watersheds were targeted to capture a gradient of urbanization relative to the rural setting (Table 1). Sites spanned channel evolution stages from 'stable' single-thread to incising, widening, and braiding (*sensu* Schumm et al., 1984; Hawley et al., 2012). With the understanding that most channels of southern California are inherently dynamic, 'stable' is defined for the purposes of this paper as Channel Evolution Model (CEM) Stages 1 (dynamic equilibrium), B1 (braided dynamic equilibrium), 4 (recovering), and 5 (recovered) from the Schumm et al. (1984) and Hawley et al. (2012) models (Table 2). From field reconnaissance at more than 50 candidate streams, 28 stream reaches were selected for data collection and analysis for this study. We excluded reaches that were reinforced through artificial means due to their inability to freely respond to hydromodification through morphologic adjustment. We also excluded streams with substantial upstream flow regulation (e.g., dams, reservoirs, and large stormwater control facilities) because flow detention in most small watersheds was uncommon at the subdivision scale. The data set was also designed to cover regionally-representative ranges of slope, bed material, channel type/planform, channel evolution stage, valley setting, drainage-basin size, and urbanization extent (Table 2). Stream reaches and watersheds used in the analysis are denoted in Fig. 1.

Along 28 stream reaches (typically 1- to 2-km), 66 geomorphically-distinct sub-reaches or 'sites' were identified for this analysis. Geomorphically-distinct sub-reaches were defined by substantial differences in channel form, contributing drainage area, or valley setting. For example, by collecting several distinct cross sections along a common reach, it was possible to isolate the effects of a downstream channel hard point on channel enlargement.

2.2. GIS and field data collection

All GIS data were acquired from public-domain sources including the USGS; U.S. Department of Agriculture (USDA); National Oceanic and Atmospheric Administration (NOAA), and State of California geospatial clearinghouse (CAL-Atlas). Changes through time were tracked using historical and present-day aerial photography from the USGS and Google Earth, along with historical USGS quadrangle topographic maps. High-resolution historic aerial photography was purchased from the USGS at twelve of our most dynamic study reaches to obtain more precise estimates of historic channel form. Publicly-available low-resolution aerial photography confirmed the lack of historical change at the remaining 16 reaches.

ArcMap software by Environmental Systems Research Institute (ESRI), including extensions such as 'spatial analyst,' was used to optimize GIS measurements where possible. Automated drainage basin delineations were cross-checked with aerial photography, field investigations, and existing shapefiles such as USGS Hydrologic Unit Code (HUC) boundaries and National Hydrography Dataset (NHD) flowlines. Watershed boundaries were independently confirmed by two analysts.

The USGS national impervious raster from 2001 provided an objective way to measure total imperviousness. Because substantial development occurred after 2001 at four study reaches (Acton, Dry, Hasley, and San Timetao), more recent aerial photography was used to quantify more reflective imperviousness estimates for the current extent (Fig. 2).

Bed material was sampled after Bunte and Abt (2001), with 100-particle pebble counts using a half-phi template across equally-spaced sampling frame transects at riffle sections. Sites with more than ~20% sand by volume required sieving and pebble counts. Volumetric gradations (pebble counts using an equally-spaced sampling frame) were composited with distributions by