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Ecologically relevant geomorphic attributes of streams are impaired by even low levels of watershed effective imperviousness

Geoff J. Vietz [a,*], Michael J. Sammonds [a], Christopher J. Walsh [a], Tim D. Fletcher [a], Ian D. Rutherfurd [a], Michael J. Stewardson [b]

[a] *Department of Resource Management and Geography, The University of Melbourne, Australia*
[b] *Department of Infrastructure Engineering, The University of Melbourne, Australia*

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ABSTRACT

Urbanization almost inevitably results in changes to stream morphology. Understanding the mechanisms for such impacts is a prerequisite to minimizing stream degradation and achieving restoration goals. However, investigations of urban-induced changes to stream morphology typically use indicators of watershed urbanization that may not adequately represent degrading mechanisms and commonly focus on geomorphic attributes such as channel dimensions that may be of little significance to the ecological goals for restoration. We address these shortcomings by testing if a measure characterizing urban stormwater drainage system connections to streams (effective imperviousness, *EI*) is a better predictor of change to ecologically relevant geomorphic attributes than a more general measure of urban density (total imperviousness, *TI*). We test this for 17 sites in independent watersheds across a gradient of urbanization. We found that *EI* was a better predictor of all geomorphic variables tested than was *TI*. Bank instability was positively correlated with *EI*, while width/depth (a measure of channel incision), bedload sediment depth, and frequency of bars, benches, and large wood were negatively correlated. Large changes in all geomorphic variables were detected at very low levels of *EI* (<2–3%). Excess urban stormwater runoff, as represented by *EI*, drives geomorphic change in urban streams, highlighting the dominant role of the stormwater drainage system in efficiently transferring stormwater runoff from impervious surfaces to the stream, as found for ecological indicators. It is likely that geomorphic condition of streams in urbanizing watersheds, particularly those attributes of ecological relevance, can only be maintained if excess urban stormwater flows are kept out of streams through retention and harvesting. The extent to which *EI* can be reduced within urban and urbanizing watersheds, through techniques such as distributed stormwater harvesting and infiltration, and the components of the hydrologic regime to be addressed, requires further investigation.

1. Introduction

> *[The] direct manipulation of land surface cover and modification of the hydrological cycle are the two most important ways in which humans influence the overall course of geomorphological processes* (Church, 2010, p. 281).

Urbanization influences stream morphology more than any other land use (Douglas, 2011): it alters hydrology and sediment inputs leading to deepening and widening of streams (Chin, 2006). Concomitantly, urbanization often directly impairs stream morphology through channel and riparian zone interventions, e.g., culverts (Hawley et al., 2012), rock protection (Vietz et al., 2012b), and constricted floodplains (Gurnell et al., 2007). These changes to channel geomorphology in turn contribute to poor in-stream ecological condition (Morley and Karr, 2002; Walsh et al., 2005b; Gurnell et al., 2007; Elosegi et al., 2010).

The common conception is that channels undergo gross morphologic alterations if >10–20% of their watershed is covered by impervious surfaces (total imperviousness, *TI*; Bledsoe and Watson, 2001; Chin, 2006; Table 1). Many of these studies may, however, underestimate the influence of urbanization by using insensitive channel metrics and assessing streams in early stages of urbanization. Most importantly, *TI*, as a measure of urban density, may not adequately represent the way in which urbanization alters the master variables of flow and sediment within a watershed.

Hydrologists have long recognized that, rather than the proportion of impervious cover within a watershed, it is the proportion that is directly connected to the stream through stormwater drainage systems that may be a better predictor of urban-induced hydrologic change (Leopold, 1968). Referred to as effective imperviousness (*EI*) the proportion of impervious cover directly connected to the stream through stormwater drainage systems may also be a better predictor of geomorphic response than is *TI*. Over the last decade a direct measure of *EI* has

* Corresponding author. Tel.: +61 3 9035 6837.
E-mail address: g.vietz@unimelb.edu.au (G.J. Vietz).

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Table 1
Reported medium-term to long-term changes to geomorphic attributes in response to urbanization (increase ↑, decrease ↓, no change ■) defined by *TI* (total imperviousness), which covers *ISC* (impervious surface cover) and *TIA* (total impervious area), unless otherwise noted.

Attribute	Direction of change		Reported *TI* at which major change occurs	References
General condition	↓	'Channel instability and abrupt declines in indices of aquatic ecosystem integrity'	10–20%	Bledsoe and Watson (2001)
	↓	Physical stream conditions index (PSCI)	Not reported	McBride and Booth (2005)
	↓	'Thresholds of stream degradation'	10–15%	Chin (2006)
W/D	↑	Increase in *W/D* reported by 100% of citations ($n = 14$)	Not reported	Chin (2006)
Substrate sediment depth	↓	Decreasing sediment depth	Not reported	Leopold (1973)
	■	Gravels selectively removed (relative to rural channels), particularly in range 2–64 mm, but urban channels not deeper	Not reported	Pizzuto et al. (2000)
	↓	Relative roughness (D_{84}/bankfull depth)		Morley and Karr (2002)
	↓	Reduced sands and pebbles Lower coarse-sediment loads	Not reported	Chin (2006)
Bars and benches	↑	50% increase in bars and benches reported	Not reported	Chin (2006)
	↓	'No significant bars'	Not reported	Colosimo and Wilcock (2007)
Bank instability	↑	Increasing instability	At 10% *EIA*[a] channels were 'universally unstable'	Booth and Jackson (1997)
	■	'No significant relationship between *TI* and bank erosion'	Not reported	Finkenbine et al. (2000)
	↑	Channel instability	10–20%	Bledsoe and Watson (2001)
	↑	Channel erosion	No reported	Wang et al. (2001)
Large wood	↓	Decrease	Not reported	Booth et al. (1997)
	↓	Decrease	At >20% wood becomes 'scarce'	Finkenbine et al. (2000)
	↓	Decrease	Not reported	Chin (2006)

[a] *EIA* (effective impervious area), used by Booth and Jackson (1997) equals *TI* multiplied by the wholesale reduction factor of Dinicola (1990).

been found to be a better predictor of ecological response in urban streams (Walsh et al., 2012), but use of such a metric has not found its way into geomorphic studies even though *TI* has been found to be ineffective (e.g., Bledsoe et al., 2012). A direct measure of *EI* – one that specifically accounts for the drainage from each impervious surface rather than using a generic reduction factor (e.g., Booth and Jackson, 1997; Wang et al., 2001) – has not previously been used in geomorphic investigations. In this paper, we advance on past studies by testing if *EI* is a stronger predictor than *TI* for urban-induced channel change.

A second limitation of previous studies of urban-induced morphologic change is the common focus on channel dimensions (Chin, 2006). These are important for infrastructure and flood protection but do not necessarily have a strong mechanistic link to stream ecosystems. While some notable exceptions exist (Finkenbine et al., 2000; McBride and Booth, 2005), other geomorphic attributes are rarely investigated.

This study examines how urbanization of a watershed can result in the impairment of a suite of geomorphic attributes of relevance to aquatic ecosystem condition, such as large wood, sediment availability, and structural and hydraulic complexity (of the bed, bank, and water column), represented by the following variables:

- Stream width/depth ratios: urban streams tend to be deeper relative to their width than comparable rural streams (Table 1). Incised channels lead to reduced macrophyte abundance (Duncan et al., 2011), lower water table levels and base flow persistence (Hardison et al., 2009), and decreased hydrologic connectivity with the floodplain. In turn, these factors negatively impact on processes such as nutrient retention (Driscoll et al., 2010) and denitrification (Groffman et al., 2005) and have been linked to instability and low quality habitat (Booth and Henshaw, 2001).
- Bedload sediment: mobile coarse-grained bedload sediments are important habitat and reductions impact on foraging and refuge for macroinvertebrates (Morley and Karr, 2002; Nilsson et al., 2003) and fish (Wheaton et al., 2010). They provide for hyporheic exchange, which is important for nutrient retention, metabolism and temperature modulation (Driscoll et al., 2010), and play a role in pollutant exchange (Ryan and Boufadel, 2007).
- Bank instability: is integral to natural river functioning; and bank *stability* is not necessarily a desired endpoint (Gregory et al., 1992; Florsheim et al., 2008). However, rates of bank erosion are higher in urban streams. Extensive bank instability provides low quality habitat (Booth and Henshaw, 2001) and reduced aquatic–terrestrial interactions (Elosegi et al., 2010).
- Bars and benches: deposits of predominantly bedload and suspended sediments, respectively (Vietz et al., 2012a), influence hydraulic habitat (Poff and Zimmerman, 2010; Vietz et al., 2013), biotic zonation, and distribution (Junk et al., 1989; Steiger et al., 2001) and provide denitrification zones (Groffman et al., 2005).
- Large wood: reduced large wood loads are linked to lower abundances of fish and macroinvertebrates through impacts on food and refuge (Sullivan et al., 2004; Elosegi et al., 2010), increased bank instability (Finkenbine et al., 2000), increased flow energy, and decreased bed diversity (Booth et al., 1997).

We investigate these geomorphic attributes in 17 sites across watersheds representing a gradient of urbanization (Fig. 1). These are the same streams used in previous ecological studies investigating the role of urban stormwater drainage connection (Hatt et al., 2004; Taylor et al., 2004; Walsh, 2004). We demonstrate that *EI* is a better predictor than *TI* of changes in geomorphic attributes and that impairment of these geomorphic attributes occurs at very low levels of *EI*, highlighting that urban stormwater runoff is a central driver of geomorphic change.

2. Methods

The 17 sites are located within independent watersheds (area 2–15 km^2 with one site per watershed) on the eastern fringe of Melbourne, Australia (Fig. 1). Watershed urbanization ranges from almost completely undeveloped to medium-density residential (Table 2). The study has been designed to address some of the confounding factors that complicate the physical response of stream channels to urbanization, including the distribution of watershed urbanization by assessing connected impervious surfaces (and recognizing the hydraulic efficiency of stormwater pipes), time since urbanization by focusing on established suburbs, and the variability in response of different stream types by focusing on alluvial streams and geomorphic attributes that are amenable to hydrologic change (sensitivity, sensu Bledsoe et al., 2012).