Urban streams and sediments: informing better management through recent findings

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Key Points

- In urban streams, coarse-grained sediment does not deposit where we want it (in the channel bed) but ends up where we don't want it (in wetlands and estuaries).
- Coarse-grained sediment supply is plentiful, driven by high levels of sediment connectivity between sources and the drainage network.
- Increased urban streamflows transport sediments efficiently through the stream system and don't allow them to build up bedforms or habitat.
- To facilitate recovery of bed sediments and prevent erosion in urban streams, we will need to address both flow and sediment regimes, using stormwater control measures and coarse-grained sediment bypass or replenishment.

Abstract

Urban streams provide ecological and social values, including habitat and human accessibility, but are subject to geomorphic threats such as erosion and sedimentation. Sediment supply regimes are important inputs to streams but their role in either enhancing or mitigating geomorphic threats is poorly understood. In this paper we provide a summary of recent research on urban coarse-grained sediment regimes, and their role in stream channel change and management. We undertook field studies of bedload sediment yields in small streams, and coarse-grained sediment supply rates from urban land surfaces to the stormwater network. Our research demonstrates that urban catchments have highly dynamic geomorphic processes, driven by high levels of sediment connectivity between sources (e.g. infill construction areas, gravel surfaces, bare soil patches) and the drainage network. Increased urban flows transport sediments efficiently through pipes and stream channels, producing higher sediment transport rates than background conditions, but not building up substrates or bed features in channels. The key to allowing bed sediments to persist in urban streams, and reducing sediment-maintenance requirements, is to address both flow and sediment regimes. Stormwater control measures such as rain gardens have the potential to trap coarse-grained sediment that would otherwise be an input to the stream, and may need to include coarse-grained sediment bypass or replenishment arrangements.

Keywords

Urbanization, geomorphology, sediment supply, bedload, coarse-grained sediment, stormwater, connectivity, drainage

Introduction

In urban areas, hydrological and sediment cycles are profoundly altered by covering land surfaces with impervious material and draining them efficiently to streams (Meyer et al., 2005; Walsh et al., 2005). The resulting degradation of stream geomorphology and ecology impacts on the social values provided by streams

(Smith et al., 2016), and necessitates huge financial costs in stabilising and restoring channels (Palmer et al., 2007; Vietz et al., 2014a).

It is recognised that stream geomorphology is the product of both flow (which drives sediment transport capacity) and sediment supply (Mackin, 1948; Kirkby, 1971; Lane, 1955). Urbanization increases streamflows and hence sediment transport capacity (Walsh et al., 2012; Booth, 1991) by delivering runoff from impervious surfaces through a highly efficient drainage network (Walsh, 2004), removing streambed substrates and enlarging channels (Vietz et al., 2014b). The effect of urbanization on sediment supply is much less clear (Chin, 2006), particularly for coarse-grained sediment (Russell et al., 2017). While fine-grained sediment from urban catchments is considered a pollutant, due to its high contaminant loading and potential to smother habitat (Owens et al., 2005), coarse-grained sediment (>0.5 mm diameter) often has low levels of contamination (Houshmand et al., 2014). Coarse-grained sediment is a key input to stream ecosystems, building substrates and bedforms (Hawley and Vietz, 2016). Furthermore, a change in coarse-grained sediment supply could either exacerbate (if reduced) or mitigate (if increased) the tendency for urban streams to incise into their beds and degrade (Lane, 1955).

The tendency of urban streams to erode their bed and banks indicates that there is an imbalance between sediment transport capacity and sediment supply. It has, until recently, been widely assumed that sediment supply is relatively low in mature urban catchments (Wolman, 1967; Chin, 2006; Gurnell et al., 2007), and that it may even decline to below background levels due to sealing of surfaces. Recent research indicates, however, that both coarse and fine-grained sediment yields from established urban catchments can remain elevated (Smith and Wilcock, 2015; Gellis et al., 2017). Observations of increasing loads of sediment in wetlands, lakes and estuaries downstream of urban areas and in purpose-built sediment ponds support this (Taylor and Owens, 2009). While undoubtedly some of that sediment comes from channel erosion in response to catchment urbanization (Trimble, 1997), substantial amounts are likely to also come from upland sources on the urban land surface (Smith et al., 2011).

Our three-year research program (2015 – 2018) informs better characterisation of the coarse-grained sediment regime of urban catchments, leading to targeted recommendations for better waterway and stormwater managers. Specifically, our aim was to understand the response of coarse-grained sediment supply (including both in-stream yields and upland supply) across a gradient of urbanization intensity, and the relative importance of flow and sediment supply changes in constraining the geomorphic condition of urban streams. From this, we can better understand the urban design arrangements leading to current patterns of stream degradation and develop recommendations for better design and management.

Summary of methods

The research findings are derived from three key studies:

1. A quantitative literature review of global responses of sediment supply to urbanization;
2. A field study comparing bedload sediment yields in small streams across a gradient of urbanization; and
3. A field study quantifying upland (urban land surface) coarse-grained sediment supply rates to the stormwater network and assessing the relative importance of different sources.

Study 1 (Russell et al., 2017) used quantitative evidence from the international body of published literature to test and update a long-established conceptual model of sediment yields in urbanizing and urban watersheds.

Study 2 (unpublished) monitored 9 sites across a gradient from completely forested to suburban (49% total impervious; 48% effective impervious) in eastern Melbourne, Australia. The more suburban sites were mostly developed during the 1950s to 1970s, although infill and renewal construction works are constantly occurring, with the instantaneous proportion of land under construction reaching 1.5% in the more urbanized catchments during the study period. We monitored bedload sediment yields from July 2016 to August 2017 using a sediment trap recessed into the bed of the stream, which was designed to capture all sediment that was transported along the stream bed. The amount captured in the trap was measured and sampled after each major rainfall event. The key outputs were the coarse-grained (> 0.5 mm) bedload yield and particle size distribution, on an event and total annual basis. We then assessed relationships between the yield and size of bedload sediment and measures of catchment urbanization and hydrology.

Study 3 (unpublished) included 9 sites nested within a suburban catchment (selected from study 2). We quantified key upland (i.e. non-channel) sources of sediment in urban areas using field measurements of sediment loads from the urban land surface from May 2017 to April 2018. Coarse-grained sediment yields were measured from street-scale catchments using sediment traps at the entry to stormwater pits. Detailed observations of land-cover and urban drainage connectivity were used to quantify some of the important sediment-supply processes in typical urban and suburban catchments and assess their relative importance in supplying coarse-grained sediment to streams.

Key findings

1. Coarse-grained sediment supply is increased in urban catchments

Our literature and field studies indicated that both coarse and fine-grained sediment yields from established urban watersheds are likely to remain higher than background yields when the catchment was forested or agricultural. This is in contrast to predictions from the widely-used model of Wolman (1967) that has prevailed for half a century.

In our field study in eastern Melbourne, we found that bedload sediment yield and particle size in streams increased greatly across a gradient of catchment urbanization, and that the increase was driven strongly by urban stormwater drainage. Bedload sediment yield (the relatively coarse portion of the sediment yield that is transported along the channel bed) was more strongly related to measures of urbanization that include drainage connection, such as effective imperviousness or pipe density, than total imperviousness. This finding demonstrated the importance of hydrological connection between urban surfaces and streams in controlling the bedload sediment regime, particularly sediment yield.

Our analysis indicated that the main mechanism by which drainage connection increases sediment yield is hydrological: i.e. connected impervious surfaces produce increased peak flows which can transport much more sediment than natural catchment runoff.

2. Upland sediment sources are plentiful in urban catchments

Contrary to previous suggestions (Wolman, 1967; Gurnell et al., 2007), we found that upland (urban land surface) sources of coarse-grained sediment are plentiful in urban catchments. Key sources included infill construction areas (even at very low rates typical of mature suburbs), gravel surfaces, and grassed and mulched surfaces (particularly areas that were bare or disturbed by landscaping activities). Impervious surfaces are important sources of coarse-grained sediment in highly urbanized catchments but are dwarfed by other sources in suburban areas. Despite this, impervious areas still provide yields of coarse-grained sediment higher than background levels.

3. Urban drainage connectivity also drives coarse-grained sediment supply, in addition to increasing transport capacity

Perhaps the more important role of impervious surfaces is as a conduit between sediment sources and the drainage network, efficiently delivering sediment to streams. In the study area, drainage density (length of pipes and channels per unit catchment area) is more than 20 times higher than likely pre-urban levels, and even higher if we include concentrated drainage paths on the urban surface like street and roof gutters and private drainage pipes. This extended drainage network effectively reduces the average distance from sediment sources on the land surface to the efficient drainage network, meaning less energy is required to transport sediment particles from an urban surface to the stream. In this way, drainage connectivity increases sediment connectivity and hence sediment supply to streams.

We developed a conceptual model of the response of coarse-grained sediment supply to increasing levels of imperviousness, based on the understanding that supply depends on both source availability, which declines with impervious cover, and drainage connectivity, which usually increases with impervious cover. While supply is thought to increase with drainage connectivity at low levels of urbanization, it plateaus through suburban levels of imperviousness (20-50%) and then declines at high levels of urbanization (Figure 1a).

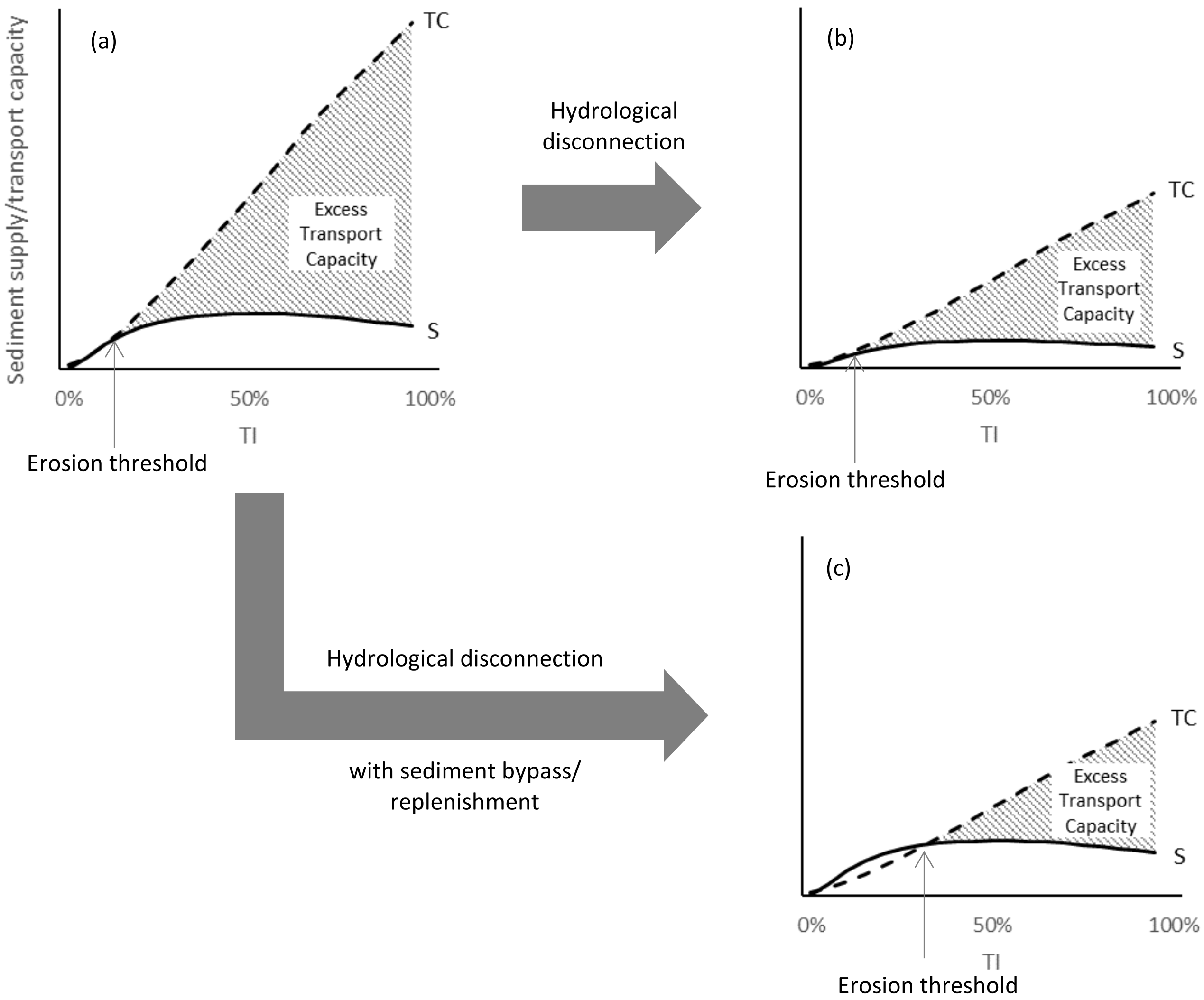

Figure 1 Conceptual model of the response of coarse-grained sediment supply (S) and transport capacity (TC) to urbanization intensity (represented by total imperviousness; TI), under (a) traditional drainage connectivity patterns, (b) hydrological and sediment connectivity reduced by 50%, e.g. by stormwater control measures, and (c) hydrological connectivity reduced by 50% with sediment bypass/replenishment arrangements.

At the same time, drainage connectivity increases urban runoff and hence sediment transport capacity in streams, probably to a greater extent than sediment supply. Sediment transport capacity keeps increasing with effective imperviousness, which, when coupled with plateauing or declining sediment supply, leads to greater and greater sediment supply limitation at high levels of urbanization. This imbalance is likely the key driver of channel incision, loss of bed sediment and bed habitat degradation in urban streams. Future work to quantify changes in sediment transport capacity beyond this conceptual understanding will help to illuminate its role and relative importance.

Management implications and recommendations

Management issues linked to the urban sediment regime fall into two categories, erosional and depositional. Erosional issues arise when sediment transport capacity is greater than supply (Lane, 1955), causing channel deepening and enlargement (Chin, 2006), and leading to degradation of aquatic and terrestrial habitat, loss of public and private land, reduced amenity and threats to infrastructure (Gurnell et al., 2007; Smith et al., 2016). Erosional issues are most commonly addressed by physically stabilising stream beds and banks (for example, with rock riffles and rip-rap), or completely reconfiguring channels, at huge financial cost (Palmer et al., 2007; Vietz et al., 2016). While such management responses can solve the immediate problem, they rarely result in an ecological benefit (Bernhardt and Palmer, 2011).

Depositional issues, on the other hand, are common in low-energy environments such as wetlands, lakes and estuaries. The elevated sediment supply from urban areas (both from the urban land surface, and from channel erosion) tends to be transported efficiently through the stream system, and then deposits in areas where flow velocities are constrained, reducing amenity of water bodies and requiring frequent clean-out. Even sediment ponds, where deposition occurs by design, represent a significant maintenance burden and future liability for waterway managers (Drake and Guo, 2008). In essence, coarse-grained sediment in the urban catchment is not where we want it (in the channel bed) and ends up where we don't want it (in our stormwater control measures and natural waterbodies).

The key to addressing both of these issues will be firstly to reduce the sediment transport capacity of the urban flow regime. This will increase sediment persistence in streams and reduce channel erosion and sediment yields to deposition zones. It has been suggested that by disconnecting impervious surfaces from the stream, for example through implementation of stormwater control measures such as rainwater tanks and rain gardens, the hydrological regime can be returned to a more natural condition, limiting the ecological impact of urbanization. However, if hydrological connectivity is reduced, then both transport capacity and coarse-grained sediment supply will decrease (Figure 1b). Therefore, while hydrological disconnection may reduce the magnitude of excess transport capacity and severity of channel erosion, it is unlikely to fully address the problem. Without sediment supply, even the best flow-regime management will not achieve return of in-stream features such as riffles and substrates, and stream recovery of any form is unlikely.

The second part of the solution will be to maintain or augment coarse-grained sediment supply. Stormwater control measures could be designed to allow coarse-grained sediment delivery while trapping fine-grained sediment, or designers could consider sediment replenishment arrangements. The potential effect of this management response is shown conceptually in Figure 1c. The threshold level of urbanization at which sediment transport capacity begins to substantially exceed supply, and cause channel erosion, could be considerably increased.

This two-pronged approach would redress the imbalance between sediment transport capacity and coarse-grained sediment supply in urban catchments by considering both sides of the equation. Once the overall balance is restored, approaches will need to be developed to ensure that any sediment that is made available is encouraged to deposit in the right places to support and enhance physical river recovery. Such an approach has the potential to prevent channel enlargement, improve habitat quality, encourage self-regeneration of streams, and reduce total yield to lakes, wetlands and estuaries.

Conclusions

Our research has demonstrated that urban streams have highly dynamic sediment regimes. Coarse-grained sediment supply from urban catchments is high but so is the sediment transport capacity of urban streamflow. Therefore, sediment is not depositing in streams where it would be beneficial to stream health, instead causing a maintenance burden in wetlands and estuaries downstream. To allow sediments to persist in stream channels we need to reduce urban runoff magnitude and frequency using stormwater control measures. However, interventions such as rain gardens block coarse-grained sediment supply at the same time as reducing transport capacity, meaning excess transport capacity is likely to persist in streams. Mitigation of the urban flow regime may need to be accompanied by coarse-grained sediment bypass or augmentation arrangements, to address this imbalance. In this way, better sediment regime management, in tandem with flow regime management, could improve the social and ecological values of urban streams and water bodies while reducing erosion-management and sediment-maintenance burdens.

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