Not just a flow problem: how does urbanization impact on the sediment regime of streams?

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Key Points

- Urban streams are highly valued, but are often physically and ecologically degraded
- It is not just stormwater flows that drive geomorphic change in urban streams, sediment supply is important too
- Changes to the sediment regime, particularly for coarse-grained sediments, are poorly understood
- Evidence from this global review points to a modest increase in sediment yield under established urban conditions, most likely driven by increased flow energy rather than increased sediment availability
- Stream managers need to consider sediment regime restoration alongside activities that address flow regime and water quality

Abstract

It is well recognised that altered flow regimes due to urban development and excess stormwater runoff can be a key driver in the degradation of streams. However, the role of the sediment regime in channel change is often neglected. Sediment, particularly bedload sediment, is a well-known driver of stream processes and form, yet the extent of sediment regime disturbance and its relative contribution to urban stream degradation, and recovery, is poorly understood. This paper presents evidence from the international literature and a preliminary field study on the change in sediment yield from non-urban to urban land use. Sediment regime disturbance may be an ongoing constraint to urban stream protection and restoration, even if the hydrologic regime can be preserved or restored. Given this, management measures for sediment regime restoration will require much greater consideration by stream managers and urban planners, and management measures will need to be developed alongside those currently considered for addressing flow and water quality.

Keywords

Urbanization, urban development, sediment yield, bedload, stream restoration, waterway rehabilitation

Introduction

The physical processes and form of streams in urban catchments are geomorphically and ecological important. Firstly, stream stability has always been a primary goal in urban areas where land values are high and development or infrastructure close to waterways limits their room to move. This was traditionally addressed by channelisation and hard-lining of streams and more recently by geomorphically sensitive channel design approaches (Vietz et al., 2016). Secondly, society places high aesthetic and amenity value on urban streams, particularly those which are accessible to people and in 'natural' condition, where public perceptions of 'natural' streams generally align with stable, clean streams without debris or litter build-up. Thirdly, biological communities depend on geomorphic health in waterways to provide habitat and breeding sites and to maintain water quality. These communities in turn provide ecosystem services to humans such as pollutant removal (Paul and Meyer, 2001).

However, streams in urban areas are commonly subject to geomorphic impacts under catchment urbanization. Flow regime disturbance has long been recognised as a key driver of degradation of stream channels downstream of urban development (Hammer, 1972; Wolman, 1967; Booth, 1991), however there is increasing recognition that channel form adjustments and ecological disturbance can also be driven by sediment regime change (Fletcher et al., 2014; Vietz et al., 2015; O'Driscoll et al., 2010). The sediment regime refers to the sediment budget (amount, type and timing of sediment inputs, transport, storage and outputs) of a river system as well as the way water and sediment interact to drive river conditions (Wohl et al., 2015).

Increased sediment yield and bed sedimentation due to urban construction in the initial stages of urban development have been widely studied (Keller, 1962; Wolman and Schick, 1967), but studies of sediment regimes of established urban catchments are limited (Chin, 2006), to the extent that even the likely direction of change of sediment yield compared to background conditions is unknown. This applies particularly to coarse-grained sediments (such as gravels, transported as bedload), where changes under urbanization are poorly understood. Without understanding changes to sediment inputs to urban streams we are potentially missing half the story. This means that our attempts to protect and restore urban streams through both catchment- and reach-scale activities are more prone to failure, and in some cases may be doing more harm than good.

Opportunities for addressing the "urban stream syndrome" (Walsh et al., 2005b) are greatly limited without understanding sediment supply from urban catchments. Stream characteristics such as bed diversity, hydraulic diversity and the presence of bars and benches, for example, are reliant on sediment. A better understanding of sediment supply to streams in urban catchments may highlight the need for management measures that consider sediment regime restoration (e.g. bypass arrangements for sediment barriers or sediment replenishment) alongside activities that address flow regime and water quality (Vietz et al., 2016).

Evidence from the international literature

A detailed literature review of sediment yields from urbanising and urban catchments was undertaken, collating the findings of almost 50 published studies (Table 1). The review was exploratory, with the aim of capturing all available measurements of sediment yield in catchments with active construction and established urban catchments, along with background (forest and rural) rates reported in the same studies, and a representative selection of worldwide background rates for comparable catchments.

The review indicated that sediment yield is likely to increase by around an order of magnitude when a catchment is converted from forested to rural land use, then by another order of magnitude during urbanization when there are significant levels of active construction in the catchment. After establishment of urban areas, sediment yields are likely to decline, but probably remain higher than background levels. Reported increases over background sediment yields typically show a 10-25 times increase for catchments with active construction and a 2-10 times increase for established urban catchments. The summarised data is based on suspended sediment or total sediment yields. It is important to note that this pattern is likely to be different for coarse-grained or bedload sediment yields.

Table 1. Study site characteristics and measured sediment yields

	Percentiles of sediment yield (t/km2/yr)						Percentiles of increase over background sediment yield					
	No. reported	5%	25%	50% (median)	75%	95%	No. reported	5%	25%	50% (median)	75%	95%
Forest	55	0.9	4	6	57	288						
Rural	168	10	35	84	235	1,592						
Construction	61	119	299	713	2,316	25,200	25	3x	5x	12x	30x	450x
Urban	31	20	97	201	394	1,512	17	1.8x	2.5x	6x	11x	19x

Preliminary field study results

A field study was undertaken in late 2015 to early 2016 in Eastern Melbourne, to provide some preliminary results of bedload sediment yields across a gradient of urbanization, from relatively pristine forested catchments, through peri-urban catchments to heavily urbanized catchments. The study was designed as a scoping study for a larger study covering nine sites, to be undertaken in 2016/17.

Four sites were selected for the scoping study: Forest Hill, Little Stringybark, Olinda and Lyrebird Creeks. The sites had 0.6-47% total imperviousness (proportion of catchment covered by impervious surfaces) and 0-25% attenuated or effective imperviousness (proportion of catchment covered by impervious surfaces directly connected to the stream by efficient drainage) (Table 2). Effective imperviousness has been shown to be a better predictor than total imperviousness of hydrological (Burns et al., 2015), ecological (Walsh et al., 2005a), and geomorphic (Vietz et al., 2014) degradation in streams with urban catchments, and is likely to be a better predictor of sediment yield also.

A sediment trap measuring 1 m wide, 0.6 m long and 0.15 m deep was constructed from heavy-duty waterproof plywood for each site. The trap was installed in the bed of the stream with the top of the trap in line with the stream bed, and anchored with star pickets. The typical trap arrangement is shown in Fig. 1. Sampling was undertaken after most major events (daily rainfall greater than 5 mm), approximately fortnightly on average. Sediment yield over the sampling period is shown in Table 2. Average annual yield was estimated using a scaling factor based on the ratio of total rainfall during the sampling period to long-term average annual rainfall.

Figure 1. Forest Hill sediment trap, showing typical sampling setup

While the data are limited, they suggest a relationship between attenuated imperviousness and sediment yield, with lowest sediment yields for non-urban catchments, highest yields for peri-urban areas, and moderate yields for fully urban catchments (Fig. 2). Without replication it is unclear whether this relationship can be generalised at this stage, however it accords with our understanding of sediment producing processes and our general findings of sediment yields in urbanizing and urban catchments from the literature review. In peri-urban catchments, higher levels of ongoing construction and land disturbance (than in fully urban catchments) are common, as are gravel roads which produce large amounts of sediment (Franz et al., 2014). Streams are also more likely to be left unarmoured and able to self-adjust through incision, as is the case in Little Stringybark Creek. As catchments are urbanized the area of exposed sediments are reduced and headwater streams are often buried (converted to drains) or stabilised (e.g. with large rock) meaning less sediment is available.

Table 2. Study site characteristics and measured sediment yields

Stream name	Catchment area (km^2)	Total imperviousness	Attenuated (effective) imperviousness	Bed slope	Bedload D50 (mm)	Dates active	Measured sediment load (kg)	Average annual sediment yield (t/km2/yr)
Lyrebird	**7.24**	**0.6%**	**0%**	**0.8%**	**Fine**	**14/09/2015 – 1/02/2016**	**41**	**0.026**
Olinda	**9.07**	**7.2%**	**0.3%**	**1.1%**	**0.8**	**14/09/2015 – 1/02/2016**	**69**	**0.033**
Little Stringybark	**4.51**	**17.4%**	**3.6%**	**1.1%**	**0.8**	**10/07/2015 – 1/02/2016**	**136**	**0.076**
Forest Hill	**5.35**	**46.6%**	**25.3%**	**1.0%**	**2.4**	**10/07/2015 – 1/02/2016**	**131**	**0.059**

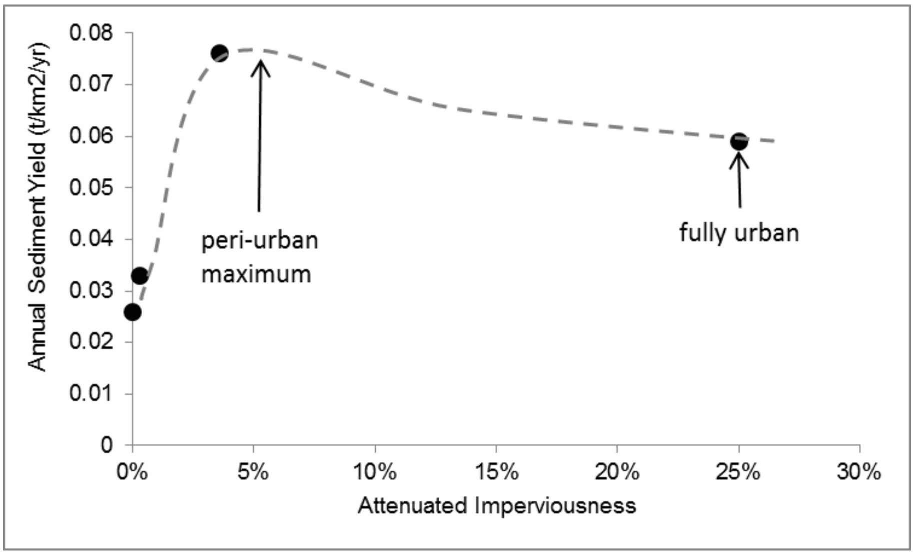

Figure 2. Sediment yield against attenuated (effective) imperviousness. Dotted line is a conceptual model of variation with imperviousness, based on the present data, to be tested in the full study.

Physical and Biological Impacts of Sediment Regime Disturbance

Catchment urbanization consistently causes ecological degradation of streams (Walsh et al., 2005a; Wenger et al., 2009), however, it is difficult to disentangle the complex influences of flow regime disturbance and sediment regime disturbance, partly because sediment regime changes are usually correlated with flow regime changes. The response time of sediment yields to urbanisation can also be very long. Up to 50 years can be required to flush out excess sediment from a stream once urbanization is complete (Chin, 2006) and much longer for the stream to adjust to the new flow regime. Therefore, changes in stream sediment loads and sedimentation impacts may persist long after urbanization is complete.

In general, it is broadly understood that the excess sediment from urbanizing catchments causes bed smothering (Wolman and Schick, 1967; Wolman, 1967; Fox, 1976), increased turbidity and increased delivery of sediment-associated nutrients and contaminants (Owens et al., 2005), with consequent impacts on biota (Wood and Armitage, 1997). By contract, the low sediment supply (coupled with greatly increased flow) from established urban catchments keeps the channel depleted of bed sediment, reducing benthic habitat and refuges, foraging, hyporheic exchange, nutrient retention and denitrification (O'Driscoll et al., 2010; Vietz et al., 2014), causing channel incision and resulting in reduced channel complexity in the long term (Vietz et al., 2014).

Implications for Management and Research

A key management challenge in future will be to continue to mitigate urban hydrologic disturbance and minimise stormwater pollution, while allowing coarse-grained sediment supply to streams to be maintained at rates consistent with natural, pre-developed levels (Fletcher et al., 2014). This requires specifically identifying and addressing the stormwater flows that might be mobilising coarse sediments (Vietz and Hawley, 2016). Stormwater control measures such as basins, gross pollutant traps, and wetlands, may exacerbate the problem by trapping coarse-grained sediment fractions.

Reducing the sediment maintenance in stormwater control measures, while maintaining appropriate sediment supply to enhance the condition of receiving streams, is a major design challenge for the future of stormwater management. The need to continue to reduce fine-grained sediment delivery to channels to protect streams and receiving waters from water quality impacts, while allowing coarse sediment to pass, makes this a particularly complex design problem. Considerations are being made for coarse sediment replenishment in urban streams, which would reduce maintenance costs and improve stream condition (Houshmand et al., 2014). For example, a recent pilot study was undertaken in which coarse-grained sediment trapped in a gross pollutant trap, with contaminant levels tested to be below guidelines, were deposited in a nearby stream (Houshmand et al., 2014).

Better understanding the role and regime of sediments – both fine and coarse – in urban catchments, will assist in fostering an urban design philosophy that moves beyond imposing channel morphology to one that seeks to preserve natural processes where possible within the constraints of the urban catchment. Vietz et al. (2016) advocate a 'stream accommodation' approach to future waterway management, whereby appropriate flow and sediment regimes are maintained by urban stormwater management and protection of coarse-grained sediment sources, and adequate freedom space is provided for the stream to remain self-adjusting. While progress has been made towards implementing this kind of approach to the hydrology of urban catchments, attempts to restore or preserve stream ecosystems will likely be limited if the sediment regime disturbance is not addressed.

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