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Invited review

Global sediment yields from urban and urbanizing watersheds

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ABSTRACT

Streams with urban watersheds are almost universally subject to degradation, largely driven by changes to flow and sediment inputs from the watershed. However, the impact of urbanization on sediment yields of urban watersheds is poorly understood. We undertook a comprehensive review of global responses of fine-grained and coarse-grained sediment yields to different phases of urbanization and compared them to a long-standing conceptual model. The summarized yields showed a great deal of variability, but were consistent with the widely-used conceptual model for watersheds with active construction. Importantly, however, the yields for established urban areas tended to be higher than previously assumed, and tended to remain higher than background levels. This is most likely because the urban drainage network has a very high sediment transport efficiency and because the increased runoff in urban watersheds is very effective at eroding the available sediment sources (mainly infill development, urban decay and renewal, and gravel surfaces in parks and gardens). The updated model provided here will assist in informing the extent to which sediment supply to stormwater drainage systems and urban streams needs to be addressed to assist the protection and restoration of streams in urban watersheds.

1. Introduction

In our rapidly urbanizing societies, urban streams are becoming increasingly valued for the products and services they provide to humans (fresh water, food, waste disposal), as well as their intrinsic and biodiversity values. However, they are subject to extensive and severe impacts from human use and land use changes, a problem that is encountered globally and known as 'the urban stream syndrome'(Walsh et al., 2005a). With more than half the world's population now living in urban areas, and with urban populations growing at 2.1% per year (The World Bank, 2014), the degradation of waterways through urbanization has never been greater. Stream restoration is now a multi-billion dollar effort worldwide, with the cost of stream restoration in the US alone exceeding a billion U.S. dollars a year (Palmer et al., 2007).

It has long been recognized that channel morphology is a function of discharge and sediment supply (Mackin, 1948). In the context of urban development, flow regime disturbance has been widely studied as a key driver of the degradation of streams (Booth, 1991; Hammer, 1972; Wolman, 1967), and the role of sediment regime change is receiving increased recognition (Fletcher et al., 2014; O'Driscoll et al., 2010; Vietz et al., 2016; Vietz et al., 2015; Wohl et al., 2015). This dual disturbance of both the flow and sediment regime is analogous to the role of dams in sediment trapping and channel change that has been well understood for several decades (Petts and Gurnell, 2005).

The prevailing and widely-used model of sediment supply from urban watersheds is based on the 'cycle of urbanization' (Fig. 1) proposed 50 years ago by Wolman (1967). The three stages described include: a stable or equilibrium condition waterway with a forested or agricultural watershed and modest sediment yields; a period of construction, when bare soil is exposed and sediment yield rapidly rises, and a final stage where the watershed is dominated by urban land cover, streams are stabilized and buried in pipes, and sediment yield further declines to values as low as or lower than in the initial equilibrium stream. The sediment response under established urbanization was represented with particular uncertainty as indicated by the dashed line. Uncertainty was also indicated for forest yields, highlighting the difficulty of measuring or inferring pre-agricultural conditions in areas with a long history of agricultural development.

Very little work has tested or built on this conceptual model, despite recognition of the impact of sediment regime disturbance on morphology and condition of streams in urban watersheds (Bledsoe and Watson, 2001; Chin, 2006; Paul and Meyer, 2001; Vietz et al., 2014). In particular, studies of sediment regimes of established urban watersheds are limited (Chin, 2006). Urbanization impacts on sediment load are highly variable (Vietz et al., 2015), and the question of whether there is a globally 'common' response is yet to be thoroughly investigated.

Opportunities for addressing the 'urban stream syndrome' (Walsh et al., 2005b) are greatly limited without understanding sediment

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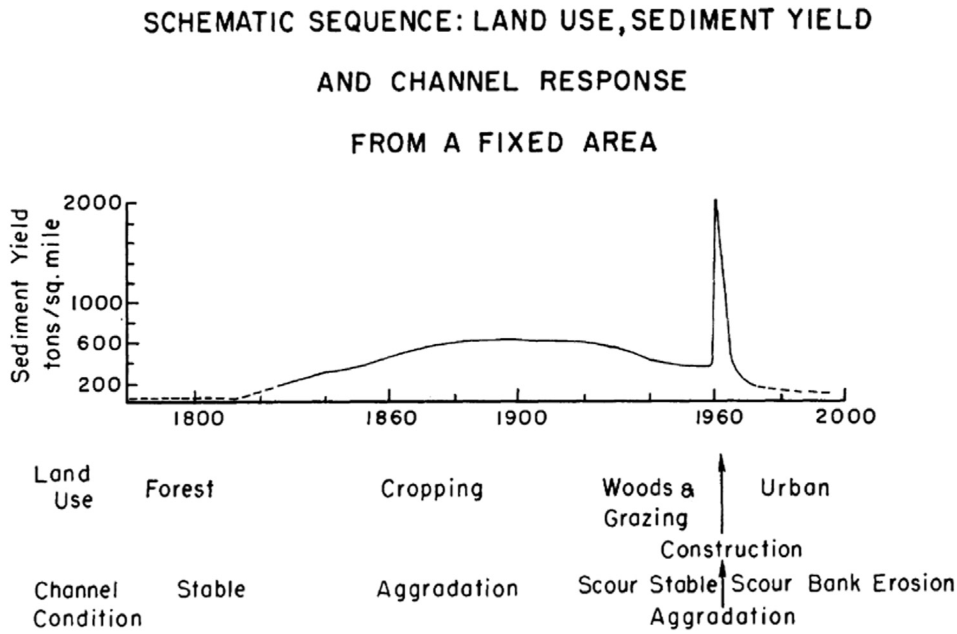

Fig. 1. Cycle of land-use change, sediment yield and channel behavior.
(Reproduced from Wolman, 1967)

supply from urban watersheds. Stream characteristics such as bed complexity, hydraulic diversity and the presence of bars and benches, for example, are reliant on sediment and these characteristics, in turn, contribute to the ecological condition of streams. Better understanding sediment supply to streams in urban watersheds may reveal the need for management measures that consider sediment regime restoration alongside activities that address flow regime and water quality (Vietz et al., 2014; Wohl et al., 2015).

2. Scope of review

Measured sediment yields from almost fifty published studies were summarized across a range of urban and non-urban land-uses. This information is provided as Table S1 in the supplementary material. We first summarized background yields, covering forested and agricultural watersheds, to provide an indication of watershed yields prior to the initiation of urbanization. Secondly, we collated sediment yields from newly urbanizing watersheds and those undergoing construction, and where available, reported increases over background yields. Finally, sediment yields from established urban watersheds were summarized. Increases over background levels were included in the review either where they had been directly reported in the literature, or where yields had been reported in nearby forested or agricultural watersheds in either the same study or a different study in the same location.

Where possible, the caliber of the sediment being investigated by each study was identified, to capture any differences between responses of suspended and bedload sediment. The distinction is crucial as suspended (fine-grained) sediments and bedload (coarse-grained) sediments are transported by different mechanisms (Ackers and White, 1973) and play different roles in the water quality, habitat and overall health of streams and receiving waters. Fine-grained sediments are often considered a pollutant, increasing turbidity, smothering habitat and rapidly carrying adsorbed nutrients and other contaminants to receiving waters (Houshmand et al., 2014; Owens et al., 2005; Taylor and Owens, 2009; Vaze and Chiew, 2004), with consequent deleterious impacts on stream biota (Wood and Armitage, 1997). In contrast, coarse-grained sediments play an important and immediate role in maintaining the geomorphic condition and ecological health of waterways (Hawley and Vietz, 2016).

While there is no agreed size classification for fine-grained versus coarse-grained sediment, in general, we refer to sediment particles with diameters greater than 0.5 mm (coarse-grained sand and greater (Wentworth, 1922)) as "coarse-grained" and particles with diameters smaller than 0.5 mm (medium-grained sand and smaller) as "fine-grained". Observations from suspended sediment sampling methods that do not report particle size have all been classified as fine-grained sediment.

The distribution of studies reviewed, classified by type of sediment, land use and study location, is shown in Table 1. Approximately half the studies were based in the United States, and the majority of those were in the Eastern states, with a particular focus on the Piedmont region. Over half the studies (and 79% of data points) measured only suspended sediment and another third measured total load (16% of data points). Only nine studies (5% of data points) included measurements of bedload. A bias towards small watersheds was also noted, with half the studies on watersheds smaller than 10 km^2.

3. Summary of published sediment yield data

Summary statistics for the collated sediment yield data are presented in Table 2 (suspended and total yield) and Table 3 (bedload yield).

3.1. Background fine-grained sediment yields

In order to assess the influence of urbanization on sediment yields, comparisons must be made with background rates from undisturbed and agricultural watersheds. Suspended sediment yields depend primarily on climate, land use, geology, soil type and position in a watershed. Observed sediment loads rarely reflect 'intact' conditions and yields measured in rural (agricultural) areas or managed forests will reflect a system that has already adjusted (or is still adjusting) to some level of disturbance. However, it is still useful to consider both undisturbed and agricultural land use as the "background" against which urbanization occurs, due to the variation in pre-urban watershed condition worldwide. Agricultural areas tend to have suspended sediment yields that are larger than comparable forested watersheds (up to 70 times higher with a median increase of 3 times), but vary greatly depending on the degree of disturbance (in turn linked to the type of agriculture) and soil conservation practices (Wolman and Schick, 1967), as well as climate.