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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.

Keywords: Sediment yield; urbanization; urban streams; urban watersheds; stormwater drainage; river management

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, which made early sediment yield assessments difficult.

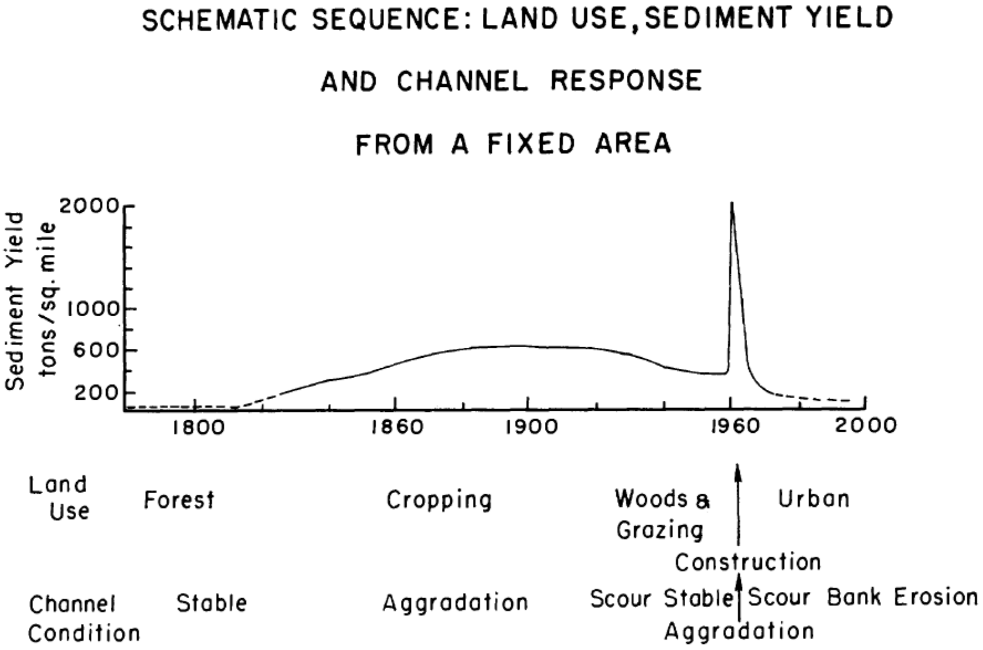

Fig. 1. Cycle of land-use change, sediment yield and channel behavior (reproduced from Wolman, 1967)

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 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).

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 square kilometers.

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

Table 1. Number of studies and data points collated, by type of sediment, land use category and location.

	Sediment yield		Increase over background	
	No. of studies	**No. of data points**	**No. of studies**	**No. of data points**
All data	48	334	26	187
Suspended and total load data	43	322	26	187
By land use category:				
Forest	16	55	-	-
Agriculture	21	181	7	109
Construction	21	64	19	57
Urban	13	22	12	21
By location:				
Americas (USA, Canada, Brazil)	24	146	15	84
Europe (UK)	6	8	2	3
Asia (Malaysia, Japan, Israel)	7	21	5	11
Africa (Kenya)	1	61	1	57
Oceania (Australia, NZ, Tahiti)	5	86	3	32
Bed load data	9	17	0	0
By land use category:				
Forest	6	13	-	-
Agriculture	3	3	0	0
Construction	0	0	0	0
Urban	1	1	0	0
By location:				
Americas (USA, Canada)	2	2	0	0
Europe (UK)	2	3	0	0
Asia (Japan, Israel)	2	4	0	0
Oceania (Australia)	3	8	0	0

Table 2. Summary statistics from collated data, suspended and total sediment yield

Land use category	Suspended/total yield (t/km^2/yr)						Increase over background (factor)					
	Sample size	**5%**	**25%**	**Median**	**75%**	**95%**	**Sample size**	**5%**	**25%**	**Median**	**75%**	**95%**
Forest	55	0.8	3.9	6.2	54	370						
Agriculture	181	10	40	90	238	1,627	109	-	1.6	3.2	9.0	68
Construction	64	115	309	737	2,267	27,300	57*	3.0	7.5	16	64	419
Increase over forest yield							24*	5.9	13	56	101	353
Increase over agricultural yield							29*	1.8	5.1	11	30	535
Construction (fully disturbed sites only)**	34	311	2788	5,287	12,669	189,525	27*	20	230	544	845	3170
Increase over forest yield							20*	54	430	675	931	3212
Increase over agricultural yield							6*		24	45	463	
Urban	22	7.1	57	240	501	1,685	21	1.7	2.6	5.0	14	68.1
Increase over forest yield							13		3.8	5.5	17	
Increase over agricultural yield							8		2.1	2.9	8.0	

*discrepancy between sample sizes for construction increase over all background, forest and agricultural conditions because some reported increases had unknown background conditions

**includes measured yields for fully disturbed sites and computed yields for fully disturbed areas from partially disturbed watersheds.

Table 3. Summary statistics from collated data, bedload sediment yield. No estimates of increase over background were available. Caution should be used making comparisons between summary statistics for different land uses due to low sample sizes and different locations of measurements in the different land use categories.

Land use category	Bedload yield (t/km^2/yr)			
	Sample size	**25%**	**Median**	**75%**
Forest	13	0.6	1.8	8.2
Agriculture	3	10	15	39
Construction	0	-	-	-
Urban	1	-	6.3	-

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.

The summarized results of published work reveal that the majority of reported yields of suspended sediment from forest areas fall in the range of 1-370 t/km^2/yr, with a median of around 6 t/km^2/yr (see Table 2). Yields from agricultural areas fall in the range of 10-1,600 t/km^2/yr, with a median of around 90 t/km^2/yr. Background rates of suspended sediment supply from forested watersheds are remarkably consistent in temperate forested areas, ranging from 2-144 (median 7) t/km^2/yr for eastern USA, and 0.5-25 (median 5) t/km^2/yr for Eastern Australia. Agricultural and mixed watershed yields, however, tend to be significantly lower for the older landscapes of Australia, with a median yield of 14 t/km^2/yr, than the USA, with a median yield of 113 t/km^2/yr.

New Zealand’s South Island, with its high rainfall and steep, erodible watersheds, has some of the highest recorded background sediment yields, reaching over 17,000 t/km^2/yr in the wettest areas (Griffiths, 1981). Fine sediment yields from forests in the Pacific Northwest USA (Nelson and Booth, 2002) are also higher than typical forest yields. These elevated values can be attributed to high relief and rainfall in these areas, but the extremely high values in logging areas may be more influenced by forestry practices which can produce large amounts of sediment (Croke and Hairsine, 2006).

Lake and reservoir sediment studies reveal the temporal changes in a single watershed over a long time period, showing the impact of changing agricultural practices. For example, studies of lake sedimentation in agricultural watersheds in the UK have found four to eight-fold increases in total sediment load due to agricultural intensification and hedgerow removal (Dearing et al., 1981; Foster et al., 1986; Foster and Walling, 1994). In contrast, improved soil conservation practices can result in a decrease in agricultural fine sediment yield over time, for example the decline to half to one third of the previous rate observed in two reservoirs in Maryland (Holeman, 1965).

Background Coarse-grained Sediment Yields

While data on fine-grained sediment yield is plentiful in many regions due to good coverage of suspended sediment sampling stations, bedload is rarely directly measured or included in reported sediment load values (Milliman and Syvitski, 1992; Wohl et al., 2015). Most commonly bedload is assumed to be approximately 10% of the total load (Dunne, 1979; Milliman and Meade, 1983; Nelson and Booth, 2002). This value is generally within the level of uncertainty of total load estimates (Dunne, 1979) and bedload is commonly ignored.

A small number of studies have directly measured bedload yield from forested and agricultural watersheds, either through reservoir sedimentation surveys or in-stream bedload traps. Coarse-grained sediment (sand and gravel) yield has been estimated in small forested watersheds of the mid-Atlantic piedmont to be 5-22 t/km^2/yr (Smith and Wilcock, 2015), although some of the finer sand could have been transported as suspended load. Bedload measurements in fire-disturbed and secondary forests in Japan (Nishimune et al., 2003) also fit within this range, whereas those reported in the older landscapes of south-eastern Australia are generally lower, ranging from 0.5-5 t/km^2/yr (Noske et al., 2010; Papworth et al., 1990; Wu et al., 1984). Bedload from forested watersheds in the UK has been found to be very low (0.003-0.004 t/km^2/yr) (Foster et al., 1985). Coarse-grained sediment yield from agricultural watersheds tends to be higher than comparable forested watersheds, for example in the mid-Atlantic piedmont (Smith and Wilcock, 2015) and the UK (Foster and Walling, 1994).

The bedload yield is highly dependent on the watershed setting and position within the watershed, with larger sediment delivery ratios for coarse-grained sediments relative to fine-grained sediments (Walling, 1983). Montane and smaller streams tend to have a greater sediment yield and also carry a greater proportion of their load as bedload, while lowland alluvial streams carry less total sediment, but proportionally more suspended load (Milliman and Syvitski, 1992). This is illustrated by a study of a glacial stream in western Canada, where bedload was estimated to account for around 50% of the total load (Schiefer et al., 2010), a proportion much higher than estimated worldwide averages. Watershed physiography makes it difficult to generalize background bedload sediment generation or transport rates, even within a single basin.

Fine-grained Sediment Yields from Urban Construction

Newly urbanizing watersheds are subject to high rates of active construction, which generate large amounts of sediment. Summarized suspended sediment yields from urbanizing watersheds mostly fall within the range 120-27,000 t/km^2/yr, with a median of 740 t/km^2/yr. These yields tend to be 3-420 times higher than background rates, with a median increase of around 60 times forest yields and 11 times agricultural yields.

Fine-grained sediment yields measured or computed at the scale of the active construction zone range can be 21-12,000 times higher than background rates, and up to 20,000 times higher in one observed case of an abandoned construction site in Malaysia (Leigh, 1982). The median increase is around 700 times forest yields and 50 times agricultural background yields when measured at this intensive scale.

Sediment load increases with the intensity of construction in the watershed, but there is considerable variation between watersheds with similar levels of construction. In studies reporting loads from ‘fully disturbed’ or similarly described watersheds (i.e. near 100% of the site disturbed), there is variation of around 3 orders of magnitude, although this may be partly due to differences in the definition of ‘fully disturbed’. While sediment yield within a basin is strongly related to the percentage of area under construction, there are significant differences in the relationship between basins (Yorke and Herb, 1978). Construction site slope, and the degree of sediment control were found to be significant factors as well as, to a lesser extent, proximity of construction to stream channels and presence of vegetated riparian buffer zones (Yorke and Herb, 1978).

Coarse-grained Sediment Yields from Urban Construction

No studies were found which explicitly measure the coarse fraction of sediment output from construction areas. Depending on the local setting, sediment provided by construction areas (generally limited to sand-sized and smaller material (Graf, 1975)) may contribute to bed material and bedload in streams, and can cause large sand slugs and clogging of the channel with coarse-grained sediment (Guy, 1970; Wolman and Schick, 1967). Sand was found to comprise 5-12% of the total sediment yield from a construction area in the USA (Guy, 1974). In one case it was estimated that approximately one third of material removed from the construction site was deposited in the stream channel (Wolman and Schick, 1967).

Urban Fine-grained Sediment Yields

Once development is complete, suspended sediment yields from established urban areas remain higher than background levels, but much lower than during construction (Chin, 2006). Summarized suspended sediment yields from urban watersheds tend to fall between 7 and 1,700 t/km^2/yr, with a median of 240 t/km^2/yr, and are mostly 2-70 times higher than background levels, with a median increase of around 6 times forest yields and 3 times agricultural yields. In the Maryland Piedmont, suspended sediment yields from established urban areas are around 1.7 times higher than rural areas, compared to active construction sites which were 15 times higher (Fox, 1976). This is supported by a recent study in the same region (Smith and Wilcock, 2015), which found that urban non-channel sources remained elevated after development was established. Increases in established urban watershed sediment yields in tropical areas are similar to those in temperate areas, estimated at twice background levels from forested watersheds in Tahiti (Wotling and Bouvier, 2002) and 8-16 times background levels in Malaysia (Balamurugan, 1991; Douglas, 1978; Wan Ruslan Ismail, 1997).

Urban Coarse-grained Sediment Yields

Impervious surfaces and storm drains in established urban areas can increase or decrease bed load in urban streams (Bull and Scott, 1974). While these processes can limit the available sediment by converting sediment-liberating headwater streams to underground pipes, they can also increase sediment transport capacity (by increasing runoff and stream flows), and efficiency of sediment transport pathways. While many have speculated that coarse-grained sediment supply from non-channel sources should decrease due to sealing of surfaces (Bledsoe and Watson, 2001; Gurnell et al., 2007; Hawley et al., 2013; Vietz et al., 2014), observed decreases have not actually been documented, and a small number of studies have documented or inferred increases in upland sediment supply (Pizzuto et al., 2000; Smith and Wilcock, 2015).

In Maryland it was found that the coarse-grained (sand and gravel) sediment load of 90 t/km^2/yr from a fully suburban first-order basin was well in excess of estimates for comparable forested basins from the same study, which yielded around 5-22 t/ km^2/yr of coarse-grained sediment (Smith and Wilcock, 2015). In gravel bed rivers in Pennsylvania, bedload transport remained significant after decades of urbanization, indicating that channel erosion and hillslope sources were enough to maintain bed material sizes to near-natural conditions (Pizzuto et al., 2000).

A bedload yield of only 6.3 t/ km^2/yr was measured for an almost entirely urbanized watershed in Tennessee (Grable, 2003). While background rates were not reported, this is fairly low compared to measurements from the mid-Atlantic piedmont (Smith and Wilcock, 2015), but still higher than suspended loads (and hence probably much higher than bedloads) for forested areas in Kentucky (Collier, 1962) and Maryland (Wolman, 1967).

Conceptual Model: Quantifying Sediment Yields in Urbanizing and Urban Watersheds

The summarized findings of the literature spanning half a century since the model of Wolman (1967) allow us to quantify sediment yield for land use changes from forest to established urban (Fig. 2). Summarized rates of sediment yield from forested, agricultural and urban construction phases from the literature over the last 50 years correspond well with the model of Wolman, which sits within the middle two quartiles of the summarized data. Wolman's postulated *urban* sediment yield, however, sits at the lower end of the range of summarized yields, and the speculation that post-urbanization sediment yields decline to levels as low as or lower than background levels is generally not supported by subsequent empirical studies. While there is a great degree of variability in yields across all land uses (2-3 orders of magnitude), the compiled data indicate that measured urban sediment yields tend to remain around 3 times higher than yields from rural watersheds and around 6 times higher than yields from forested watersheds.

Sediment yield is likely to increase by around an order of magnitude when a watershed 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 watershed. After establishment of urban areas, sediment yields are likely to decline but still remain much higher than background levels. The summarized data is based on suspended sediment and total sediment yields, and the pattern may be different for coarse-grained sediment yields.

The high sediment yields in established urban areas may be partially explained by the relatively few studies which capture genuinely established conditions (where the river system has adjusted fully to the new hydrologic and sediment input conditions). Given that this adjustment can take more than 50 years areas (Chin, 2006), it is likely that some of the watersheds that are identified as fully urbanized have channels that are still adjusting with elevated rates of channel erosion contributing to high sediment yields. The extent to which infill development and urban renewal keeps altering watershed hydrology and sediment regimes is also difficult to discern from studies.

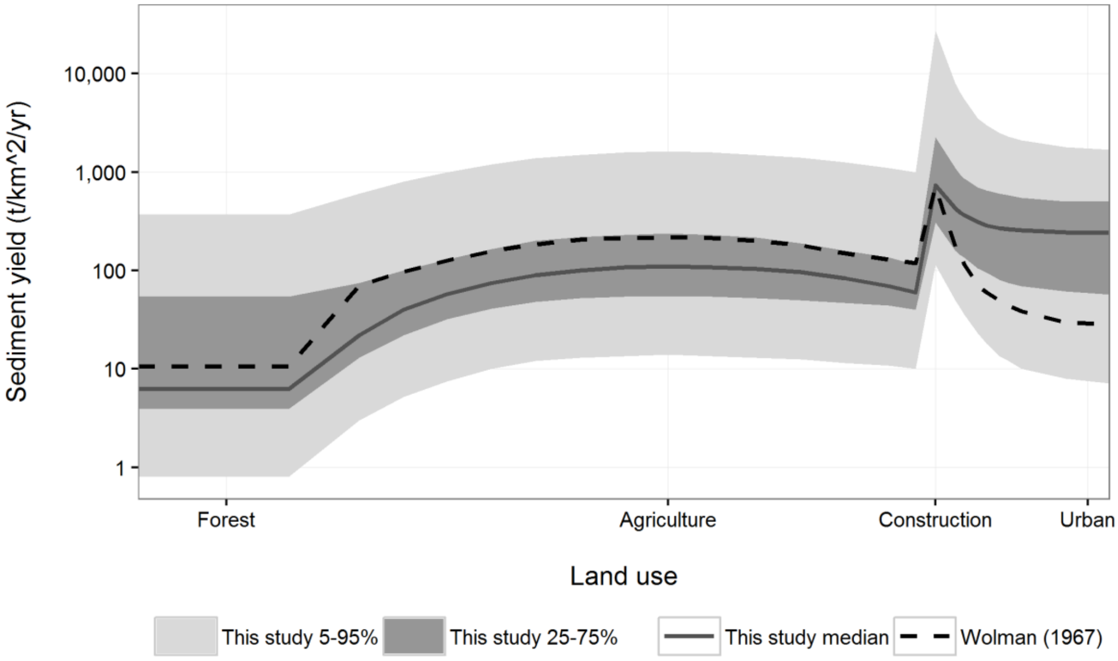

Fig. 2. Quartiles of summarized sediment yield data compared to the conceptual sediment yield curve of Wolman (1967), digitized from the original.

Sources of Sediment in Urban Watersheds

Given that a large proportion of the land surface in urban watersheds is stabilized and sealed, the higher sediment yield than background levels raises the question of where the elevated sediment loads may be coming from.

A major and widely-documented sediment source is channel erosion, which is a common response to altered urban flow conditions (Chin, 2006), and can supply excess sediment to downstream areas. A notable example is San Diego Creek in southern California, where stream channel erosion provided around 70% of the sediment yield at the point of observation (Trimble, 1997). This was measured over a period of active urbanization in the watershed, however stream channel erosion can persist long after establishment of urban land use (Chin, 2006).

Other sources include sediment from sealed and unsealed roads and imported, anthropogenic particles. In particular, gravel roads or roads with gravel shoulders can produce significant sediment loads on the same order of magnitude as construction sites. The supply of sediment from these areas is effectively unlimited, as they tend to be repaired by adding sediment sourced from external watersheds. Average fine-grained sediment yields for gravel forest roads range from 150 to 166,000 t/ km^2/yr, depending on level of usage (Reid and Dunne, 1984) and have been estimated to be 4-8 times higher than background erosion rates in similar settings (Fahey and Coker, 1992). Gravel roads and gravel-shouldered roads tend to be a feature of peri-urban and lower density areas rather than inner-urban areas, but gravel surfaces in house yards, parks and gardens are common even in medium to high-density urban areas. Unpaved road sources provide around 15% of the urban sediment yield in suburban Brasilia, despite covering only a small portion of the area (Franz et al., 2014).

Runoff from sealed roads can also deliver road-deposited sediment (RDS) to waterways. RDS is generally fine-grained in caliber (mostly less than 1 mm), and runoff from sealed roads preferentially transports only the finer fractions of RDS (Zhao et al., 2010), however, one study has found that particles larger than 1 mm account for up to 35% of the sediment load in road runoff (Kim and Sansalone, 2008). RDS yields are similar to general urban sources at around 50 t/ km^2/yr (Mar et al., 1982).

Urban areas can also be a significant source of anthropogenic particles (riprap, concrete, asphalt, glass, brick etc.) to streams, supplementing the coarse sediment loading to urban streams. These particles can make up a significant proportion of bed sediment (2-21% of particles), and are generally coarser than natural sediment particles (Grable and Harden, 2006; Grable, 2003).

It is also important to note that construction is never fully complete in an urban catchment with decay, renewal, infill development and landscaping constantly occurring. Given that sediment yields from construction areas tend to be around 50 times higher than from agricultural areas and 700 times higher than from forested areas, even a small amount of renewal or infill development could supply a significant amount of sediment and produce an overall increase over background conditions.

Influence of Stormwater Design and Sediment Control Measures

Sediment yields from urbanizing and established watersheds also depend on local stormwater design arrangements. For example, sediment control measures are usually required by environmental and planning authorities at construction sites. Sediment control measures are highly effective when applied correctly (Benik, 2003), however given that construction increases sediment loads up to 300-fold, and commonly more than 10-fold, removal efficiencies need to be very high to mitigate to background levels. In addition, poor design, compliance and maintenance are commonplace (Hogan et al., 2014; Kaufman, 2000), and can lead to failure of sediment control measures.

After establishment of urban land cover, infrastructure used to remove sediment from runoff may actually deplete sediment loads to below pre-urbanization levels. Depending on design and bypass arrangements, stormwater treatment measures such as gully pots, gross pollutant traps, sediment ponds and check dams can form a complete barrier to coarse-grained sediment supply (Butler and Karunaratne, 1995; Houshmand et al., 2014). Non-complete barriers such as grassed filter strips and swales can also trap a significant proportion of the coarse sediment load (Deletic, 2005). Sediment loads in urban streams, particularly coarse-sediment loads, are therefore greatly influenced by the design of sediment trapping measures and stormwater systems. The interruption of coarse sediment supply is a harmful by-product of such efforts to decrease fine sediment and nutrient inputs to streams, which can exacerbate channel instability and degradation (Vietz et al., 2016).

Factors Contributing to Variability

The collated sediment yields for all land use categories show great variability (by 2-3 orders of magnitude), even at a given watershed area or location. The high levels of variability illustrate the complexity of sediment yield quantification and the difficulty of making comparisons between urban and non-urban watersheds using space-for-time substitution methods.

Climate significantly influences variability in sediment yield. Sediment yields tend to be higher in tropical areas (Wasson et al., 1996) due to increased runoff, and may also be higher in very arid areas than semi-arid and temperate climates, where the amount of runoff is adequate to erode material, but not to encourage growth of protective vegetation (Douglas, 1967; Langbein and Schumm, 1958). In New Zealand, where rainfall is highly variable, a strong relationship between sediment yield and annual rainfall has been observed (Griffiths, 1981). Such relationships are highly localized depending on climate regime (Wilson, 1973) and vegetation type (Dunne, 1979).

Suspended sediment yield also depends on watershed area and relief, typically decreasing with increasing watershed area due to lower slope gradients reducing sediment liberation and transport. There is also increased sediment storage on the lower slopes, channels and floodplains in flatter catchments (Walling, 1983). This trend is discernable in the sediment yields collated for construction areas, but not in the data for forest, agricultural or urban areas. For construction areas, the trend is partly driven by a dilution effect (Wolman and Schick, 1967) whereby larger watersheds tend to have only part of the area under construction at any one time, whereas the smaller watersheds being monitored are under intensive construction. However even when considering only the yields reported for areas completely under construction, yields still appear to decline with increasing watershed area, which may indicate a negative relationship between watershed area and slope. Watershed slope is an important driver of sediment yield (given its primary role in sediment transport), however, perhaps surprisingly, it was not reported in an adequate number of studies or with a level of consistency that would allow for broad comparisons.

As well as the question of watershed area, the relative scale of urbanization and the spatial organization of urban areas within a watershed are important variables that drive sediment yield. Most studies are undertaken on small watersheds with relatively homogeneous land uses, but the impact of cities on large rivers (given that cities tend to be located at the outlets of large, mixed-use watersheds) also requires further investigation.

Implications for Management and Research

The highly variable effects of urbanization on the sediment regimes of rivers can lead to complex responses in stream health. While it is known that watershed urbanization consistently causes ecological and geomorphic degradation of streams (Walsh et al., 2005a; Wenger et al., 2009), it is difficult to disentangle the influences of flow regime disturbance and sediment regime disturbance. Sediment regime changes often co-vary with flow regime changes in urbanizing areas, so the effects of each are particularly difficult to differentiate. Stream response to urbanization also depends on past land uses in the watershed and direct channel interventions such as channel stabilization (Vietz et al., 2016).

Increases in the delivery of fine-grained sediments from urbanizing watersheds to streams can decrease bed sediment size (Booth and Jackson, 1997), or increase smothering of the channel bed (Fox, 1976; Wolman, 1967; Wolman and Schick, 1967). Excessive fine-grained sediment input from construction and channel erosion sources reduces primary production and has deleterious impacts on macroinvertebrates and fish reliant on benthic habitat (Mebane, 2001; Wood and Armitage, 1997). Suspended sediment in the water column impacts on fish (Walters et al., 2009) and filter feeders such as mussels (Wood and Armitage, 1997). Increased delivery of sediment associated nutrients and contaminants (such as heavy metals) causes eutrophication in receiving waters, toxicity to aquatic life and detrimental effects to human health (Owens et al., 2005). While channel contraction is common downstream of construction areas (Leopold et al., 2005; Wolman, 1967; Wolman and Schick, 1967), channel widening (Chin and Gregory, 2001; Fox, 1976) and planform changes (Hawley et al., 2012) have also been observed.

After establishment of urban areas, increases in sediment transport capacity are likely to produce channel incision (deepening and widening), loss of bed features (Vietz, 2013), and bed coarsening as finer sediments are preferentially removed (Finkenbine et al., 2000; Hawley et al., 2013). Even if the sediment supply remains higher than background levels, the greatly increased flow energy is likely to dominate the flow-sediment balance. This maintains reduced depths of mobile bed sediments and results in long-term reductions in channel complexity and the hydraulic and sedimentologic heterogeneity required for healthy ecological habitats (Vietz et al., 2014).

Sedimentation impacts associated with early stages of construction are transient in nature (Fox, 1976), however the time period required for excess sediment to be flushed from the system can vary from 5 to 50 years (Chin, 2006), and the time required for the stream to adjust to the new flow regime can be even longer. Therefore sedimentation impacts from urban development may persist long after the urban watershed is established.

A future management challenge will be to continue to mitigate urban hydrologic disturbance and minimize stormwater pollution, while maintaining coarse-grained sediment supply to streams (Fletcher et al., 2014) at rates consistent with natural, pre-developed levels. In systems where coarse-grained sediments are currently being trapped in stormwater control measures such as basins, gross pollutant traps, and wetlands, coarse-grained sediment fractions can be redirected into the stream, reducing maintenance costs and improving stream condition (Houshmand et al., 2014). Sediment replenishment downstream of dams has been trialed with some success (Merz et al., 2005; Zeug et al., 2014). The replenishment method must be tailored to the post-disturbance flow regime

(Ock et al., 2013), which will be particularly important under a highly modified post-urban flow regime.

The need to continue to reduce fine-grained sediment delivery to channels to protect streams and receiving waters from water quality impacts, while maintaining ecologically-important coarse sediment loads, is a major design challenge for the future of stormwater management. However, opportunities exist to reduce the sediment maintenance in stormwater control measures by bypassing or redirecting coarse-grained sediment, as trialed in a recent pilot study in south-eastern Australia (Houshmand et al., 2014).

Research is required to investigate the implications of sediment yield changes from urban and urbanizing watersheds on the physical and ecological condition of receiving streams. If altered sediment inputs are a significant driver of urban stream degradation then opportunities for better management of sediments in stormwater systems require field testing at a watershed, street and plot scale. In particular, standardizing the way in which studies on sediment yields are undertaken and reported will assist in improving our understanding of a ‘common’ response of sediment yield to urbanization of a watershed. For example, this could include ensuring details of land cover and land use, and background factors such as watershed slope, rainfall, and natural vegetation type, are consistently reported, and that these background factors are controlled as much as possible when using space-for-time substitution.

Improved understanding and management of sediment from urbanizing and established urban watersheds will assist in moving beyond the common urban stream management philosophy of imposing channel morphology towards one that seeks to preserve natural watershed processes where possible (Wohl et al., 2015). In this ‘stream accommodation’ approach to waterway management, appropriate flow and sediment regimes would be maintained by urban stormwater management and protection of coarse-grained sediment sources, and adequate space would be provided for the stream to remain self-adjusting (Vietz et al., 2016). While progress has been made towards implementing this kind of approach to the hydrology of urban watersheds, attempts to restore or preserve stream ecosystems will likely be limited if the sediment regime disturbance is not better understood and addressed.

Conclusion

The reported sediment yields from urbanizing and urban watersheds collated and summarized for this study have demonstrated that suspended and total sediment yields are likely to greatly increase in watersheds under urbanization, then decline, but remain elevated above background conditions once fully urban land cover is established. While these findings have, in many respects, validated the model suggested by Wolman (1967), evidence from the literature suggest that Wolman’s speculation that fully urban watersheds would have sediment yields lower than background levels is incorrect. While urban land cover locks up some sediment sources, other sediment sources are introduced, such as construction for infill development, gravel landscaping surfaces and road deposited sediments. These sources are easily eroded by high-energy urban runoff and are transported to streams via efficient urban drainage systems. The summarized data was predominantly based on measurements of suspended yield or total yield, with very little data on bedload yield in urbanizing and urban watersheds. The pattern for coarse-grained sediment, which is of great importance in maintaining stability and ecological health of streams, may be different. In any case, the urban flow regime appears to produce increases in sediment transport capacity that overwhelm any increase in sediment supply, causing channel erosion and loss of bed sediment and habitat complexity. Efforts to address the urban flow problem will need to be sensitive to the need to maintain coarse-grained sediment supply to the channel, potentially using bypass or supplementation arrangements. In the long term, efforts need to be made to preserve the natural function of catchments and stream corridors in urban areas, maintaining runoff and sediment supply as close as possible to background conditions, and allowing streams room to move and adjust.

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