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Urban catchment runoff increases bedload sediment yield and particle size in stream channels

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Abstract

Physical degradation of urban rivers negatively impacts the environmental and social values they provide, and imposes significant financial costs on waterway management agencies. While the impact of urban stormwater runoff on streams is well recognised, the influence of altered bed sediment regimes on urban stream geomorphology is poorly understood. This study reports bedload sediment yields and bedload particle size distributions measured with sediment traps in nine small streams in eastern Melbourne, Australia, across a gradient of urbanization. We assessed relationships between the yield and size of bedload sediment and measures of catchment urbanization (including total imperviousness, effective imperviousness, road density and pipe density) and hydrology (measured through flow gauging at each site). Bedload yields were greater and bedload sediments were coarser-grained in more urbanized catchments. Bedload yields were strongly related to drainage connection of the urban land surface to the stream (captured by

measures such as effective imperviousness and pipe density). The increase in bedload yield and calibre in urban catchments was driven mainly by the increase in sediment-transporting runoff from connected impervious surfaces. This study found no evidence of urban land cover severely limiting coarse-grained sediment supply. Most of the bedload material appeared to originate from imported sediment sources (e.g. construction and surfacing materials) in upland urban hillslope areas, which were connected to the channel by efficient transport reaches such as pipes and rock-lined channels, rather than from channel-derived erosion. Findings of this study suggest a rethink of the coarse-grained sediment-supplying potential of urban catchments, which has long been assumed to be low due to sealing of the land surface with hard materials.

Keywords: bedload, sediment transport, urbanization, geomorphology, stormwater, hydromodification

1. INTRODUCTION

Urban streams worldwide are subject to physical and ecological degradation, which threatens their integrity and limits the ecosystem services they provide (Walsh et al., 2005). This complex but near-universal pattern of urbanization-induced degradation is known as the ‘urban stream syndrome’ (Meyer et al., 2005). Stream restoration is commonly employed to arrest or reverse some of the impacts of urbanization, and is a multi-billion-dollar industry worldwide (Palmer et al., 2007). Physical restoration at the location of impacts (i.e. in the stream), however, rarely achieves ecological benefits (Palmer et al., 2014; Violin et al., 2011). Instead, addressing the root causes of stream degradation where they occur (i.e. in the catchment) could avert the need for such restoration (Walsh et al., 2015; Vietz et al., 2016).

The urban flow regime, characterised by higher and more frequent peak flows and higher runoff volumes, is the primary cause of physical stream degradation (Walsh et al., 2012; Booth, 1991). Mimicking the ecologically important elements of the pre-urbanization runoff regime is increasingly acknowledged as a critical element of stream restoration (Walsh et al., 2016). Workers have long

recognised, however, that the physical form of streams is a product of both the incoming flow and sediment regimes (Mackin, 1948; Lane, 1955). Early work investigated changes in sediments with urbanization (Guy, 1963; Wolman, 1967; Wolman and Schick, 1967) but mainly focused on the immediate and obvious impacts associated with construction rather than long-term urban land cover. More recent work has recognized the sediment regime as an important driver of stream degradation under established urban land cover conditions (Wohl et al., 2015; Walsh et al., 2016; Vietz et al., 2016; Russell et al., 2017). Coarse-grained sediments, defined here as particles > 0.5 mm after Houshmand et al. (2014), contribute to bed material and bedload transport, and are considered particularly important in maintaining the geomorphic condition and ecological health of streams (Hawley and Vietz, 2016). Thus, a need exists to consider how coarse-grained sediment regimes are managed in urban streams and how they might interact with the management of flow regimes (Vietz et al., 2016). Achieving such an integrated approach requires an understanding of how bedload sediment supply and transport are affected by catchment urbanization.

While very little literature exists on bedload sediment regimes in urban streams (Russell et al., 2017), the larger body of research on suspended sediment may provide useful clues. The conceptual model of Wolman (1967) indicated that catchment sediment yields decrease after establishment of urban land cover, due to sealing of soil surfaces with impervious areas and stabilisation and burial of streams (Gurnell et al., 2007). Quantitative evidence, however, points to the opposite: an increase in suspended sediment yield from established urban catchments (Russell et al., 2017; Gellis et al., 2017). New sources, such as infill construction, resurfacing and landscaping, can provide additional supply, and the increase in runoff energy and drainage efficiency in urban areas can easily erode and transport these sediment sources. The limited available research indicates that bedload sediment supply can also increase in urban catchments (Smith and Wilcock, 2015; Utz and Hilderbrand, 2011). While comprehensive summaries of global responses of suspended sediment supply to urbanization are available (Chin, 2006; Russell et al., 2017), whether a common global response of coarse-grained sediment supply to urbanization exists is currently unclear. This question is important because, while

the increase in flow energy from urban catchments is recognized as a key driver of physical stream degradation, a change in coarse-grained sediment supply could either exacerbate (if reduced) or mitigate (if increased) the tendency for urban streams to degrade (Lane, 1955).

Urban stormwater flow regimes can also alter bedload particle size distributions. Increased peak flows have higher competence and capacity to transport coarser materials where they are available (Dietrich et al., 1989), meaning bedload should coarsen (Utz and Hilderbrand, 2011). Studies have most commonly found bed sediment (the material present on the bed at any time) to coarsen in streams with established urban catchments (Hawley et al., 2013; Finkenbine et al., 2000; Pizzuto et al., 2000). Utz and Hilderbrand (2011) found that both bed sediment and the bedload itself (the material in transport along the bed through a section or reach) were coarser in urban than rural sites. The distinction between changes in bed sediment and bedload particle size is important because they can result from different catchment inputs and in-channel processes. Coarsening of bed sediment, particularly its surface layer, can occur under severely limited sediment supply conditions (Dietrich et al., 1989). For a coarser-grained bedload to persist in the long term, however, it must be matched by supply of coarse-grained sediment from the catchment. Altering the size of particles available to be supplied to streams in urban catchments may constrain the resulting bedload particle size distribution.

This study addresses gaps in understanding of the urban bedload sediment regime by investigating bedload sediment yield (the rate of bedload sediment supply from the upstream catchment and channel) and bedload particle size in small streams with a range of catchment urbanization intensities. Key questions are:

- How do bedload sediment yield and median particle size differ over a gradient of catchment urbanization?
- Which landscape or hydrologic variables best explain the difference?

- How does the level of catchment urbanization modify the relationship between flow and bedload sediment yield or particle size?

Key to the approach in this study is the consideration of landscape variables that account for both imperviousness and drainage connection of urban areas. Such variables describe the hydrologic effect of impervious areas. For example, effective imperviousness (EI) describes the proportion of the catchment that is impervious *and* directly connected to the stormwater drainage network (and hence directly connected to the stream). Numerous studies have found that EI better predicts stream condition than total imperviousness (TI) (e.g. Hatt et al., 2004; Booth and Jackson, 1997; Wenger et al., 2008; Walsh, 2004; Vietz et al., 2014; Lee and Heaney, 2003). Burns et al. (2015) demonstrated that EI better predicted ecological condition than a suite of hydrological indicators, as it captured complex urbanization effects that are difficult to incorporate in simple flow metrics. Only a handful of studies have focused on the impact of urban stormwater connection on fluvial geomorphology, with some finding strong relationships between channel stability and complexity and EI (Booth and Jackson, 1997; Vietz et al., 2014) while others found a lack of such relationships (Booth and Henshaw, 2001).

This study links bedload sediment yield to both drainage connection and hydrology, demonstrating that urbanization can greatly increase bedload sediment yield and particle size over natural levels. We challenge the notion that urban land cover limits bedload sediment supply, instead suggesting that upland sources of coarse-grained sediment are plentiful, even in mature urban areas. A better understanding of the coarse-grained sediment dynamics of urban catchments is essential to developing management responses that address both hydrological and sediment regime alterations. Addressing the root cause of urban stream erosion will improve the environmental and social values provided by streams, and limit the financial costs of stabilising eroding channels.

2. MATERIALS AND METHODS

1.1 Catchment characteristics

This study took place in nine headwater streams in eastern Melbourne, Australia (Figure 1). The catchments followed a gradient of urbanization intensity from natural, forested conditions to suburban land cover. A range of GIS datasets allowed compilation of land cover, urban drainage, topography, climate and geology data for the catchments (Table 1). Detailed land cover mapping by Grace Detailed-GIS Service (www.gracegis.com.au) in 2009 (unpublished) provided the basis for land cover estimates. Tree cover, sealed road cover and unsealed road cover were derived directly from the 2009 mapping and verified through aerial imagery and ground truthing. Total imperviousness (TI) was derived from the 2009 mapping with a growth factor to 2017. Detailed inspection of aerial imagery and ground observations in four study catchments (*Ly*, *Ol*, *Lt*, *Br*) and two other nearby catchments (Dobsons and Sassafras Creeks) were used to estimate a 2009-2017 TI growth factor for the other catchments. The growth factor ranged from 1% in the least urbanized catchments to 10% in the most urbanized catchments. Unsealed roads were not classified as impervious cover. Effective imperviousness (EI) was calculated based on the TI estimates, and 2001/2009 connection-to-stream data. Updated 2009 connection rates were available for 5 catchments (*Ly*, *Ol*, *Lt*, *Fe* and *Br*); the remainder used 2001 connection rates (Walsh et al., 2004). TI ranged from 0.3% to 49% in the study catchments whereas EI ranged from 0 to 48%. An alternative analysis using the statistically-driven ‘attenuated imperviousness’ method (Walsh and Kunapo 2008) resulted in lower EI values (max 30%) for these catchments. We used the original connectivity estimates, however, because we prefer the binary and physically-based connected/unconnected assessment for modelling of physical catchment processes. The suburban areas were mainly single-family residential areas originally developed in the 1950s-1970s, with median lot sizes around 600 m².

To avoid effects from land uses other than urbanization, the selected catchments had as little non-urban, non-forested (i.e. agricultural) land cover as possible (<13% agricultural land use). Construction activities in the catchments (assessed visually from NearMap orthophoto imagery

captured late 2016; www.nearmap.com) did not exceed 1.5% of the catchment area for any of the sites during the monitoring period.

The suburban catchments in the west were relatively low-lying with low relief, whereas the less urbanised catchments were situated around the Dandenong Ranges, and had higher relief, elevation, and rainfall. The underlying lithology was mainly igneous (extrusive, mainly rhyolite and rhyodacite) around the Dandenong Ranges, and sedimentary (marine, sandstone and siltstone) in the flatter, suburban areas (Department of Economic Development Jobs Transport and Resources, 2014). Historic patterns of urbanization in Melbourne favoured flatter, drier catchments over steeper, wetter ones, making it difficult to avoid these biases.

Cross-sectional surveys undertaken between 2011 and 2017 allowed compilation of channel characteristics at the catchment outlets. Study sites with more urbanized catchments tended to have incised (deepened and widened) channels and extensive rock protection on the bed and banks, to prevent further erosion. The full history of these channel modifications is unknown, whether they were rock-lined in response to the initiation of channel incision, or intentionally excavated and rock-lined to increase conveyance and reduce flooding. In either case, they are now constrained to deep, geomorphically simple channels that are unable to adjust further. While the sampling sites for these catchments were in sections of open stream channel, much of the original stream length upstream of the study sites (particularly for sites *Br*, *Sc* and *Fo*) had been converted to pipe or concrete channel. Two of the sites with moderately urbanized catchments (*Lt* and *Bg*) were undergoing incision, reflected by their relatively deep channels and low width-depth ratios.

Flow control and stormwater improvement structures within urban catchments may impact sediment supply and transport processes. A program of installation of source control measures, such as rain gardens and rainwater tanks, has progressed in the Little Stringybark Creek catchment since 2009 as part of a catchment-scale experiment to mitigate the urban flow regime (Walsh et al., 2015). Various methods have estimated the proportion of the catchment that has been disconnected from

the drainage network as between 1% and 5%, reducing the EI from 10% to 5-9%. Given the uncertainty and likely lags between implementation and effects on in-stream physical processes, the unmitigated EI (10.2%) was used in this analysis for *Lt*, with a sensitivity check on the lower EI value. None of the other catchments had significant water-sensitive urban design (WSUD) elements such as wetlands or rain gardens. Catchments *Bg* and *Fo* had online flow-retarding basins designed for flood control, which likely limit peak flows, but had low-flow outlets that allowed sediment transport. Other potential coarse-grained sediment barriers in the study catchments included gross pollutant traps (affecting part of catchment *Sc*), farm dams on small drainage lines (common in rural areas, e.g. *Bg* and *Lt*) and small weirs such as those used for gauging (*Ol*, *Br*).

Figure 1 Study catchments, with impervious area shown in grey and forest cover in green. Catchments *Sc* and *Fo* have typical suburban land cover, *Ly* is fully forested, and the remaining catchments are in fringe areas with varying levels of urbanization and forest cover.

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Table 1 Attributes of study catchments and reaches. CA = catchment area, MAR = mean annual rainfall, EA Slope = equal area slope, TI = total imperviousness, EI = effective imperviousness, Const. = construction, W = average bankfull width from surveyed cross sections, D = average bankfull depth from surveyed cross sections, W/D = average width/depth ratio from surveyed cross sections.

Site Code	Stream	Catchment characteristics												Channel characteristics				
		CA (km ²)	MAR ¹ (mm)	EA Slope ²	TI ³ (%)	EI ⁴ (%)	Stream Density ⁵ (km km ⁻²)	Pipe Density ³ (km km ⁻²)	Const. ⁶ (%)	Tree Cover ⁷ (%)	Sealed Road Cover ⁶ (%)	Unsealed Road Cover ⁶ (%)	Dominant Geology ⁸	Reach Slope	W (m)	D (m)	W/D	Rock protection
Ly	Lyrebird Ck	7.18	1162	0.038	0.3	0.0	0.9	0	0.1	89	0.1	0.6	Igneous (Extrusive)	0.008	3.8	0.5	7.2	None
Ol	Olinda Ck	8.71	1101	0.039	4.9	0.1	1.1	0.1	0.3	81	1.2	1.6	Igneous (Extrusive)	0.005	3.9	0.9	4.8	None
Sh	Sherbrooke Ck	6.56	1163	0.040	2.2	0.2	0.5	0.2	0.1	83	1.3	1.4	Igneous (Extrusive)	0.025	2.6	0.8	3.5	Minor
Bg	Bungalook Ck	6	1024	0.030	6.8	3.9	0.6	2.4	1.0	76	2.4	0.4	Igneous (Extrusive)	0.026	3.1	1.3	2.4	Medium
Lt	Little Stringybark Ck	4.28	997	0.018	14.3	10.2	0.9	4.4	0.3	52	3.7	0.2	Igneous (Extrusive)	0.008	3.2	1.3	2.4	None
Fe	Ferny Ck	6.38	1078	0.028	17.6	12.6	1.4	6.6	0.6	74	6.5	1.1	Igneous (Extrusive)	0.006	3.9	1.2	3.4	Medium
Br	Brushy Ck	14.77	945	0.011	29.1	25.2	0.2	10.6	1.2	41	8.3	0.04	Igneous (Extrusive) (43%), Sedimentary (Marine) (34%)	0.008	7.0	2.0	3.6	Medium
Sc	Scotchman's Ck	5.46	803	0.011	47.4	46.8	0.1	19.5	1.5	30	13.4	0.02	Sedimentary (Marine)	0.016	6.1	1.4	4.5	Extensive
Fo	Forest Hill Drain	5.36	806	0.011	49	48.1	0.1	13.4	1.3	39	14.9	0	Sedimentary (Marine)	0.009	4.1	1.3	3.2	Extensive

¹ Bureau of Meteorology. (2018) *Australian Daily Rainfall Gridded Data*. Available at: <http://www.bom.gov.au/climate/how/newproducts/IDCdrgrids.shtml>.

² Average slope of main flow path from drainage divide to sampling site, based on the equal area slope method

³ 2009 land cover mapping with growth factor to 2017 (full methods in-text)

⁴ 2009 land cover mapping with growth factor to 2017, and 2001/2009 connection-to-stream data (full methods in-text)

⁵ Melbourne Water drainage GIS layers

⁶ Assessed visually from NearMap orthophoto imagery captured late 2016

⁷ 2009 land cover mapping with ground-truthing

⁸ Department of Economic Development Jobs Transport and Resources. (2014) Geological polygons (1:250,000) layer. 01/08/2014 ed.: State Government of Victoria.

1.2 Bedload Sampling

This study used sediment traps to capture bedload material in transport along the stream bed. Bedload samples were collected at each site 28 times over a one-year period (13 July 2016 to 2 August 2017) using custom-made sediment traps. Daily rainfall > 10 mm (indicating a significant runoff event) at a nearby weather station (Scoresby, Australian Bureau of Meteorology, BOM, site 86104) triggered sampling events. Samples were collected from sediment traps after rainfall had ceased and streams had returned to near baseflow conditions.

The custom-made sediment traps were installed in stream beds. The plywood structures measured 1 m wide across the stream bed, 0.6 m long in the direction of flow, and 0.15 m deep (Figure 2). The traps were embedded in the stream bed with the top of the trap level with the surrounding bed surface. The standard dimensions of the traps meant that bypass of sediment was possible in the wider streams (e.g. Scotchman's Creek; Sc). To reduce the potential for sediment bypassing, traps were placed in the lowest part of the stream bed and rocks or sand bags were packed around their sides at a slightly higher level than the top of the trap. Bed disturbance was minimised during installation by undertaking works by hand and minimising the excavation footprint. No data was collected for the first flow event after installation to allow the bed to adjust and re-stabilise around the traps without affecting results. The bed at site Lt was subject to ongoing degradation which was locally rectified by placing sandbags around the trap.

While accepted standards for bedload trap design are not available, similar designs have been implemented in past studies. For example, the concrete trough bedload trap developed by Leopold and Emmett (1976) and the traps of Carling (1983) were slot-type traps spanning the entire width of stream. Whereas those traps were somewhat deeper than ours (0.3-0.77 m), the width of the slot in comparison to the grain diameter is considered the critical dimension for preventing saltation over the trap (Reid et al., 1980). In this study, the slot width of 0.6 m is at least 100 times the median

bedload grain diameter for the various sites (see Figure 4), a ratio that should allow near-total bedload-capture efficiency (Hubbell, 1964).

To assess the potential for sediment re-suspension from the traps, bedload-trapping efficiency was measured for two of the traps (sites *OI* and *Lt*) in a moderate flow event using a Helley-Smith bedload sampler with an opening of 7.62 x 7.62 cm. Samples were taken along the upstream and downstream edges of the trap. Sampling was undertaken for one minute, then the sampler was moved along the trap edge. This procedure was repeated nine times until an integrated sample of bedload across the whole trap edge had been collected. The upstream and downstream edge samples were wet-sieved to > 0.5 mm, dried and weighed. The calculated trap efficiency was the difference between the rate of transport into the trap and the rate of transport out of the trap, divided by the rate of transport into the trap. The trap efficiency for coarse-grained (> 0.5 mm) sediment at these two traps was 86-98%. The bedload at these traps is relatively fine-grained ($D_{50} = 0.7$ mm) and the trap efficiency is expected to be even higher for streams with coarser bedload.

The sediment trap capacity was exceeded after some rainfall events at five of the sites (5 times at *Br*, 4 times at *Sc*, 3 times at *Bg*, once at *Fe*, and once at *Sh*) and sediment bypass may have been significant. Sediment bypass was ignored in the final calculations, but initial sensitivity tests were undertaken including and excluding bypass events, and using censored peak analysis to ensure the bypass events did not substantially change the study outcomes.

Figure 2 Typical sampling site arrangement showing bedload trap, Sherbrooke Creek site (Sh)

Sampling comprised manually measuring the volume of sediment in the trap with a scoop and measuring bucket, and taking a composite 1 L sample of sediment from multiple points in the trap. The trap was cleared and the sediment emptied downstream of the trap after volumetric measurement and sampling. After drying the 1 L composite sample at 105°C for 24 hours, the sediment was weighed and wet-sieved through a 0.5 mm sieve to remove fine particles. The retained material was then dried again at 105°C for another 24 hours. Organic matter was manually skimmed off the samples and discarded during wet sieving.

Some of the bedload traps collected a high proportion of fine sediment and organic matter (e.g. *Ly* and *Bg*). In most cases, the fine and organic matter was deposited from suspended material on the recession limb of a flow event. Some streams (e.g. *Bg*) had fine material contributed by bank erosion, either by slumping directly into the trap, or by transport of clay aggregates as pseudo-bedload from a short distance upstream. The fines (including clay aggregates) and organic matter were not considered true bedload and were removed from the samples.

The resulting coarse-grained sample was dry-sieved through 5 sieves with descending aperture sizes ranging from 5 mm to 0.8 mm. Each fraction was weighed to determine particle size distribution. Bedload mass and the median diameter (D_{50}) of the bedload (> 0.5 mm) fraction were the key metrics produced from the analysis. When a sample was particularly coarse-grained ($D_{50} > 5$ mm), the largest particles were measured and weighed to assist with estimating the sample D_{50} .

The equation below enabled calculation of the specific annual bedload yield (bedload yield per unit catchment area per year) for each catchment:

$$Y_b = \frac{\sum S_b * MAR}{CA * R}$$

where Y_b is the bedload yield ($\text{kg km}^{-2} \text{ a}^{-1}$), $\sum S_b$ is the sum of the event coarse-grained sediment loads (kg), MAR is mean annual rainfall (mm), CA is catchment area (km^2), and R is total rainfall over the sampling period (mm). The total rainfall was compiled from BOM gridded daily rainfall estimates for each catchment (<http://www.bom.gov.au/climate/how/newproducts/IDCdrgrids.shtml>) and was 1-7% higher than the mean annual rainfall. Estimated average annual conditions included a correction for mean annual rainfall relative to sample rainfall (MAR/R), which allowed comparisons between sites, some of which were closer to average conditions during the sampling period than others. Whereas a linear relationship between bedload yield and rainfall was not necessarily expected mechanistically, it was supported by this dataset. We explored linear mixed-effects models between event yield and the total rainfall in the period between samples, with site as a random effect (intercept only). We used both fourth-root and log transformations of variables to satisfy the linear model assumptions. Both approaches indicated a near-linear relationship between bedload yield and rainfall depth.

1.3 Hydrologic data

Flow gauging data (water level and flow at a six-minute time step) were available for 5 of the sites (*Br, Fe, Lt, Ol, Ly*) from the Little Stringybark Creek project (Walsh et al., 2015). Automatic water level gauges (Odyssey capacitance loggers) installed at the four remaining sites recorded at six-minute increments. The loggers were calibrated in the laboratory using the procedure supplied by the manufacturer, then recalibrated using in situ water level data. Stage-discharge rating curves were developed using HEC-RAS one dimensional hydraulic models, calibrated to flows measured using a handheld velocity meter (OTT/Sontek). Ratings were based on 8 to 11 stage-discharge pairs from 3 to 4 events at each site. The challenges of flow gauging in small urban streams are well-documented (e.g. Booth and Konrad, 2017), due mainly to their flashiness, making the mobilisation of flow gauging crews during high-flow events difficult. Our flow gauging efforts, particularly in the more urbanized streams (*Fo* and *Sc*), were limited by these issues, and the maximum gauged flow was

small compared to the maximum flow during the sampling period at these sites. A hydraulic modelling approach to rating curve development addresses these difficulties by using physical information about the channel cross-section and slope to extrapolate beyond the gauged flow range. The hydraulic models were based on survey of 7 cross-sections and the thalweg (centreline) over a reach length of 40-80 m at each site. Key features such as bridges and logs crossing the stream were surveyed and included in the models. The key parameter used to calibrate each hydraulic model was roughness, represented by the Manning's n value. For calibration to the gauged flow data, relatively high roughness values were required (Manning's n of 0.065 to 0.14), which were not considered appropriate for higher flows, based on our modelling experience and guidance from widely-used references such as Chow (1959). Furthermore, the calibration indicated that a depth-varying roughness was required. The apparent roughness of a stream bed, and its effect on flow behaviour, is often greater when the flow depth is lower (Arcement and Schneider, 1989). Therefore, lowering the roughness coefficient with increasing flow for extrapolation of the flow-water level rating curve beyond the measured data was considered appropriate. The calibrated Manning's n values were reduced with increasing flow to a minimum value based on visual assessment of the channel (0.04 for Sh , 0.045 for Sc and Bg , and 0.05 for Fo) (Chow, 1959). A 6-minute flow time series was computed from the recorded water level and the modelled rating curve for each site.

Metrics derived from the validated flow time series described the flow regime for each sampling period, including peak flow and standardised peak flow. Standardised peak flows were computed by dividing peak flow by catchment area, for comparison between sites, and for prediction of specific bedload yield (which is also standardised for catchment area).

The gauge limit was exceeded once at Fo and twice at Sc . Peak flows were infilled for these events using observed flood debris heights and the rating curves. The Bg gauge record had a data gap of approximately 4 months. Peak flow data was infilled for this period using a linear regression model

($R^2 = 0.93$) between the natural log of peak flow at an upstream gauge (gauge 228369A operated by Melbourne Water) and the corresponding peak flow at *Bg* for the non-gap period.

1.4 Statistical Methods

Linear models were fitted to predict specific annual bedload yield and annual total D_{50} . Linear mixed-effects models predicted specific event bedload yield and event D_{50} (Table 2). A fourth-root transformation of response and predictor variables (following an offset of -0.7 in the case of event D_{50}) enabled validation of the assumptions of the general linear model.

We evaluated the plausibility of the alternative models by comparing Akaike information criteria adjusted for small sample sizes (AIC_c) (Burnham and Anderson, 2003). The model with the lowest AIC_c is considered the most plausible model. The difference between AIC_c scores of each model and the most plausible model (ΔAIC_c) indicates relative plausibility: Models with $\Delta AIC_c \sim 0-2$ have substantial empirical support, models with $\Delta AIC_c \sim 4-7$ have considerably less support, and models with $\Delta AIC_c > 10$ have essentially no support (Burnham and Anderson, 2003).

Predictor variables for linear models for specific annual bedload yield and D_{50} were the landscape variables listed in Table 3. The key urbanization-related variables were TI, EI, sealed road density, pipe density and construction intensity. TI is a measure of total impervious land cover, whereas EI also accounts for the drainage connection of impervious surfaces. We included sealed road density as a measure of ground-level connected imperviousness, following the logic that most coarse-grained sediment will deposit at ground level rather than on roofs, and that most sealed roads are directly connected to drainage networks. Pipe density was also included as an easily-computed surrogate for urban drainage connection (as local government authorities often have more accurate information about stormwater pipes than imperviousness). Construction intensity also likely impacts sediment supply greatly (Wolman and Schick, 1967; Guy, 1970). Whereas most research has focused on fine-grained sediment inputs from construction areas, coarse-grained sediment inputs may also be significant. The suite of linear models also included background catchment variables likely to have

an impact on sediment supply, including catchment and reach slope, and unsealed road density, to assess their potential impact on the results.

Only a single landscape variable was fitted in each model due to multicollinearity and limited sample size. The only landscape variable not highly correlated with the others was reach slope ($|r| \leq 0.16$ for variable pairs including reach slope compared to $|r| \geq 0.72$ for all other variable pairs), which was not a plausible predictor for any of the model classes. Fitting of multiple landscape variables did not improve the plausibility of models. R^2 indicated the goodness of fit of models.

Fixed predictor variables for linear mixed-effects models for event bedload yield and event D_{50} were the same landscape variables, and hydrologic variables (standardised peak flow for event bedload yield and raw peak flow for event D_{50}). Only a single hydrologic variable, and either no landscape variable, or a single landscape variable, were fitted in each model due to multicollinearity. Initial tests exploring the relative plausibility of different hydrologic metrics as predictors for bedload yield and particle size showed that peak flow was by far the best predictor, better than flow volume. All subsequent analyses were therefore undertaken on standardised peak flow (for event bedload yield) and raw peak flow (for event D_{50}).

Site was included as a random effect, to allow for the non-independence of repeated samples for each site. The random effect accounts for intrinsic but unknown properties of the different sites that affect the bedload regime, but are not necessarily related to the modelled predictor variables. A random intercept and slope model was adopted for event bedload yield and a random intercept model was adopted for event D_{50} , based on the results of initial competitive modelling tests between the two approaches. Marginal and conditional R^2 values indicated goodness of fit for the linear mixed-effects models. The marginal R^2 is a measure of the variance explained by the fixed effects only, whereas the conditional R^2 is a measure of the variance explained by the fixed and random effects.

Several models returned physically implausible results. For example, a model fitted between bedload yield and equal area slope showed sediment yield decreasing with increasing slope. This model conflicts with well-established understanding of the physical processes of sediment supply and is caused by the confounding bias between urbanization and slope in our study sites, rather than a physical effect. Models producing physically implausible results were rejected, as listed in the Results (Section 3).

The true sediment loads for events with trap bypass would be higher than the recorded values, but their actual magnitude was unknown. Models were fitted both with these recorded values included and excluded for comparison. Including the data did not materially change the relative plausibility of different models, therefore we incorporated the recorded values from trap bypass events.

Table 2 Suite of models fitted

Response variable	Predictor variables (fixed effects)	Random effects
Total bedload yield	Landscape variable	-
Total D ₅₀	Landscape variable	-
Event bedload yield	Standardised peak flow	Site (intercept and slope)
Event bedload yield	Standardised peak flow + landscape variable	Site (intercept and slope)
Event D ₅₀	Peak flow	Site (intercept only)
Event D ₅₀	Peak flow + landscape variable	Site (intercept only)

Table 3 Landscape variables included in models

Landscape variable	Units
<i>Urbanization-related variables:</i>	
Total imperviousness (TI)	%
Effective imperviousness (EI)	%
Sealed road density	%
Pipe density	km km ⁻²
Construction	%
<i>Background variables:</i>	
Reach slope	Unitless
Equal area slope	Unitless
Unsealed road density	%

3. RESULTS

3.1 Summary of bedload characteristics

Specific annual coarse-grained bedload sediment yields ranged from $1.3 \text{ kg km}^{-2} \text{ a}^{-1}$ for the least urbanized catchment (*Ly*) to $326 \text{ kg km}^{-2} \text{ a}^{-1}$ for the second-most urbanized catchment (*Sc*) (Figure 3). Bedload material was coarser for the more urbanized sites (e.g. D_{50} of 6.1 mm for *Sc*) than the less urbanized sites (e.g. D_{50} of 0.7 mm for *Ly* and *Ol*) (Figure 4).

Figure 3 Specific annual bedload (> 0.5 mm) sediment yield partitioned into 0.5-2 mm particles and > 2 mm particles. Lines show urbanization intensity of catchments, measured by effective imperviousness (EI) and total impervious (TI).

Figure 4 Particle size distributions of total coarse-grained (> 0.5 mm) bedload over sampling period. The sites are ordered from top to bottom in legend by increasing urbanization intensity, measured by effective imperviousness (EI).

Figure 5 shows the typical character of the dried coarse-grained sediment samples. Angular dark grey gravel typical of road base and surfacing material was abundant in the samples from the more urbanized sites, as was angular granite gravel typical of ornamental toppings, and other particles typical of an exogenous source. Sites *Sc* and *Fo* had different underlying lithology to the other sites (sandstone/siltstone rather than rhyolite/rhyodacite). The parent material was discernible in the samples by its greenish/yellowish colour and rounded particles. From a visual assessment of larger (>5 mm) particles in *Sc* and *Fo* samples, we estimated that around 30% of the total was native for both catchments. Site *Lt*, which had moderate catchment urbanization levels, had pale grey, poorly-sorted sand bedload material. Site *Bg* had orange-reddish sand/gravel bedload material that was embedded in a clay matrix indicative of a bank-material origin. The clay was subsequently washed off and discarded during the wet sieving process. The least urbanized catchments produced very fine bedload with high organic matter. Once the organic matter and fine particles (<0.5 mm) were discarded from these samples (particularly *Ly*), very little coarse material remained. Catchment *Sh*,

although not highly urbanized, produced material that was more similar in character to the nearby, more urbanized site *Fe* rather than the other forested sites *Ly* and *OI*.

Figure 5 Dried coarse-grained (> 0.5 mm) fraction of 1 L bedload sediment samples collected during one event (27 January 2017). The sites are ordered in increasing urbanization intensity, measured by effective imperviousness (EI).

3.2 Landscape effects on bedload yield

Linear models fitted between specific annual bedload yield and landscape variables indicated that yield is positively correlated with level of urbanization (Figure 6). Urbanization-related variables are much more plausible predictors of sediment yield than background landscape variables (Table 4). The most plausible predictor variables were pipe density, sealed road density and effective imperviousness (EI). These metrics, which account for the connection of impervious surfaces to the stream via an efficient drainage network, were more plausible predictors than total imperviousness (TI). The high R^2 values indicate that most of the variance is explained by urbanization-related variables, whereas unmodelled background factors play a relatively minor role.

The two most urbanized catchments (*Fo* and *Sc*) produced very different yields with *Sc* producing nearly 6 times more bedload per catchment area than *Fo*. A sensitivity analysis showed that the findings were robust if either of these catchments were omitted. Omitting *Sc* weakened the strength of each relationship ($R^2 = 0.70$ for pipe density model) but did not substantially change the relative plausibility of the models. If anything, it slightly increased the relative plausibility of the pipe density, sealed road density and EI models (those accounting for drainage connection) compared to the TI model. Omitting *Fo* resulted in stronger relationships ($R^2 = 0.84$ for pipe density model) and made sealed roads a more plausible predictor than the other urbanization-related variables. The level of empirical support for the TI model remained lower than for the EI and pipe density models.

Table 4 Results of model fitting for specific annual bedload yield (*Y*). R^2 values are only reported for models with substantial empirical support ($\Delta AIC_c < 2$). TI = total imperviousness, EI = effective imperviousness.

Model	Type of landscape variable	ΔAIC_c	Level of support for model	R^2
Y ~ Pipe Density	Urbanization-related	0	Substantial empirical support	0.75
Y ~ Sealed Roads	Urbanization-related	1.3	Substantial empirical support	0.71
Y ~ EI	Urbanization-related	1.9	Substantial empirical support	0.68
Y ~ TI	Urbanization-related	2.8	Less support	
Y ~ Equal Area Slope	Background	6.1	Rejected due to physical implausibility (indicated a decrease in yield with increasing slope)	
Y ~ Construction	Urbanization-related	6.8	Considerably less support	
Y ~ 1 (intercept only)	None	7.5	Considerably less support	
Y ~ Unsealed Roads	Background	10.6	Rejected due to physical implausibility (indicated a decrease in yield with increasing unsealed roads)	
Y ~ Reach Slope	Background	12.0	Essentially no support

Figure 6 Models of specific annual bedload yield predicted by urbanization-related landscape variables total imperviousness (A), effective imperviousness (B), sealed road density (C), pipe density (D) and construction intensity (E). Open circles are sites that had known trap bypass and for which the actual yield is higher than indicated. Fitted models (solid lines) and 5-95% confidence intervals (dashed lines) are shown, back-transformed to linear axes.

3.3 Landscape effects on bedload particle size

The relationship between bedload D_{50} and level of urbanization was also positive, but weaker than that for bedload yield (Figure 7). The most plausible predictor variables were construction, pipe density, sealed roads and EI (Table 5). EI, pipe density and sealed roads all account for effective drainage connection as well as impervious surface cover, whereas construction accounts for availability of coarse-grained sediment sources. The model with TI was less plausible than the EI

model and only slightly more plausible than an intercept-only model. The R^2 values indicate that most of the variance is explained by urbanization-related variables while the remainder is likely explained by other, unmodeled factors (background characteristics of the sites and available sediment sources).

The findings were somewhat robust to the omission of site Fo but not Sc . These sites had different bedload median grain sizes (2.0 and 6.1 mm, respectively) despite similar levels of urbanization. Omitting Fo resulted in stronger relationships ($R^2 = 0.66$ for construction model) but reduced the relative plausibility of the different urbanization-related predictor variables. Omitting Sc resulted in weaker relationships and lower significance for the urbanization-related effects. The intercept-only model became highly plausible in this scenario, meaning that if Sc is the ‘true’ outlier, an urbanization- D_{50} relationship is not supported.

Table 5 Results of model fitting for total bedload median particle diameter (D_{50}). R^2 values are only reported for models with substantial empirical support ($\Delta AIC_c < 2$). TI = total imperviousness, EI = effective imperviousness.

Model	Type of landscape variable	ΔAIC_c	Level of support for model	R^2
$D_{50} \sim$ Construction	Urbanization-related	0	Substantial empirical support	0.61
$D_{50} \sim$ Pipe Density	Urbanization-related	1.1	Substantial empirical support	0.56
$D_{50} \sim$ Sealed Roads	Urbanization-related	1.5	Substantial empirical support	0.54
$D_{50} \sim$ EI	Urbanization-related	1.7	Substantial empirical support	0.53
$D_{50} \sim$ TI	Urbanization-related	2.2	Less support	
$D_{50} \sim$ Equal Area Slope	Background	3.0	Rejected due to physical implausibility (indicated a decrease in yield with increasing slope)	
$D_{50} \sim$ Unsealed Roads	Background	3.1	Less support	
$D_{50} \sim 1$ (intercept only)	None	3.6	Considerably less support	
$D_{50} \sim$ Reach Slope	Background	7.3	Considerably less support

Figure 7 Models of total bedload median particle size (D_{50}) predicted by urbanization-related landscape variables total imperviousness (A), effective imperviousness (B), sealed road density (C), pipe density (D) and construction intensity (E). Fitted models (solid lines) and 5-95% confidence intervals (dashed lines) are shown, back-transformed to linear axes.

3.4 Hydrological effects on bedload yield

Linear mixed-effects models fitted between specific event bedload yield, standardised peak flow and landscape variables (with site as a random effect) indicated that bedload yield increased with flow (Figure 8). For a given peak flow, the yield tended to be lower at the more urbanized sites than the less urbanized sites. Adding a landscape variable to the model allowed testing of whether this trend was likely due to an urbanization-related effect, a non-urbanization related background effect, or a random effect.

Once the effect of flow was included, adding an urbanization-related landscape variable (e.g. EI) to the model did not increase its plausibility (Table 6). Adding a background variable (equal area slope, unsealed road density or local slope) to the peak flow model increased its plausibility. The model with flow and equal area slope was most plausible. This model indicates that the lower sediment yields at the more urbanized sites (for a given peak flow) are likely partly due to lower catchment slope. The effect of urbanization on event bedload yields (once flow was already considered) could not be disentangled because of the bias between catchment slope and urbanization in the study area. The number of catchments to control for catchment slope with level of urbanization was inadequate.

Inspection of residual plots for the model fit revealed that site *Lt* had the highest residuals, but they did not have high leverage on the model fit. Excluding these points improved the strength of correlations ($R^2_m = 0.73$ for Q + Equal Area Slope model) but otherwise had minimal influence on the results (i.e. relative plausibility or preferred model).

Table 6 Results of model fitting for specific event bedload yield (Y). Q = standardised peak flow (peak flow/catchment area), TI = total imperviousness, EI = effective imperviousness, R^2_m = marginal R^2 , R^2_c = conditional R^2 . R^2 values are only reported for models with substantial empirical support ($\Delta AIC_c < 2$). Site was included in all models as a random effect (intercept and slope).

Model	Type of landscape variable	ΔAIC_c	Level of support for model	R^2_m	R^2_c
Y ~ Q + Equal Area Slope	Background	0	Substantial empirical support	0.65	0.84
Y ~ Q + Unsealed Roads	Background	2.5	Less support		
Y ~ Q + Construction	Urbanization-related	2.7	Rejected due to physical implausibility (indicated a decrease in yield with increasing slope)		
Y ~ Q + Reach Slope	Background	2.9	Less support		
Y ~ Q	None	3.8	Less support		
Y ~ Q + TI	Urbanization-related	4.7	Considerably less support		
Y ~ Q + Sealed Roads	Urbanization-related	5.0	Considerably less support		
Y ~ Q + EI	Urbanization-related	5.8	Considerably less support		
Y ~ Q + Pipe Density	Urbanization-related	6.2	Considerably less support

Figure 8 Relationship between specific event bedload yield and standardised peak flow, showing fitted linear mixed-effects model with site as a random effect. Sites are ordered in the legend from lowest (*Ly*) to highest (*Fo*) urbanization intensity (represented by effective imperviousness percentage in brackets). The axes are linear in fourth-root-transformed space. Axis labels are shown as native values for ease of interpretation.

3.5 Hydrological effects on bedload particle size

Linear mixed-effects models fitted between event bedload particle size (D_{50}), peak flow and landscape variables (with site as a random effect) indicated that particle size increased with flow (Figure 9), although the relationship was weaker than that of bedload yield. The most plausible

models, as indicated by AIC_c , were those including flow and construction or reach slope (Table 7), but the landscape effects were not significant. A simpler model, with only peak flow as a fixed effect, was almost equally plausible ($\Delta AIC_c = 3.4$) and was preferred due to parsimony. The marginal and conditional R^2 values indicate that the fixed effects explained very little of the variance (e.g. 6% for the flow only model) and the random effect explained a significant proportion of the variance.

Inspection of residuals revealed two main populations of D_{50} ; the finer sediments in *Ly*, *Ol* and *Lt*, and the coarser materials in the other catchments. Fitting the model on only the other six catchments (*Sh*, *Bg*, *Fe*, *Br*, *Sc* and *Fo*) resulted in a stronger correlation between D_{50} and flow, although the fixed effects still explained little of the total variance ($R^2_m = 0.13$ for $D_{50} \sim Q$ model). The greatest residuals occurred in the data for site *Fe* but they did not exert high leverage on the model fit. Excluding these points made minimal difference to the results.

Table 7 Results of model fitting for event bedload particle size (D_{50}). Q = peak flow, TI = total imperviousness, EI = effective imperviousness, R^2_m = marginal R^2 , R^2_c = conditional R^2 . R^2 values are only reported for models with substantial empirical support ($\Delta AIC_c < 2$; and flow only model, which is preferred due to parsimony). Site was included in all models as a random effect (intercept only).

Model	Type of landscape variable	ΔAIC_c	Level of support for model	R^2_m	R^2_c
$D_{50} \sim Q + EA \text{ Slope}$	Background	0	Rejected due to physical implausibility (indicated a decrease in D_{50} with increasing slope)		
$D_{50} \sim Q + Construction$	Urbanization-related	0.3	Substantial empirical support, but Construction effect not significant ($p = 0.05$)	0.36	0.65
$D_{50} \sim Q + Reach \text{ Slope}$	Background	0.6	Substantial empirical support, but Reach Slope effect not significant ($p = 0.34$)	0.12	0.61
$D_{50} \sim Q + Sealed \text{ Road}$	Urbanization-related	2.7	Less support		
$D_{50} \sim Q$	None	3.4	Less support but preferred due to parsimony	0.06	0.59
$D_{50} \sim Q + Pipe \text{ Density}$	Urbanization-related	3.8	Less support		
$D_{50} \sim Q + Unsealed \text{ Road}$	Background	4.0	Less support		
$D_{50} \sim Q + TI$	Urbanization-related	4.2	Less support		
$D_{50} \sim Q + EI$	Urbanization-related	4.5	Less support

Figure 9 Relationship between event bedload median particle size (D_{50}) and peak flow, showing fitted linear mixed-effects model with site as a random effect (intercept only). Sites are ordered in the legend from lowest (Ly) to highest (Sc) urbanization intensity (represented by effective imperviousness percentage in brackets). The axes are linear in fourth-root-transformed space. Axis labels are shown as native values for ease of interpretation.

4. DISCUSSION

4.1 Urbanization effect on total bedload yield and size

The results showed that bedload sediment yield was significantly higher in suburban catchments than forested catchments, suggesting that urbanization is a strong driver of sediment yield. Quantitative evidence from the limited previous studies on urban bedload (Smith and Wilcock, 2015; Utz and Hilderbrand, 2011) supports this finding.

As shown for other hydrological, geomorphological and ecological signals (Hatt et al., 2004; Walsh, 2004; Vietz et al., 2014; Burns et al., 2015), this study found that drainage connectivity in the catchment, represented by effective imperviousness (EI), pipe density, or sealed road density, was a more plausible predictor of bedload yield and particle size than total imperviousness (TI). The explanatory power of these landscape variables for bedload yield was high ($R^2 = 0.68-0.75$), whereas their explanatory power for bedload particle size was lower ($R^2 = 0.53-0.56$). The findings for bedload yield were robust to the omission of high-leverage points (possible outliers) *Fo* or *Sc*, while the findings for bedload particle size were less robust. If the coarseness of the bedload at site *Sc* is truly an outlier, then our data provides little support for a relationship between urbanization and bedload D_{50} . Given the relationship can collapse by omission of a single point, less credence is given to the correlation between urbanization and bedload D_{50} than the findings for bedload yield. This finding suggests that universal catchment processes that operate across a range of catchment contexts (e.g., hydrology) strongly drive urban bedload yield, whereas intrinsic catchment or channel properties (e.g., geology) constrain bedload particle size.

Overall, these findings demonstrate the importance of drainage connection of urban surfaces in controlling the bedload sediment regime, particularly sediment yield. Whereas increased connectivity of drainage systems impacts streams by producing an inhospitable and erosive

hydrologic regime, it also drives the supply of coarse-grained sediment to streams, which can buffer these harmful effects.

Previous studies have attributed increased sediment yields in established urban areas to legacy construction sediments being liberated from lag deposits, or to ongoing erosional adjustment of the channel to the urban flow regime, which can continue for several decades after urban land cover is established (Trimble, 1997; Chin, 2006). Erosion of bed and bank material was likely a large contributor to the coarse-grained sediment yield in the peri-urban catchments, particularly *Bg* and *Lt*. Both sites showed signs of active erosion in the study reaches and the bedload material captured in the trap corresponded to the coarser fraction of the bank material (coarse sand in *Lt* and gravel embedded in a clay matrix in *Bg*). In the more urbanized catchments, however, channel erosion was considered likely a relatively minor contributor to sediment supply.

In the most urbanized catchments (*Br*, *Fo* and *Sc*), around 80-90% of the original stream length upstream of the study reach had been converted to pipes, and the remaining open channel was mostly rock-lined and showed no signs of ongoing erosion or adjustment. While the highest flow events were capable of transporting stream bed and bank materials (including large cobbles up to 205 mm in diameter), a consistently erosional regime was not apparent in the urban streams. Rather, these streams, and the pipe networks upstream of them, appeared to be highly efficient sediment transport conduits from upland hillslopes (i.e. the urban land surface). Therefore, we conclude that most of the sediment yield measured in the bedload trap was sourced from the upland catchment surface, including deteriorating urban surface materials, rather than erosion of stream bed or banks. These observations are consistent with findings of elevated suspended sediment supply from non-channel urban sources elsewhere (Smith and Wilcock, 2015; Gellis et al., 2017).

The type of sediment can point to the likely source. Qualitative observations of the sediment character in the more urbanized catchments (*Sc* and *Fo*) indicated that most of the bedload material

in these streams originated outside the catchment. Fluxes of aggregate materials in urban areas (quarrying, transport, construction, landscaping) are enormous in comparison to natural rates of sediment movement (Decker et al., 2000). That exogenous sediment should make up a large proportion of coarse-grained sediment supply to streams is therefore unsurprising. Sources such as gravel toppings and decay of constructed materials are essentially unlimited in supply, because they are replenished or replaced as they erode.

Construction activities are known to greatly increase catchment sediment yields (Wolman, 1967; Chin, 2006; Russell et al., 2017). Previous conceptual models of the effects of construction activities and subsequent urban land cover on sediment yields (Wolman, 1967; Chin, 2006) relied on an assumption that, at some point, construction stops, and land cover is stable. Construction is never truly complete, however, but continues in the form of infill and renewal. Infill development produces a trend of increasing imperviousness, and therefore runoff, as well as providing pulses of sediment supply to the stream. The intensity and type of construction activity observed in the more suburban study catchments (1.5% for *Sc* and 1.3% for *Fo*) are typical of renewal and infill development across the established suburbs of Melbourne (Department of Environment Land Water & Planning, 2016). These developments were mainly at the lot scale, involving construction of additional dwellings, or replacement of smaller dwellings with larger ones. Given that construction activities produce suspended sediment yields potentially several orders of magnitude higher than general urban areas (Russell et al., 2017), these activities could provide a substantial proportion of the sediment supply to the stream, even if they cover a relatively small area of the catchment. While previous work has focused on fine rather than coarse-grained sediment supply from construction areas, we speculate that the effect on coarse-grained sediment supply may be similar. Construction was a plausible explanatory variable for bedload particle size, indicating that construction activities may be an important source of coarser sediments in suburban catchments.

Development of a conceptual urban sediment budget at the catchment scale (including the coarse-grained sediment yield from infill construction areas) will help to characterise the relative

importance of different activities, surface types and drainage arrangements in providing coarse-grained sediment to streams.

4.2 Unravelling hydrological and land cover effects on bedload regimes

By analysing bedload yield on an event basis, the effects of hydrology (e.g. peak flow) could be resolved and compared to residual (i.e. non-hydrological) landscape effects. Catchment urbanization has a clear hydrological effect (Booth, 1991), which drives increased sediment transport capacity, but may also influence sediment supply, making the sediment regime more or less supply-limited.

This analysis indicates that the enhanced peak flows of the urban regime overwhelmingly drove the increases in bedload yield and particle size. This result indicates that the mechanism by which increased drainage connection drives increased *total* bedload yield and median bedload particle size is largely hydrological. Higher connected imperviousness in the catchment leads to higher peak flows, which drive greater sediment transport and delivery, and transport of larger particles as bedload.

Once the effect of flow was included, adding an urbanization-related landscape variable (e.g. EI) to the model for event bedload yield did not increase its plausibility. A tendency for the more urbanized catchments to produce lower yields at the same peak flow was apparent. The current results, however, provided no evidence that urbanization caused this supply-limiting. It was more plausible that this effect was produced by a background catchment characteristic such as lower catchment slope. A correlation in the study catchments between geology and urbanization, which wasn't included in the statistical model, could also influence results.

These findings produce a contradiction. While we found no evidence of urbanization modifying the flow-sediment yield relationship, bed sediment is often depleted in urban streams (Vietz et al., 2014) and channel enlargement is common, indicating excess flow energy (Leopold et al., 2005; Chin,

2006). Either urbanization does limit coarse-grained sediment supply relative to flow but the effect is too subtle to be detected in the current dataset, or the channel hydraulics produce a change in transport capacity that is more severe than what is indicated by the hydrology alone. In the former case, with more sites and better control of background variables, an effect may be detectable. In the latter case, channel evolution towards a deeper, more efficient channel may produce a hydraulic regime capable of transporting more sediment with the same flow. The more urbanized study streams have enlarged (mainly deepened and slightly widened) channels, which can contain higher in-channel stream energy, and are likely capable of transporting more sediment with the same flow, particularly in high flow events. Upstream of the bedload traps at the study sites, reaches that have been converted to pipes are also highly efficient transporters. A hydraulic assessment of the transport capacity of the study streams would help to establish the role of urban channel form in driving bed sediment depletion and channel enlargement.

The relationship between flow and event median particle size was relatively weak, only explaining 6% of the variance with random effects associated with sites explaining an additional 53% of the variance. This result indicates that intrinsic, unmodeled properties of the study sites or catchments, such as geology or soil type, possibly control the bedload particle size distribution. A tendency for the more urbanized catchments to produce coarser bedload material at the same peak flow was apparent, but no evidence was obvious that any of the modelled landscape variables caused the effects.

The bedload particle size distributions (Figure 4) indicated three sites that produced characteristically fine (<2 mm) bedload material that was not well-correlated with peak flow: the non-urban *Ly* and *OI* and the peri-urban *Lt*. These sites had large in-stream wood loads that limit the longitudinal connectivity of coarse sediments, meaning that coarse particles captured in the sediment traps were most likely local in origin (e.g. from local bank disturbances). The woody debris in *Lt* is somewhat unusual for an urbanized system and hints at a broader difference between *Lt* and the other partly-urbanized sites: the spatial arrangement of urban land cover. In other partially-

urbanized study catchments, development is mainly situated in the lower parts of the catchment near the outlet. This pattern is typical for the broader Melbourne region, and many urban areas, where lower, flatter lands are developed more intensely than higher, steeper areas. In *Lt*, the urban area is at the top of the catchment, and farmland and forested areas buffer its influence at the catchment outlet. The *Lt* study reach is in remnant forest that provides its woody debris load. Although *Lt* receives runoff from urban areas, the coarse-grained sediment supplied by urban areas must be stored upstream of our site. The other possible source-limiting influence is that stormwater control measures such as rain gardens and rainwater tanks have been installed extensively in *Lt* (Walsh et al., 2015), disconnecting around half of its effective impervious area from direct stormwater drainage. Those devices (particularly those intercepting ground-level runoff, such as rain gardens) may block the supply of coarse-grained sediments from urban upland areas.

The impact of flow control infrastructure was not explicitly investigated in this study, but might contribute to variation between sites. Large flow-retarding basins (intercepting only flood flows) were present in two catchments (*Bg* and *Fo*) but appeared to have sediment-transporting low flow outlets. Although these retarding basins shouldn't limit sediment supply, they do affect the high flow hydrology and therefore the sediment transport capacity of these streams. The maximum flows (standardised by catchment area) were reduced approximately threefold, and yields were reduced approximately sixfold in these catchments compared to those with similar levels of urbanization but without retarding basins (*Lt* and *Sc*). We believe this result contributes to the large discrepancy in bedload yields and particle sizes between the two most urbanized catchments, *Fo* and *Sc*.

5. CONCLUSION

The findings of this study suggest a rethink of the coarse-grained sediment-supplying potential of urban catchments, which has long been assumed to be low due to sealing of the land surface with hard materials (e.g. Wolman, 1967; Gurnell et al., 2007). Established suburban land surfaces can produce coarse-grained sediment yields significantly higher than natural catchments, an increase

that is driven by the increase in sediment-transporting runoff and streamflow from efficiently-drained urban catchments. The degree of connection of impervious surfaces to the drainage network is critical in determining the urban impact on the sediment regime.

Upland sources of coarse-grained sediment in urban catchments, including infill construction, urban decay and renewal, landscaping and road deposited sediment, appear plentiful. The study results challenge the concept of 'established urban land cover': we observed widespread and ongoing small-scale construction activities in the more urbanized study catchments, despite their establishment as urban areas over 40 years ago. These activities could provide a significant proportion of the urban sediment budget, even if the land use covers only a small proportion of the catchment.

Future research priorities include generalising the results to other regions and a wider range of urbanization intensities, conceptualising the coarse-grained sediment budget of urban areas, investigating the effect of altered hydraulics in modified or enlarged urban streams on sediment transport capacity, and developing management responses to protect and re-establish sources of coarse-grained sediment while addressing the urban flow regime. Management responses that address the root cause of urban stream degradation will not only prevent erosion, loss of land and damage to infrastructure, but will also help to provide diverse habitat and make streams self-sustaining and resilient.

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