

Improving Urban Stream Condition by Redirecting Sediments: A Review of Associated Contaminants

Arezou Houshmand¹, Geoff J. Vietz² and Belinda E. Hatt¹

1. CRC for Water Sensitive Cities, Monash Water for Liveability, Department of Civil Engineering, Building 60, Monash University, Victoria, 3800. Email: arezou.houshmand@monash.edu

2. CRC for Water Sensitive Cities, Department of Resource Management and Geography, The University of Melbourne, 500 Yarra Boulevard, Burnley, Victoria, 3121. Email: g.vietz@unimelb.edu.au

3. CRC for Water Sensitive Cities, Monash Water for Liveability, Department of Civil Engineering, Building 60, Monash University, Victoria, 3800. Email: belinda.hatt@monash.edu

Key Points

- Contaminants to streams can be associated with specific sediment sizes from urban catchments
- Heavy metals are mostly attached to medium sand and smaller particles (<500 µm).
- PAHs are more associated with particles smaller than fine sands (<250 µm).
- Far less is known about the association between sediment particle size and TN, TP, herbicides and pesticides.
- Coarse sediments can feasibly be redirected around sediment basins to maintain the geomorphic and ecological condition of urban streams, and reduce maintenance at the same time.

Abstract

It is well known that established urban catchments often result in increased flow to receiving streams, but they can also lead to reduction in coarse-grained sediment to receiving streams. The resulting loss of coarse-grained sediments (e.g. sands, gravels etc.) in streams has negative consequences for aquatic ecosystems, including reduced foraging and refuge for macroinvertebrates and fish. Stormwater harvesting and treatment systems often exacerbate the problem. Gross Pollutant Traps (GPTs) are commonly designed to remove particles and particulate-associated contaminants from reaching the water body, further starving streams of coarse-grained sediments. Passing coarse-grained sediments through these systems, however, risks transporting associated pollutants to the receiving water body. This paper reviews the literature on particle size distribution, pollutant concentration and the effect of particle size on pollutant concentration before and after GPTs. We also outline initial findings from a field sampling study on a GPT on the outskirts of Melbourne, Victoria. The results suggest that stormwater treatment systems may be more effectively designed for specific sediment sizes, with the high pollutant particles captured and low pollutant particles redirected to the stream. This will help us consider alternative designs to simultaneously mitigate pollution, maintain stream health and reduce the cost of maintenance.

Keywords

Urbanisation, waterway rehabilitation, heavy metals, PAHs, nutrients, pesticides, herbicides, particle size, Gross pollutant trap, substrate

Introduction

Urbanisation increases impervious surfaces and modifies drainage leading to altered stream flows, sediment regimes and pollutant loads to rivers (Hatt et al., 2004). Sediment load often increases in the early stages of urbanisation (Pomeroy et al., 2008; Schumm, 1977) and after establishment it decreases with time (Gurnell et al., 2007; Wolman, 1967). While changes to the sediment regime are poorly understood, in general urbanisation increases the mass of suspended solids such as silts and clays (particularly in the range 1-50 µm) (Duncan, 1999) and reduces coarse-grained sediments of sand-size and greater (Pizzuto et al., 2000; Vietz et al., 2014). It is the decrease in coarse-grained sediments that are of most interest to this paper.

Stormwater treatment technologies such as GPTs and sedimentation ponds, while addressing flow and pollutants to waterways, also affect sediment supply to streams. These devices can trap coarse-grained sediments and reduce supply to the stream. This reduces the substrate sediment loads in the stream, can result in stream beds scoured down to clay or bedrock, and can reduce the geomorphic condition of urban streams (Vietz et al. 2014). By trapping sediment, GPTs leave no passing sediment to reduce water flow energy, hence exacerbating erosion of the stream bed and banks (Kondolf, 1997). These channel changes can reduce conditions for ecological values such as benthic macroinvertebrates

(Walsh et al., 2005) and fish species (Gurnell et al., 2007). In addition, GPTs require regular clean outs, making GPTs an expensive ongoing maintenance concern for Council's and authorities who are often forced to dispose of sediments as contaminated land fill.

Many studies have investigated levels of contaminants, especially metals and PAHs, in various urban sediment sources such as roads, pavements, residential and industrial areas. However, levels of contamination and how they relate to particle size in GPT sediments have not been specifically studied. This paper provides a review of the literature that identifies the level of contamination associated with sediments, distinguished by size, in GPTs and similar devices. The aim of this study is to inform GPT design to improve stream health and reduce the cost of maintenance for asset owners. GPT contamination characteristics could be different to sediments from other sources since the contaminants in GPTs potentially undergo biochemical reactions during and between storm events in GPTs. We also outline a scoping study case study that characterises the nature of the sediment captured and the extent of contamination.

Literature Review

Identifying associations between contaminants and sediment size can help us to understand which fraction has a lower level of contamination and thus the potential to be sent to waterways. In this paper we refer to fine-grained sediments (fine sediments) as silts, clays and fine-grained sands (<500 microns) and coarse-grained sediments (coarse sediments) as medium-sized sand particles and greater (>500 microns). Urban stormwater transports a significant amount of sediment-bound pollutants, including: heavy metals, polycyclic aromatic hydrocarbons (PAH), Polychlorinated biphenyl (PCB), pesticides, herbicides, nutrients (phosphorus, nitrogen) (Taylora et al., 2007). Heavy metals and PAHs are of particular concern in urban runoff; their concentration levels in relation to sediment particle sizes are the most studied in comparison to other contaminants because of their popularity, toxicity to aquatic organisms and persistence in the environment (Brown & Peake, 2006). In contrast, there are few studies on the sediment particle size relationship with other contaminants such as nutrients, pesticides and herbicides, despite the presence of these contaminants in urban system being well studied.

Many studies have demonstrated that contaminants tend to attach to fine sediment rather than coarse sediments (Selbig et al., 2013; Viklander, 1998). The main reason for this is the large surface to volume ratios of small diameter particles resulting in greater reactive surface for adsorption and transport of pollutants (Kayhanian et al., 2012; Owens et al., 2011). However this trend is less obvious in some cases (Bartoli et al., 2012; Stone & Marsalek, 1996). The relationship between pollutants and particle size is discussed in more details in the following sections.

Metals

A consistent message from the literature is that metal contaminants attach to particles less than 500 μm (Table 1). 50 percent of studies have shown that higher metal concentration is associated with finer particle size sediments of less than 75 μm in urban systems. 31 percent of studies have suggested that metal contaminant concentration is highest in medium sand and smaller particle sizes (<500 μm). However, there are a few studies which could not find any relationship between particle size and contaminant, or found heavy metals to be equally associated with clay, silt and sand particles. Moreover, there are some metals like Cu tend to to be more correlated with particles >75 μm (See Table 1).

There are some other factors can also impact particle size and contaminant association.(Muthukaruppan et al., 2002) have shown metal concentration in the basaltic catchments increases as the particle size decrease. This trend, however, is less obvious in sedimentary catchments. Initial finding suggested that when there is more level of contamination in an area, contaminant tend to attach to coarser sediments (e.g. Bian & Zhu, 2009; Dempsey et al., 1993).

The reasons for adsorption of contaminant by fine sediments are relating to the higher specific surface area, higher organic carbon content, effective cation exchange capacity and greater clay forming minerals content (Gunawardana et al., 2014).

Table 1. Studies of particular sediment particle sizes associated with high heavy metal concentrations

Heavy metal contaminant	Highest concentration was found in	Sediment source	Exception to the general trends	References
Pb	coarse sand and smaller	Road sediment from curb side	NA	(Sutherland 2003)
Zn, Fe, Pb, Cd, Cu, Cr, Al and Mn	Silt	Road surface residential, industrial commercial	Al : 0.45-150 µm, Cu in residential and commercial area: 151-300µm	(Herngren, Goonetilleke et al. 2006)
Cd, Pb, Zn and Cu	Silt and clay	Housing area, city centre with 4500 vehicles per day	NA	(Viklander 1998)
	Silt and clay	the city center with over 20000 vehicles per day	Cd and Pb: 500 and 250 µm respectively.	
Zn, Cr, Pb, Ni	Silt and clay	Single family residential	Cd: 43-100 µm, the relationship between particle size and contaminant is less apparent for Cu.	(Lau and Stenstrom 2005)
	Very fine sand, silt and clay	Multi-family residential	Zn: 100-250 µm	
	No trend	Industrial	Cu: 250-841µm, Pb, Ni:100-250, Zn<43 µm, Cr:43-100 µm	
	Very fine sand, silt and clay	Roads	For Cu distribution is similar in different particle size and in 150-841 µm is a bit higher than others	
	Silt and clay	commercial,	Cu and Cd: 100-250µm and Cr: 43-100µm	
Al, Cu, Pb, and Zn	Very fine sand	Road deposited sediment	Zn : < 63 µm	(Sutherland et al., 2012)
Cu, Pb, Zn	Very fine sand, silt and clay	dry pavement	Cu and Pb: 75-125µm Zn <38 µm	(Kayhanian et al., 2012)
	Fine sand and smaller	highway runoff	Cu and Pb: 125-250 µm, Zn <38µm	
	No trend	dry detention basin 457 Litre	Cu: 425-600 , Pb: 250-600 and >1000, Zn concentration was in the same range for particles less than1000 µm	
	Medium sand and smaller	dry detention basin 535 Litre	Cu 125-600µm and >1000 , pb 125-250µm, Zn: 75-425 µm	
Zn, Mn, Ni, Pb, Fe, Cu, Cr, Ca, As	Silt and clay	stormwater bed, stormwater suspended, street dirt, streambed	NA	(Selbig, Bannerman et al. 2013)
Pb, Zn, Cu, Cr, Ni, Cd, Fe, Mn and Co	Silt and clay	small urban zones with 20% impervious area	NA	(Zafra, Temprano et al. 2011)
		Average urban zones with 70% impervious area	Cu :250-500 µm	

Heavy metal contaminant	Highest concentration was found in	Sediment source	Exception to the general trends	References
Cu, Pb, Zn	Fine sand and smaller	Commercial	Zn, <54µm, Cu: 125-250µm, Pb <125 µm	(Bian & Zhu, 2009)
	Silt and clay	Park		
	Silt and clay	Residential	Pb: <54µm and 63-125 µm	
	Coarse sand, silt and coarse silt	Traffic	Cu <54 µm	
Cu, Pb, Zn	Fine and very fine sand	Urban road	Pb:250-840 µm	(Dempsey, Tai et al. 1993)
Cr, Ni, Cu, Zn, Pb	Fine and medium sand	Urban road	NA	(German & Svensson, 2002)
Zn, Cu, Pb, Ni, Hg, Cr	Fine sand and smaller	Urban road	NA	(Sartor, Boyd et al. 1974)
AL, Cr, Mn, Fe, Ni, Cu, ZN, Cd, Pb	Silt and clay	Urban road	Cu: 75-300µm and Zn: 75-150 µm	(Gunawardana et al., 2014)
Cu, Ni, Zn, Pb	Very fine sand, silt and clay	residential areas in urban area	Pb, highest 94-150µm except sedimentary <43 µm-Zn, in <43 except Sedimentary, 94-150µm-Ni, in 94-150µm-Cu in <300µm different trend for each one	(Muthukaruppan et al., 2002)
Cr, Cu, Pb, Ni, and Zn	Very fine sand, silt and clay	Urban stream bed	NA	(Rhoads & Cahill, 1999)

Polycyclic Aromatic Hydrocarbons

There have been conflicting reports on the relationship between PAHs and sediment particle sizes. More than 70 percent of studies suggest that, similar to metals, PAH attach to fine sand and smaller particles. There are a few studies, about 20 percent investigated PAH content has been found to be greater in the sand fraction rather than silt fraction. 10% of studies found a bimodal distribution of PAH concentrations to sediment particle size, in which the distribution peaks are related to fine and coarse sediments. There are also some studies on associated PAHs among different size and density fractions of sediment samples. Low density particles were found to contain higher PAH and PCB concentrations (Ahrens & Depree, 2004; Huang et al., 2011). As per metals, land use and source areas may affect the trend of associated PAHs with particle size distribution (Bathi et al., 2012; Lau & Stenstrom, 2005).

The tendency for association between PAHs and sediment particles relates to the amount of organic content, in both coarse particles, such as leaves and grass, and fine particles found in native material like silts and clays (Bathi et al., 2012; Evans et al., 1990; Wang et al., 2001). Table 2 summarises the findings of previous studies on the relationship between particle size distribution and highest PAH concentration.

Table 2. Studies of particular sediment particle sizes associated with high PAH concentration

Contaminant	Highest concentration was found in	Sediment source	Exceptions and Comments	References
PAH	Coarse sand and larger	Urban area	In some cases highest concentrations were found in particles <63 µm and it depends on organic matter content	(Evans, Gill et al. 1990)
PAH	larger than silt fraction	stormwater bed, stormwater suspended, street dirt, streambed	street dirt had higher concentration in <63 µm	(Selbig et al., 2013)
PAH	Clay	Single family residential	PAH increase with decreasing particle size	(Lau & Stenstrom, 2005)
	Clay	Multi family residential	PAH increase with decreasing particle size	
	Very fine and fine sand	Industrial	Lowest concentration found in 250-840 µm (µm)	
	Clay	Roads	PAH increase with decreasing particle size	
	Clay	commercial	The PAH concentration decreased with increasing particle size however in one of the sources, there was a sudden increase in 250-841 µm	
PAH	Pebbles and larger	Urban area	The second highest PAH concentrations were found with smaller (<90 µm) and larger (>710 µm) fractions	(Bathi, Pitt et al. 2012)
PAH	Very fine sand	low density fractions <2.15 g/ cm ³ in urban area	The low density fraction particles had up to 155 and 150 times higher concentrations of PAHs compare to high density particles- Bimodal distribution	(Huang, Lee et al. 2011)
	Fine sand	(high density fractions>2.15 g/ cm ³) in rban area	In high density particles, urban area has higher PAHs compare to industrial area There is a bimodal distribution with highest in 125-250 µm, 62-125 µm for urban and industrial respectively.	
	Very fine and fine sand	Industrial area (low density fractions <2.15 g/cm ₃)	In low density particles, industrial area has got higher PAHs concentrations compare to urban are. The second highest was found in 500-1000 µm particles	
	Very fine sand	Industrial area (high density fractions>2.15 g/cm ₃)	The second highest was found in 250-500µm particles –bimodal	
PAH	Larger than coarse sand and smaller than very fine sand	3 urban creek, affected by run off from residential areas, commercial areas and heavy traffic, high density residential area	NA	(Bathi, Pitt et al. 2009)
PAH	Silt	Bay area with inputs from high density residential area, high shipping and industrial activities.	NA	(Ünlü & Alpar, 2006)
PAH	Fine sand	Light	Bimodal distribution- Highest concentration found in low density particles	(Ahrens and Depree 2004)

Contaminant	Highest concentration was found in	Sediment source	Exceptions and Comments	References
	Very fine sand	Heavy	the second highest found in 250-500 µm	
PAH	Larger than medium sand	Urban harbor polluted by municipal and industrial runoff	NA	(Wang et al., 2001)

Nutrients, Pesticides & Herbicides

Relationships between particle size and contaminants such as nutrients and pesticides have not been well studied (Table 3). About 60 percent of studies illustrate Total Nitrogen (TN) attach to sand and pebbles rather than silt and clay. And 30 percent of studies report a bimodal distribution, where nutrients were associated with both coarser and finer sediments. Only 10 percent of researches show a correlation between silt particles and TN.

According to literature, Total Phosphorus (TP) shows correlation with fine sand and smaller particles. Only one study found a relationship between pesticides and particle sizes that illustrated pesticides are attached to particles smaller than 246 µm (Sartor et al., 1974).

Table 3. Studies on the particular sediment particle size with highest TN, TP and pesticide concentrations.

Contaminant	Highest concentration was found in	Sample source	Comments	References
TN	Coarse sand	Commercial	Bimodal- Less than 54 µm is the second highest	(Bian & Zhu, 2009)
	Very coarse sand	Park	Bimodal, Decrease with decreasing particle size up to 250-500 µm and then increase with decreasing particle size.	
	Coarse sand and smaller than coarse silt	Residential	NA	
	Coarse sand and smaller than coarse silt	Traffic	NA	
TN	Medium silt to fine sand	Road	NA	(Vaze and Chiew 2004)
TN	Larger than very fine sand	Residential area, in urban area from road surfaces and along gutters.	TN in different sampling locations is not following any special trend in this size range	(Muthukaruppan, Chiew et al. 2002)
TN	larger than medium sand	Urban harbor polluted by municipal and industrial runoff	NA	(Wang, Zhang et al. 2001)
TP	Medium silt to fine sand	Road	NA	(Vaze and Chiew 2004)
TP	Very fine and fine sand	Urban road	Increase with increasing particle size to 250 µm and then drop to the minimum and after that picking up with decreasing particle size	(Dempsey, Tai et al. 1993)
TP	Clay	Urban road	The amount of P adsorbed by clay surfaces would be 10 times greater than from the silt	Dong, Simsiman et al. 1983)

Contaminant	Highest concentration was found in	Sample source	Comments	References
TP	Silt and clay	Residential area, in urban area from road surfaces and along gutters.	except one location in which highest TP found in particles >755 µm	(Muthukaruppan, Chiew et al. 2002)
Phosphate	Medium silt and smaller	Urban road	Decrease with increasing particle sizes	(Sartor, Boyd et al. 1974)
Nitrate	Coarse silt and fine sand	Urban road	NA	
Pesticides	Smaller than fine sand	Urban road	NA	

A Case Study: Wicks Reserve

A scoping study has been conducted at a continuous deflective separation GPT, draining an impervious catchment of approximately 12 ha, at Wicks Reserve in Melbourne. Sediment sampling and laboratory analysis was undertaken to determine grain size fractions and identify associated contaminants.

While the short nature of this paper does not allow all results to be discussed, the initial findings suggest that the attached heavy metals to particles finer than 1 mm were relatively low and well below the ANZFMQG limits. While coarser sediment fractions have not yet been analysed, it is likely that heavy metal concentrations are even lower, particularly based on the findings from the above review.

Ongoing detailed investigation into the sediments and associated contaminants in Wicks Reserve is being undertaken. If further findings confirm that the contaminant concentration (heavy metals, PAHs, PCBs, TN and TP) attached to trapped coarse sediments in the GPT is below the Sediment quality guidelines of ANZECC, table 3.5.1 (ARMCANZ, 2000), then there is potential for redirecting sediments past the GPT to the stream. This not only reduces the maintenance of stormwater systems but helps to replenish dwindling supplies of coarse-grained sediments in the stream.

Conclusions and Recommendations

Managing sediments in drainage system is critical due to the relatively high volume of sediment generated by urban catchments, expensive disposal process, and high potential for more productive use of these sediments. Redirecting sediments to urban streams is likely to be not only a cost-effective solution but also improve stream health.

The key points can be drawn from the literature are as follows:

- Heavy metals are more attached to medium sand and smaller particles (<500 µm).
- In more polluted areas such as industrial area, heavy metals attach to larger particle sizes.
- Some metals like Cu, tend to attach to sand particles rather than silt and clay.
- PAHs are more associated with particles smaller than fine sands (<250 µm). PAHs also correlated with the organic content of sediments.
- Far less is known about the association between particle size and TN, TP, herbicides and pesticides, than for other contaminants. However according to available studies, TN is more attached to sand and pebbles, and TP is associated with silt, clay and fine sand.

According to the literature, the general trend suggests contaminants are associated with finer fractions, but it is important to further ascertain the association of contaminants with the coarse-grained fractions that might be desirable for stream condition. If coarse sediments can be passed through stormwater systems there are benefits for both reduced maintenance and improved stream condition.

Acknowledgements

The authors would like to thank Rob James and Peter Poelsma for their help in field sampling and gratefully acknowledge financial support from CRC for Water Sensitive Cities.

References

- Ahrens, M. J., & Depree, C. V. (2004). Inhomogeneous distribution of polycyclic aromatic hydrocarbons in different size and density fractions of contaminated sediment from Auckland Harbour, New Zealand: an opportunity for mitigation. *Marine Pollution Bulletin*, 48(3), 341-350.
- ARMCANZ, A. (2000). Australian and New Zealand guidelines for fresh and marine water quality. *National water quality management strategy paper*(4).
- Bartoli, G., Papa, S., Sagnella, E., & Fioretto, A. (2012). Heavy metal content in sediments along the Calore river: relationships with physical–chemical characteristics. *Journal of Environmental Management*, 95, S9-S14.
- Bathi, J. R., Pitt, R. E., & Clark, S. E. (2012). Polycyclic Aromatic Hydrocarbons in Urban Stream Sediments. *Advances in Civil Engineering*, 2012.
- Bian, B., & Zhu, W. (2009). Particle size distribution and pollutants in road-deposited sediments in different areas of Zhenjiang, China. *Environmental geochemistry and health*, 31(4), 511-520.
- Brown, J. N., & Peake, B. M. (2006). Sources of heavy metals and polycyclic aromatic hydrocarbons in urban stormwater runoff. *Science of The Total Environment*, 359(1), 145-155.
- Dempsey, B. A., Tai, Y.-L., & Harrison, S. (1993). Mobilization and removal of contaminants associated with urban dust and dirt. *Water Science & Technology*, 28(3-5), 225-230.
- Duncan, H. (1999). *Urban stormwater quality: a statistical overview*: CRC for Catchment Hydrology.
- Evans, K., Gill, R., & Robotham, P. (1990). The PAH and organic content of sediment particle size fractions. *Water, Air, and Soil Pollution*, 51(1-2), 13-31.
- German, J., & Svensson, G. (2002). Metal content and particle size distribution of street sediments and street sweeping waste (Vol. 45): IWA Publishing, Alliance House 12 Caxton Street London SW 1 H 0 QS UK.
- Gunawardana, C., Egodawatta, P., & Goonetilleke, A. (2014). Role of particle size and composition in metal adsorption by solids deposited on urban road surfaces. *Environmental pollution*, 184, 44-53.
- Gurnell, A., Lee, M., & Souch, C. (2007). Urban rivers: hydrology, geomorphology, ecology and opportunities for change. *Geography Compass*, 1(5), 1118-1137.
- Hatt, B. E., Fletcher, T. D., Walsh, C. J., & Taylor, S. L. (2004). The influence of urban density and drainage infrastructure on the concentrations and loads of pollutants in small streams. *Environmental management*, 34(1), 112-124.
- Huang, Y.-J., Lee, C.-L., & Fang, M.-D. (2011). Distribution and source differentiation of PAHs and PCBs among size and density fractions in contaminated harbor sediment particles and their implications in toxicological assessment. *Marine Pollution Bulletin*, 62(2), 432-439.
- Kayhanian, M., McKenzie, E., Leatherbarrow, J., & Young, T. (2012). Characteristics of road sediment fractionated particles captured from paved surfaces, surface run-off and detention basins. *Science of The Total Environment*, 439, 172-186.
- Kondolf, G. M. (1997). PROFILE: hungry water: effects of dams and gravel mining on river channels. *Environmental management*, 21(4), 533-551.
- Lau, S.-L., & Stenstrom, M. K. (2005). Metals and PAHs adsorbed to street particles. *Water Research*, 39(17), 4083-4092.
- Muthukaruppan, M., Chiew, F., & Wong, T. (2002). Size distribution and partitioning of urban pollutants. *Global Solutions for Urban Drainage*, 1-12.
- Owens, P. N., Caley, K. A., Campbell, S., Koiter, A. J., Droppo, I. G., & Taylor, K. G. (2011). Total and size-fractionated mass of road-deposited sediment in the city of Prince George, British Columbia, Canada: implications for air and water quality in an urban environment. *Journal of Soils and Sediments*, 11(6), 1040-1051.
- Pizzuto, J., Hession, W., & McBride, M. (2000). Comparing gravel-bed rivers in paired urban and rural catchments of southeastern Pennsylvania. *Geology*, 28(1), 79-82.
- Pomeroy, C. A., Postel, N. A., O'Neill, P. A., & Roesner, L. A. (2008). Development of storm-water management design criteria to maintain geomorphic stability in Kansas City metropolitan area streams. *Journal of irrigation and drainage engineering*, 134(5), 562-566.
- Rhoads, B. L., & Cahill, R. A. (1999). Geomorphological assessment of sediment contamination in an urban stream system. *Applied Geochemistry*, 14(4), 459-483.
- Sartor, J. D., Boyd, G. B., & Agardy, F. J. (1974). Water Pollution Aspects of Street Surface Contaminants. *Journal (Water Pollution Control Federation)*, 46(3), 458-467. doi: 10.2307/25038149

- Schumm, S. A. (1977). *The fluvial system* (Vol. 338): Wiley New York.
- Selbig, W. R., Bannerman, R., & Corsi, S. R. (2013). From streets to streams: Assessing the toxicity potential of urban sediment by particle size. *Science of The Total Environment*, 444(0), 381-391. doi: <http://dx.doi.org/10.1016/j.scitotenv.2012.11.094>
- Stone, M., & Marsalek, J. (1996). Trace metal composition and speciation in street sediment: Sault Ste. Marie, Canada. *Water, Air, and Soil Pollution*, 87(1-4), 149-169.
- Sutherland, R. A., Tack, F. M., & Ziegler, A. D. (2012). Road-deposited sediments in an urban environment: A first look at sequentially extracted element loads in grain size fractions. *Journal of hazardous materials*, 225, 54-62.
- Taylor, K. G., Owens, P. N., Batallac, R. J., & Garciad, C. (2007). Sediment and contaminant sources and transfers in river basins. *Sediment Management at the River Basin Scale*, 4, 83.
- Ünlü, S., & Alpar, B. (2006). Distribution and sources of hydrocarbons in surface sediments of Gemlik Bay (Marmara Sea, Turkey). *Chemosphere*, 64(5), 764-777.
- Vietz, G. J., Sammonds, M. J., Walsh, C. J., Fletcher, T. D., Rutherford, I. D., & Stewardson, M. J. (2014). Ecologically relevant geomorphic attributes of streams are impaired by even low levels of watershed effective imperviousness. *Geomorphology*.
- Viklander, M. (1998). Particle size distribution and metal content in street sediments. *Journal of Environmental Engineering*, 124(8), 761-766.
- Walsh, C. J., Roy, A. H., Feminella, J. W., Cottingham, P. D., Groffman, P. M., & Morgan II, R. P. (2005). The urban stream syndrome: current knowledge and the search for a cure. *Journal Information*, 24(3).
- Wang, X.-C., Zhang, Y.-X., & Chen, R. F. (2001). Distribution and partitioning of polycyclic aromatic hydrocarbons (PAHs) in different size fractions in sediments from Boston Harbor, United States. *Marine Pollution Bulletin*, 42(11), 1139-1149.
- Wolman, M. G. (1967). A cycle of sedimentation and erosion in urban river channels. *Geografiska Annaler. Series A. Physical Geography*, 385-395.