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Critical Thresholds for Sediment Mobility in an Urban Stream

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CRITICAL THRESHOLDS FOR SEDIMENT MOBILITY IN AN URBAN STREAM

by

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Under the Direction of Jordan Clayton

ABSTRACT

Bed load transport measurements were made in a small urban stream in Decatur, GA, from which thresholds for motion were calculated using methodologies from the published literature. These methodologies are discussed in terms of their limitations and assumptions. Mobility frequencies were calculated for single grains of each grain size fraction to illustrate the transition from size selective transport to equal mobility. In general, urban streams behave differently than many gravel rivers in non-urban settings because of differences in the availability and character of sediment sources and altered flow hydrographs. This comparison allows for discussion about the way sediment is transported in urban streams versus typical gravel-bed, armored channels.

INDEX WORDS: Sediment transport, Fluvial geomorphology, Shields stress

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Introduction

The movement of sediments across a landscape will determine how the landscape evolves over time. This can have huge implications in many fields of study across a range of temporal and spatial scales. Landscape evolution on a large scale can dictate where populations congregate, while sediment mobility can determine habitat viability for many species. The quantification of landscape evolution via sediment transport is an important, and long-standing goal of earth science.

Fluvial environments are a major, if not the primary, contributor to the evolution of a landscape. Rivers and streams mobilize sediment as the flow increases and overcomes a threshold in the balance of forces keeping sediment grains on the bed and the shear force placed on the grain by the flow of water. Determining the ratio of these forces for a variety of field conditions and configurations is the goal of many studies (see Buffington and Montgomery, 1997 for an exhaustive list of incipient motion studies). Estimates for the critical thresholds for mobility vary greatly depending upon the study environment and methodology which created the equation.

The variation in critical thresholds for sediment entrainment in gravel rivers comes from the different methodologies employed and variation in stream environment. There is a relatively large range in reported threshold values that could arrive from differing experimental or natural conditions (such as bed textural effects) and definitions for sediment entrainment (such as particle rotation, full discussion follows in subsequent sections) (Tison 1953; Miller et al. 1977; Carson and Griffiths 1985; Lavvelle and Mofield 1987; Wilcock 1988; 1992; Buffington and Montgomery, 1997). Thus, estimates of critical shear stress are difficult to interpret if the goal is to explore and understand trends in sediment transport. Given the common dependency of entrainment threshold estimates on environmental and observational characteristics, it is useful to explore alternative ways of assessing sediment transport thresholds that are objective and transferable to locations outside the study realm. A new way to visualize and quantify sediment entrainment and transport must overcome the problems with threshold estimates that cause the greatest degree of uncertainty. This research effort will explore new ways to discuss entrainment and transport in terms of mobility frequency, which can be thought of as a recurrence interval for the mobilization of specific grain size fractions. A review of historical efforts to quantify sediment motion will set the context for this study and provide a basis for understanding the significance of this study.

This study explores sediment mobility in an urban stream and seeks to reveal some insight into urban stream transport processes using the mobility frequency framework. Understanding the patterns of transport will lead to understanding of the stream evolution that occurs with and urbanizing watershed.

Urbanization and Sediment Mobility

As a watershed undergoes urbanization several things occur concurrently which affect the sediment transport mechanics in streams. The initial phase of urban development is characterized by two to ten fold increases in sediment mobilization (usually from disruptions in the watershed) which results in deposition in the channels, This is followed by a phase which sees a reduction in sediment yield concurrent with increased runoff which results in increased erosion and enlarged channels (Chin 2006).

Stream morphology changes with urbanization in response to concurrent changes in sediment yield and hydrologic conditions (Paul and Meyer 2001). The influence of these two factors vary independently in both time and intensity, while they concurrently affect morphology- as such there are a myriad of stream morphologies (Mollard 1973; Schumm 1985; Church 2006).

Hydrography

The type of flow regime present in streams will affect how often and for how long sediments become entrained. On one end of the spectrum are perennial mountain streams which experience seasonal flooding, and at the opposite end of the spectrum there are ephemeral streams in desert environments which experience very flashy hydrographs only after storm events (Cao et al. 2010). Urban streams exist somewhere in the middle of these two extremes, evolving towards the flashier ephemeral stream end of the spectrum as urbanization covers more of the watershed. The majority of urban streams are perennial, but they tend to experience events with a flashy hydrograph, similar to ephemeral streams (Chin, 2006). It is during these flashy events that most of the sediment transport occurs in urban streams. It is therefore important to understand how the and if the hydrograph of a stream will affects sediment transport when using sediment transport models.

The mechanics of sediment transport require that a certain critical shear stress be exceeded by the flow of water for each grain size present, in order for that sediment to become mobilized (Shields 1936). The rate at which these critical stresses are exceeded for progressively larger grain size fractions is central to the discussion about how hydrograph characteristics might change sediment transport and initial motion. A seasonally flooding mountain stream will exceed the critical values for certain grain sizes for long periods of time. The rate of increase and consequent decrease in shear stress associated with the rising and falling limbs of the hydrograph is slow or subdued (Chin 2006). Therefore theoretically, a relatively larger portion of a particular grain size can be mobilized before the shear stress increases enough so that the next larger grain size becomes entrained. This pattern may be reduced by the effect of armoring, but here it is important to consider the transport capacity of different shape hydrographs independently.

Urban streams experience flashy hydrographs which translates into a sediment transport system in which the rate of increase in shear stress is relatively fast. This means that as one grain becomes entrained the next largest grain size will become mobilized shortly thereafter. So, if the influence of the transported material and stream bed surface is held constant, the shape of the hydrograph can dictate extremely different transport environments. Urban streams can be typified by having a flashy hydrology, as the flashiness of the hydrograph is largely dependent on the amount of impervious surface cover present in the watershed. There are multiple other factors that can affect urban streams, but of principle importance is that when watersheds become urbanized the hydrographs of the affected streams or rivers will become flashier (Leopold 1968; Chin 2006). It is therefore important to explore how a flashy, urban hydrograph will affect sediment transport. This research effort presents data from only one urban stream (for a basin with a moderate level of imperviousness), and therefore is not able to assess how varying degrees of urbanization affect sediment transport. Instead the research presented here provides a novel method for visualizing and exploring sediment transport that will allow future research efforts to examine the rate and character of sediment mobilization in similar environments.

Characteristics of Bed load source material

As watersheds undergo urbanization, not only does the hydrograph change, but sediment source material also changes. The sediment for most streams originates both in the watershed and from in-stream sources. As a watershed becomes urbanized, sediment sources progress in size, type and there is a shift in the mean and standard deviation of the size fractions present. (Wolman 1967; Trimble 1997; Paul and Meyer 2001; Chin 2006). As the land is initially disturbed in processes associated with urbanization, a proportionally large amount of fine sediments are introduced (Chin 2006). Jackson and Beschta (1984), Ikeda and Iseya (1988), and Curran (2007) found that an increase in fine sediments in a flume setting caused an increase in transport capacity. While this tendency may appear counterintuitive, it may be explained in that increased amounts of fine sand in the source material caused both bed material and slope to change so that equilibrium transport was maintained (Curran 2007). The bed surface before the addition of fines (from urbanization) consisted of some sand and pebble clusters which in effect caused a large portion of the total shear stress to come from form drag with the total shear stress being relatively low (Curran 2007). As more sand was introduced the bed surface became smoother and the slope lessened. The reduction in the slope and the associated lower bed shear stress coupled with increased rates of sand transport yields lower reference shear stresses (Curran 2007). Thus, the texture of the stream bed surface can affect changes in critical shear stress, which occur concurrently with changes in the hydrograph. This creates a feed back loop where the critical threshold of large amounts of sand has been lowered, and flow events are able to mobilize that sand more quickly because of the increase in slope of the rising limb (i.e. flashiness) of the hydrograph. This provides a mechanism for rapidly moving sediments (and the effects of urbanization) downstream. When the sediment source is cut off after the initial phases of urban development, the lowered critical shear stresses and flashiness continue to exist, which causes rapid erosion and geomorphic degradation (Paul and Meyer, 2001).

Thresholds for Motion

For decades, there have been attempts to estimate critical thresholds of incipient motion for bed load sediments in rivers, with notable early contributions from Gilbert (1914), Nikuradse (1933) and Shields (1936). Buffington and Montgomery (1997) document four general methodologies which have been employed to approximate thresholds for incipient motion. Each has an environment for which the particular method is best suited (Buffington and Montgomery, 1997). These methods include: [1] The extrapolation of measured transport rates to negligible values (Shields 1936, Day 1980, Parker and Klingeman 1982); [2] visual observations where a researcher will document the depth (which will be used to calculate a shear stress) at which grains are seen to mobilize, in either natural settings or flumes (Gilbert 1914, Kramer 1935, Yalin and Karahan 1979); [3] the development of theoretical thresholds rooted in physics, where the force of the water on the grain must exceed the force needed to rotate the grain enough to move the grain from its initial position, in either uniform or mixed-bed rivers (White

1940, Wiberg and Smith 1987, Jiang and Haff 1993); [4] and finally development of relationships based on the largest mobile grains (Andrews 1983, Carling 1983, Komar 1987). As discussed in subsequent paragraphs, the shortcomings of each method vary from bias toward larger grains because of the sampling procedure to the inability to gather the necessary data. It is important to consider the suitability of each method for a particular field setting and research goal.

First, the method of extrapolating measured transport rates to negligible values requires several transport samples to be taken before relationships can be established. The deficiency with the first methodology is that the resulting relationship is highly dependent upon what is considered a negligible transport rate (Wilcock 1988; Buffington and Montgomery 1997). The volume and time and space about which transport would be considered is crucial. A given volume X in transport can be considered initial motion, but it is crucial to acknowledge that the same volume may not necessarily represent initial transport if the time and space values of the observation are different. For example, consider the difference if volume X is transported over a large area in a long time period versus a short time and small space. The method of deriving a threshold for motion based on visual observation relies on the subjective eye of an individual over a varying, and often unstated, area and time in order to document when initial mobility occurs (Buffington and Montgomery 1997). The time and space about which initial motion is considered is therefore crucial when defining initial motion. By not understanding the spatial and temporal constraints of a threshold methodology, one reduces the accuracy of the transport estimates.

The third type of methodology described is the development of theoretical thresholds based upon the physics of grain pivot angles, bed slope, and friction and lift forces (Miller and Byrne 1966; Coleman 1967; Wiberg and Smith 1987; Buffington et al. 1992). It is very likely that this type of approach would be able to very precisely determine critical threshold values, if the proper data are available. The type of data this method requires varies greatly- even within river reaches- and is therefore difficult to assess. For example, assumptions must be made for values of pivot angles, a parameter upon which critical threshold value is highly dependent (Wiberg and Smith 1987). The pivot angle of a grain is the amount a grain must rotate upon a horizontal axis in order to move out of the place where it rests. This angle is determined by the diameter of the grain itself and the diameter of the surrounding grains. For example a larger grain surrounded by much smaller grains would have a small pivot angle, while a small grain surrounded by large grains would have high pivot angles. Obviously, estimating pivot angles for a heterogeneous bed can be quite difficult. Theoretically determined thresholds for motion are limited by the difficulty in supplying the research effort with sufficiently accurate field data.

The final methodology relies on the transport rates of the largest mobile grains to create a relationship between grain size and incipient motion thresholds. By assuming the largest grains captured during a sampling event are at or near their threshold for motion, one can define a relationship between a critical shear stress and grain size. This method is highly sensitive to sampling methodology and coarse grain availability (Wilcock 1992; Wathen et al. 1995; Buffington and Montgomery 1997). While this method assumes that coarser grains are preferentially transported by higher flow strengths (selective transport)

(Wilcock 1988, 1992; Buffington and Montgomery 1997), it does not necessarily preclude a transport relation with a very steep slope (i.e. a transport close approaching equal mobility). This contradiction shows that more research is needed to understand how this methodology is affected by the extremes of transport relationships.

Selective transport occurs where the flow disproportionately transports certain size fractions; typically, the competent grain size monotonically increases with flow rate (Clayton, 2010). The opposite condition would be described as equal or full mobility, where transport occurs for all size fractions equally proportionate to their respective abundance on the bed (Parker et al, 1982; Wilcock and McArdell, 1993). As the discharge of a stream increases it can transition from size selective transport to equal mobility (Ashworth and Ferguson, 1989; Clayton and Pitlick, 2007).

Each method produces equations which will be more suited to one environment than another. It is therefore important to explore how each type of initial motion calculation reflects the continuum of transport environments, ranging from equal mobility to size selective transport. The ongoing exploration of each of the different methods in a range of environments has required, and will continue to require, copious amounts of data and time. This study, instead, looks at the motion of sediments in a new way, where the initiation of movement is considered in the terms of a recurrence interval. A recurrence interval depicts the time lag between an event occurring and re-occurring. Recurrence intervals are more familiarly used for large scale events such as floods and earthquakes. This study describes the movement of individual grains in a similar fashion.

This Study

Location

Peavine Creek is a small, urbanized stream in Decatur, Georgia, located in the Chattahoochee River watershed, in the Atlanta metropolitan region.

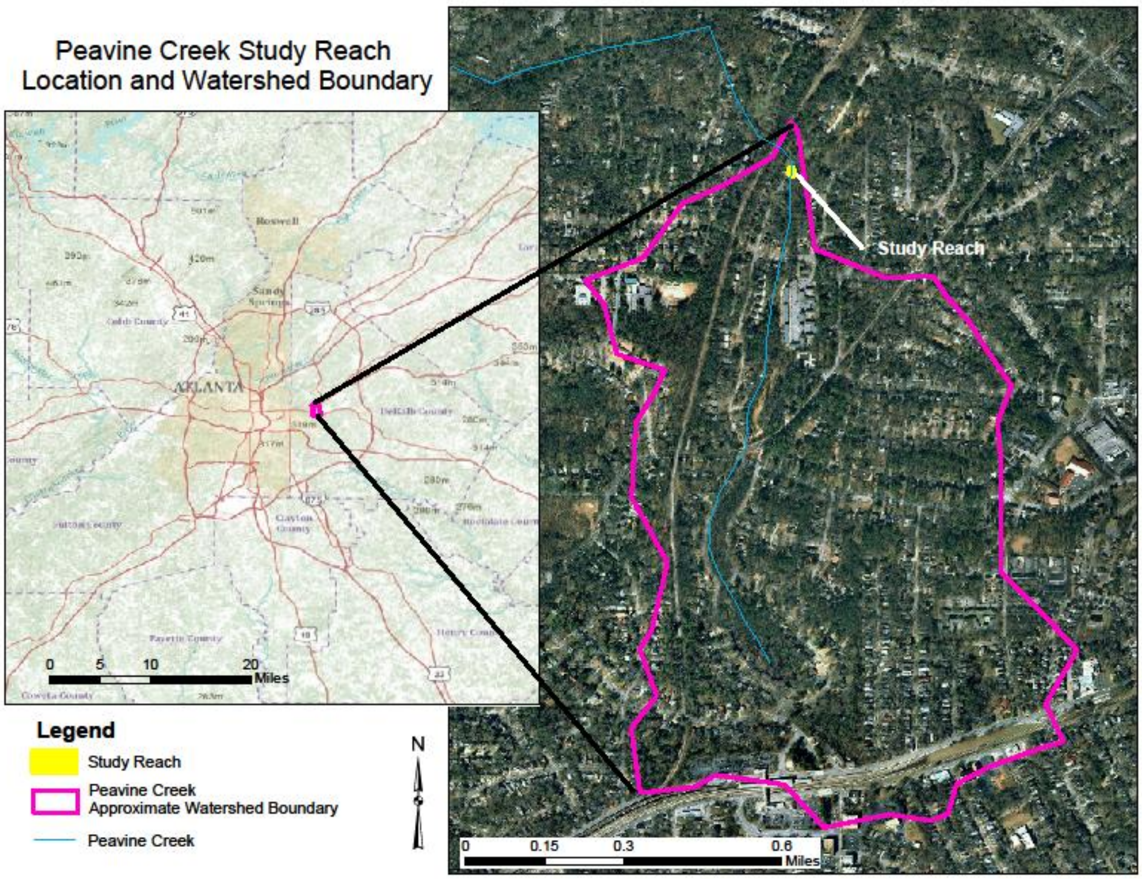

Figure 1: Study reach location and watershed boundary.

Peavine Creek shown in Figure 1 was selected for this study because: 1) it exhibits a typical urban stream morphology with low width to depth ratios and a flashy hydrograph (Paul and Meyer 2001), 2) it is small enough that bed load sampling 3) flow measurement could safely be undertaken during competent events by one person, and 4) it was close enough to be accessed quickly during storm events.

Previous unpublished research documented many aspects of Peavine Creek. A pressure transducer placed in the stream shows that stream exhibits a typical urban hydrograph, as seen in figure (2).

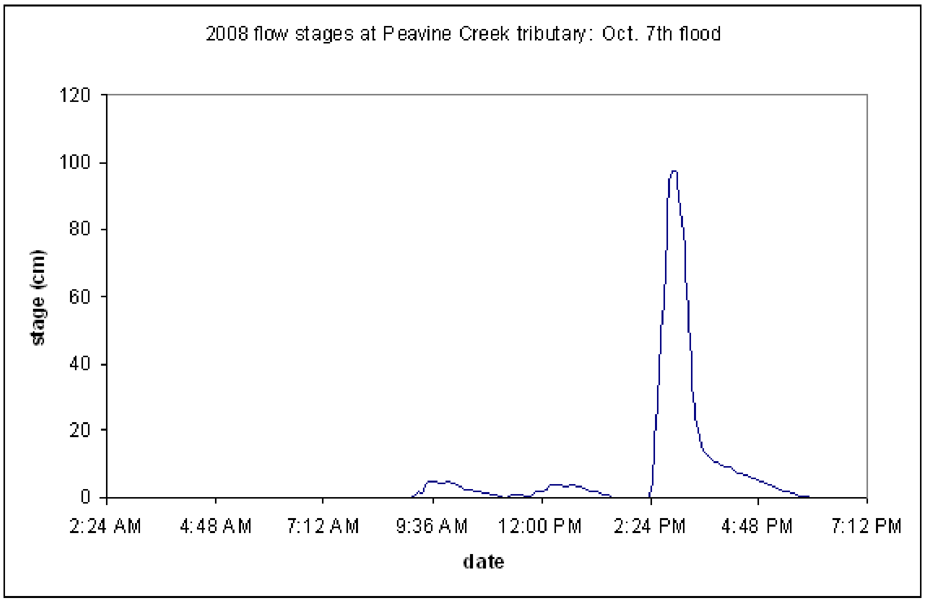

Figure 2. Hydrograph of a typical event from October 7th 2008

There is low vegetation density on the banks, mostly grasses and shrubs. The entire watershed is covered with a loamy soil comprised of almost equal parts of sand, silt and clay (USDA 2010). The entire area is underlain by mica schist and gneissic rock (USDA 2010). The watershed has undergone urbanization and reached stability, meaning that currently there is very little to no active construction in the watershed (USDA 2010). This is important because as land use changes are occurring, the processes involved can introduce sediments into the stream (Trimble 1997).

Methodology

Topographic surveying

The current morphology of the stream reach was measured using a Nikon total station and prism rod. These data enabled the calculation of bankfull width which is the width of the top of the maximum flow before the stream banks are overtopped, and the water spreads out over the floodplain. The streambed width was also determined; this is the width of the stream bed between the sharp breaks in slope leading up to the stream banks. The water surface slope down the reach was measured in several intervals down stream with a hand level and stadia rod.

Sampling

It is important to consider bed grain size when selecting an appropriate bed load sampling methodology. A Helley-Smith sampler (figure 3)with an orifice of 0.076 m^2, similar to the one used in this study, has an effectiveness of almost 100% for particles from 0.5mm to 32mm (table 1) (Hubbell 1987). The flows that were sampled did not reach sufficient depth to mobilize the coarsest grain sizes (21.6 mm) present on the bed, therefore this sampler can be assumed to accurately sample the bed load in Peavine Creek. The particle size distribution of surficial sediments was obtained by using a slightly modified version of the methodology described by Wolman (1954). This method calls for systematic random sampling of bed grains, at intervals roughly equivalent to one footstep along transects that are perpendicular to the direction of flow. After each step is taken, a grain at the tip of the toe was sampled blindly and sizes were determined using a metal template with openings at half-phi intervals (gravelometer). This process was repeated until 100 grains have been sampled. Six samples were taken in the study reach, each approximately equally spaced from one another, to get an average of the entire study reach. The grain size distributions in the stream (presented in the Results section, Figure 7) reinforce that the particle sizes present in the channel are within the appropriate range for use of the Helley-Smith sampler.

UNIFIED SOILS CLASSIFICATION		ASTM MESH	MM SIZE	PHI SIZE	WENTWORTH CLASSIFICATION	
			4096.00	-12.0		
			1024.00	-10.0	BOULDER	
			256.00	-8.0		
COBBLE			128.00	-7.0		G
			107.64	-6.75	COBBLE	
			90.51	-6.5		
			76.00	-6.25		
			64.00	-6.0		R
			58.82	-5.75		
COARSE GRAVEL			45.26	-5.5		
			38.00	-5.25		
			32.00	-5.0		A
			26.91	-4.75		
			22.63	-4.5		
			19.00	-4.25	PEBBLE	
			16.00	-4.0		V
			13.45	-3.75		
FINE GRAVEL			11.31	-3.5		
			9.51	-3.25		
		2.5	8.00	-3.0		E
		3	6.73	-2.75		
		3.5	5.66	-2.5		
		4	4.76	-2.25		
		5	4.00	-2.0		L
	Coarse	6	3.36	-1.75		
		7	2.85	-1.5	GRANULE	
		8	2.35	-1.25		
S		10	2.00	-1.0		
		12	1.68	-0.75	Very Coarse	
		14	1.41	-0.5		
		16	1.19	-0.25		
A	Medium	18	1.00	0.0		S
		20	0.84	0.25		
		25	0.71	0.5	Coarse	
		30	0.59	0.75		
N		35	0.50	1.0		A
		40	0.42	1.25		
		45	0.35	1.5	Medium	
		50	0.30	1.75		
D		60	0.25	2.0		N
		70	0.210	2.25		
	Fine	80	0.177	2.5	Fine	
		100	0.149	2.75		
		120	0.125	3.0		D
		140	0.105	3.25	Very Fine	
		170	0.088	3.5		
		200	0.074	3.75		
		230	0.0625	4.0		
		270	0.053	4.25		
		325	0.044	4.5		
SILT		400	0.037	4.75	SILT	
			0.031	5.0		M
			0.0156	6.0		
			0.0078	7.0		
			0.0039	8.0		
			0.0020	9.0		U
			0.00098	10.0	CLAY	
CLAY			0.00049	11.0		
			0.00024	12.0		
			0.00012	13.0	COLLOID	D
			0.00006	14.0		

Table 1: Grain Size Classifications

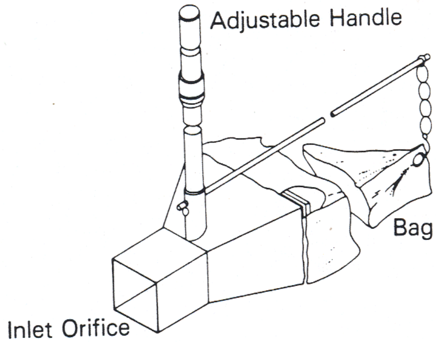

Figure 3: Helley-Smith sediment sampler.

Nine bed load samples were obtained in the thalweg of Peavine Creek at stages from 0.16 to 0.36 meters (compared with 1.1 to 1.2m bankfull stage) during four moderate flow events from the fall of 2009 to spring 2010. The sample duration was ten minutes for each sample. The depth was monitored for the duration of the sample and if any change in depth was observed the average of the beginning and ending depth was used as the depth for the sample. In order to accurately characterize the stage during sampling and to minimize the influence of unsteady flows, if the depth was seen to increase more than 5 cm over the 10 minute time span, the sample duration was reduced; this affected two of the samples and resulted in a sample time of 5 minutes. Samples were taken on both the falling and rising ends of individual storm hydrographs. Individual bed load samples were combined to assess net bed load transport and entrainment thresholds, as this was the focus of this study.

The samples were taken to the laboratory for particle size analysis. Each of the samples was oven-dried for up to 48 hours. Large leaf litter and other large organic materials were removed prior to weighing and sieving the samples. Each of the samples was placed into a standard Ro-tap sieve shaker which separated the samples into half phi size fractions from coarse gravel to fine sand; silt and finer particles were combined into a single size class. Size fractions were weighed to determine the particle size distributions for individual samples as well as the cumulative weights per size fraction.

Transformation into Common Variables.

Once the dry weights were obtained from each sample they were transformed into transport rates by considering several factors from the sampling event. The weight was divided by a density of 2.65 grams per cubic centimeter to obtain a volume (Dietrich and Smith, 1984). This volume was divided by the sampler width and sample time, which gives the bed load transport in volume per time per unit width. Given the rectangular channel morphology, this rate was assumed to be constant across the width of the bottom of the channel.

Transport relations

The Einstein (1950) bed load transport parameter is a dimensionless value that is derived from the transport volume obtained over a given sampling interval and is normalized by the grain size. The function of the Einstein equation is to non-dimensionalize the transport rate to allow for comparisons between studies. The transport parameter, q*, is determined as follows:

$$q^* = q_b[(g(s-1)D^3]^{-1/2} \qquad (1)$$

where q_b is the volumetric transport rate in cubic meters per unit width per second, g is the acceleration due to gravity in meters per second, s is the specific gravity of the sediment in grams per cubic meter, and D is the bed load median grain size in meters.

Defining the flow characteristics in a similar non-dimensionalized form is necessary so that transport relations can be compared to other sites and studies. As such, the Shields number, a dimensionless shear stress value, was obtained for each flow event, and is calculated by non-dimensionalizing the shear stress (τ).

$$\tau = \rho ghs \qquad (2)$$

where ρ is the density of water, h is the depth of the water, and s is the water surface slope through the reach. For hydrostatic, fairly uniform channels, the Shields stress, τ^*, can be determined by assuming constant values for density and gravity, and dividing the flow depth and water surface slope by the median surface grain size using the following equation:

$$\tau^* = \tau\,[(\rho_s - \rho)gD]^{-1} \qquad (3)$$

where D is the median surface grain size in meters, ρ is the density of water, and ρ_s is the density of sediment (Shields 1936).

Comparing Thresholds

The Shields curve has become a standard for estimating the critical shear stress required for particle entrainment. Barry et al. (2004) assumed a constant Shields threshold value of 0.047, while Bagnold (1980) assumed a critical value of 0.04. A commonly cited threshold value of Shields stress is 0.03. The 0.03 value was documented by Buffington and Montgomery (1997) as being the threshold for incipient motion based on visual assessments of coarse grained channels.

The discussion of initial motion has increasingly considered the effects of sheltering and hiding. Relatively small particles are blocked from the full shear stress of a stream when hidden behind a larger particle. In this instance the apparent critical threshold for the small grain is the same as that of the larger grain or the smaller grain appears has a higher shear stress than if it were mobilized on a homogenous bed. Conversely, the larger surface area exposed on a larger grain may result in a lower critical shear stress than if that same grain size was mobilized in a homogenous bed (Powell 1998; Clayton 2010). The role of relative grain size can therefore heavily influence transport.

Assessment of particle sheltering requires evaluating entrainment based on ratios of individual grain sizes relative to the distribution of grain sizes available on the bed. These ratios take into account the relative homogeneity of a bed and the extent to which larger grains effect the mobility of the smaller grains, and vice versa. In addition to accounting for the sheltering of grains, these equations account for the greater surface area protrusion of larger grains. Consequently, these estimates may not necessarily be applicable for urban streams that either lack surficial armor or have a smaller range of bed particle sizes.

Parker et al (1982) was able to establish a relationship between transport rates of individual size fractions and threshold stresses. He was able to obtain the relationship,

$$\tau^*_{ci} = 0.088(d_i/d_{50})^{-0.98} \qquad (4)$$

where d_i is the diameter of any grain size, d_{50} is the mean diameter of the subsurface material.

Ashworth and Ferguson (1989) provide a methodology which was adapted from Parker et al (1982). Their method provides virtually the same analysis and outcome as Parker's (1982), but Ashworth and Ferguson (1989) have streamlined the process and chose to establish a relationship based upon the surficial grains instead of the subsurface material. Ashworth and Ferguson (1989) found

$$\tau^*_{ci} = 0.054(d_i/d_{50})^{-0.67} \tag{5}$$

where in this equation d_{50} is the mean diameter of the bed surface material.

The critical Shields stress, τ^*, was evaluated by using several published equations. The equations used represent the spectrum of initial motion relationships expressed in the Buffington and Montgomery (1997) study. These relationships (Table 2) include several of the methodologies discussed previously.

Author	Coefficient in transport relationship	Exponent in transport relationship	Methodology
Parker and Klingeman (1982)	0.088	-0.98	Reference Transport Rate (flume)
Ashworth and Ferguson (1989)	0.072	-0.65	Largest Mobile Grain
Hammond et al. (1984)	0.025	-0.6	Largest Mobile Grain
Ferguson et al. (1989)	0.047	-0.88	Largest Mobile Grain
Komar and Carling (1991)	0.039	-0.82	Largest Mobile Grain
Lepp et al. (1993)	0.149	-0.4	Largest Mobile Grain
Wilcock (1987)	0.3	-1	Reference Transport Rate
Petit (1994)	0.058	-0.66	Visual Observation

Table 2. Components of some critical shear stress equations, and methodology type.

Mobility Frequency

Another possible way to estimate sediment transport relations, and a novel aspect of this research, is to consider the mobility frequency of transported particles. A mobility frequency describes how often a grain is mobilized, or how often a grain moves through a plane perpendicular to stream flow. To determine the mobility frequency the time it would take to move one grain of each size fraction was calculated by dividing the transport rates of each of the samples taken in Peavine Creek by the volume of one grain of each size fraction. Using the Equation 6 (below), mobility frequency values were calculated for all grain sizes for each bed load sample.

The development of the mobility frequency relation is as follows. First, it is necessary to simplify the grain shape so that an representative particle volume may be calculated for each grain size fraction. This study assumed that representative particle shapes may be estimated by determining the volume for a sphere and cube of a given radius or axis length, and taking the mean of these values to account for complexities in the shape of natural particles. The following equation gives the average of the volume of a sphere and a cube:

$$V_{prob} = ((3/4\pi R^3)+(D^3))\ /2 \qquad (6)$$

where V_{prob} is the probable volume of one grain, R is the radius of the grain and D is the diameter of the grain. This equation may be used for each grain size fraction present in the samples. The probable volume of each given grain size fraction can be divided by the unit width and time variables to obtain a transport rate as follows:

$$q_b = V_{prob}/width/time \qquad (7)$$

This transport rate represents the movement of one grain per the unit width and time and has the same dimensions as the dimensional version of the Einstein parameter, q*. Since the goal is to obtain a mobility frequency, the measured transport rate of individual grain size fractions obtained from bed load measurements are used to solve for time. The q_b of the transported material is set equal to the minimum volume of transport possible (i.e. one grain for each size fraction) which allows one to solve for the recurrence interval time for that size fraction.

$$t_r = qb(V_{prob}/W_{bed})^{-1} \qquad (8)$$

where qb_{sample} is shown above, W_{bed} is the stream bed width and t_r is the recurrence interval. The variable W_{bed} allows the equation to account for the mobility frequency for the entire stream bed, it could be set equal to the width (from equation 7) of the sampler bottom, or any other relevant width.

The bed load data gave transport rates in volumes per time per unit width, by dividing the transport rate by the probable volume of a single grain one obtains a time, which is in effect the mobility frequency. This time or mobility frequency can be thought of in terms of a return interval, quite literally, since it describes how often a grain of a given size should move.

This type of evaluation will show whether or not smaller size fractions can reach equal mobility defined in mobility frequency terms (explained below), even if coarser size fractions continue to suggest selective transport conditions. The conditions of equal mobility and size selective transport exist on opposing ends of a continuum of transport patterns. On one end exists equal mobility a pattern where each size fractions is transported equally, or proportionally, relative to its abundance on the bed (Wilcock and McArdell, 1993). The opposing condition, size-selective transport, assumes that each consecutively-larger grain size is transported with decreasing frequency because of the need to overcome increasingly large particle mass (Ashworth and Ferguson, 1989; Church and Hassan, 2002). As noted previously, streams may transition from selective transport to equal mobility as the stage increases. The changes in the shape of the hydrograph associated with urban streams, as discussed earlier, makes it valuable to understand the transport dynamics of an urban stream as it evolves and undergoes that transformation from selective transport to equal mobility.

Results

Location Results

The survey data gathered in the previous study of Peavine Creek were used to create the following 3-D representation of the study reach in Peavine creek. In this representation the water would be flowing from bottom to top. Also included for reference are pictures of the study reach during low flow and approximately ¾ bankfull condtions (figures 4 and 5)

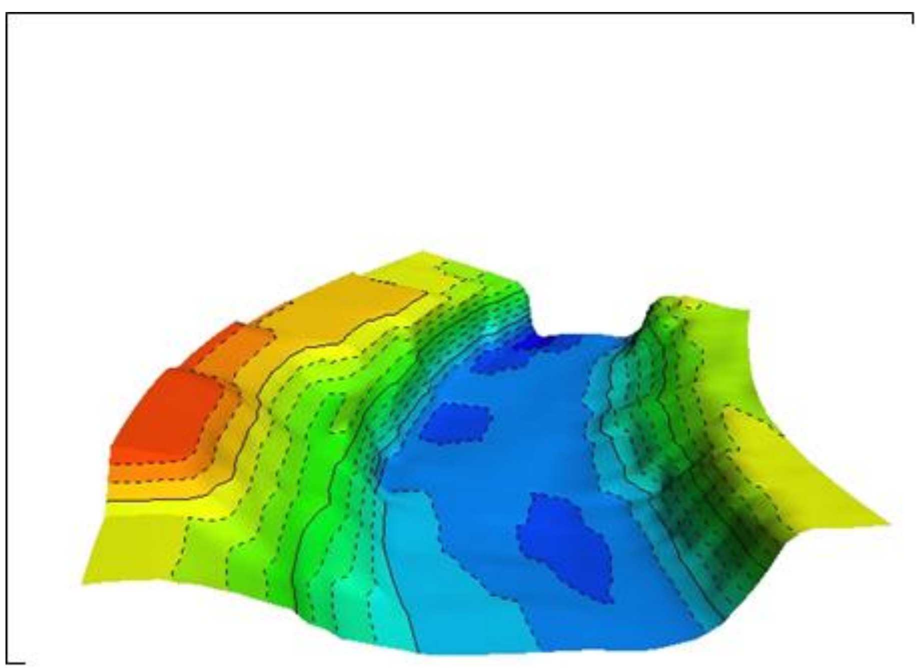

Figure 4. Stream Morphology. Water flows from bottom to top. Index contour interval is 1m.

Figures 5: Pictures of the study reach during low flow and ~3/4 bankfull.

The same survey data was also used to find the average reach slope of 0.002 and the average stream bed width of 2.2 meters. The stream bed width is the width across the bed, where the bed is constrained on both sides by sharp breaks in slope as the stream bed gives way to the channel walls. Both the slope and bed width parameters are utilized in subsequent calculations.

A previous study of Peavine creek provided the grain size distribution and corresponding D_{50} of the surficial stream bed grains using the Wolman (1954) method, see Table (3).

Location in channel	**Bankfull Stage (m)**	**D50 (mm)**	**Slope**
Upstream	1.2	10.67	0.002
Mid-reach	1.1	14.72	0.002
Downstream	1.2	20.56	0.002
Reach Average	1.1	15.45	0.002

Table 3. Stream Characteristics

Transport Results

The preliminary bed load transport results can be seen in Table 3. This table describes the conditions during each sample and the total transport captured. This also includes the transport rates used for calculating the mobility frequency.

Sample #	Stage (m)	Bed Width (m)	D50 (mm)	q_b g/sec/width	Total Sample Volume (m^3)	Shear Stress (Newtons)	τ^*	Largest Grain Moved (mm)
1	0.17	2.3	1.6	0.50	0.01	0.324	0.014	9.5
1.2	0.24	2.3	2.0	0.92	0.02	0.473	0.021	8
2	0.25	2.1	2.2	1.68	0.03	0.498	0.022	19
2.2	0.24	2.1	1.7	1.14	0.02	0.473	0.021	8
4	0.29	2.3	2.4	1.07	0.02	0.573	0.025	13.5
5	0.37	2.1	2.6	9.40	0.16	0.722	0.032	36.5
6	0.36	2.4	2.1	6.42	0.11	0.697	0.031	19
6.2	0.42	2.4	6.8	6.76	0.06	0.821	0.036	16
7	0.30	2.3	5.6	5.35	0.09	0.597	0.026	36.5

Table 4. Bed load sample conditions and results. Here τ^* is calculated using the Shields equation (2).

These numbers describe the sampling location. If the number is followed by .2 then, that sample was the second sample in that location. Each sample was taken in the thalweg of the channel. The bed load D_{50} ranges from about 0.5mm to 2.8mm. This grain size distribution is smaller than that of the bed surface material.

The bed load material captured in each event was plotted as a cumulative frequency or percent finer graph (Figure 5).

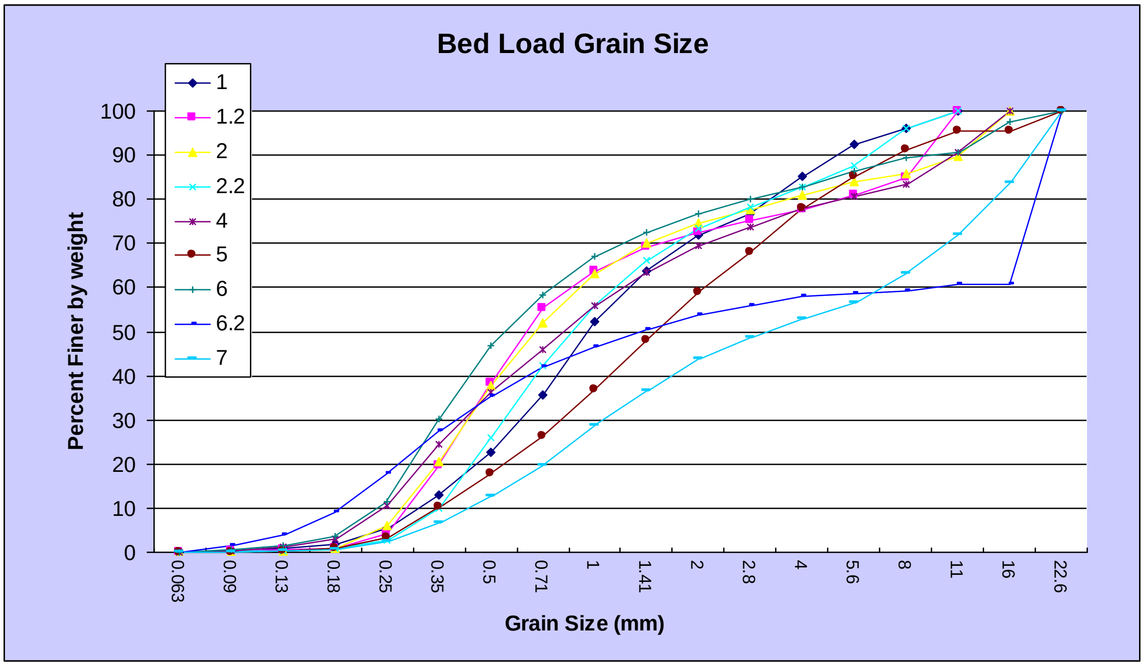

Figure 6. Grain size cumulative frequency distribution in bed load samples.

Shear Stress and τ* Results

Once the shear stress (τ) on the stream was calculated the Shields stress (τ*) was calculated for each sample event. The shear stress values are non-dimensionalized by the mean grain size on the bed surface to obtain τ* values for each flow level.

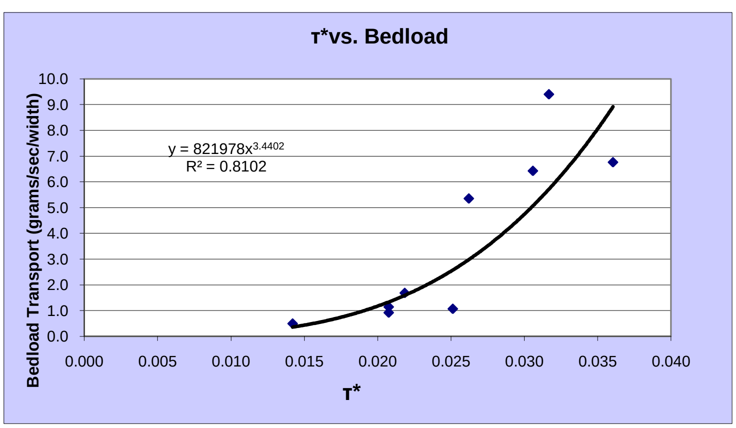

Figure 8. Relationship between critical Shields stress and bed load

These values were plotted against the bed load transport rates in Figure 6. This plot shows that there is a strong correlation between the dimensionless shear stress and the amount of bed load material mobilized during an event. The relationship is described by the following equation:

$$y=8.21978x^{3.4402} \tag{9}$$

where x is τ* or the dimensionless shear stress, and y is the bed load transport rate in grams/second/unit width. The R^2 of the relationship is 0.81. This relationship describes the effect of relative grain size and armoring in the coefficients and exponents. The systematic evaluation of the variation of coefficients and exponents produced by this type of relationship could enhance our understanding of relative grain size effects in urban environments.

Comparison of critical τ* between this study and previous work

Many previous studies developed relations for the critical, dimensionless shear stress per size fraction. Graphing these theoretical relations together underscores the large range of values reported (see figure 9). These different threshold values for each size fraction show that there is an envelope within which initial motion can occur for a given sediment size. The results included in figure 9 are not meant to be an exhaustive list, but rather represent the range of values common to the many initial motion equations complied by Buffington and Montgomery (1997) and others. Since each of these relationships is based on a ratio of grain size to the median bed surface grain size (D_i/D_{50}), the terms of initial motion are contained within the coefficients and exponents (as given in Table 1). The coefficient and exponent of a relationship between τ^* and D_i/D_{50} is determined by what can be thought of as the terms of initial motion, which can include the time and space about which initial motion is considered, and the effect of sorting and armoring. While the relationship compares dimensionless quantities, the effects of time and space can be thought of in the following way: consider a flow that is at the critical value for τ * (not exceeding it) for a particular grain size. For two different sections of the same stream, different rates of mobility may exist due to spatial differences in bed heterogeneity (even if the reach, overall, could still be characterized as relatively well sorted). Therefore, some sediments of a particular grain size class will mobilize before others because even within the same reach, there are significant spatial variations in transport phase for a given flow due to local heterogeneities on the bed surface. Similarly, significant temporal variations exist locally. Figure 6 depicts threshold for mobility using several different equations based on the same d_i/d_{50} ratios. The inconsistencies here have to be based on how each empirical methodology perceives the physical realities of the site in which the equation was developed. It is important to acknowledge the physical limitations of each different empirical methodology which attempts to estimate critical thresholds for motion. However, by utilizing a mobility frequency to explore sediment mobility, the possible spatial and temporal inconsistencies are reduced because both time and space are explicit within the formulation of the mobility frequency.

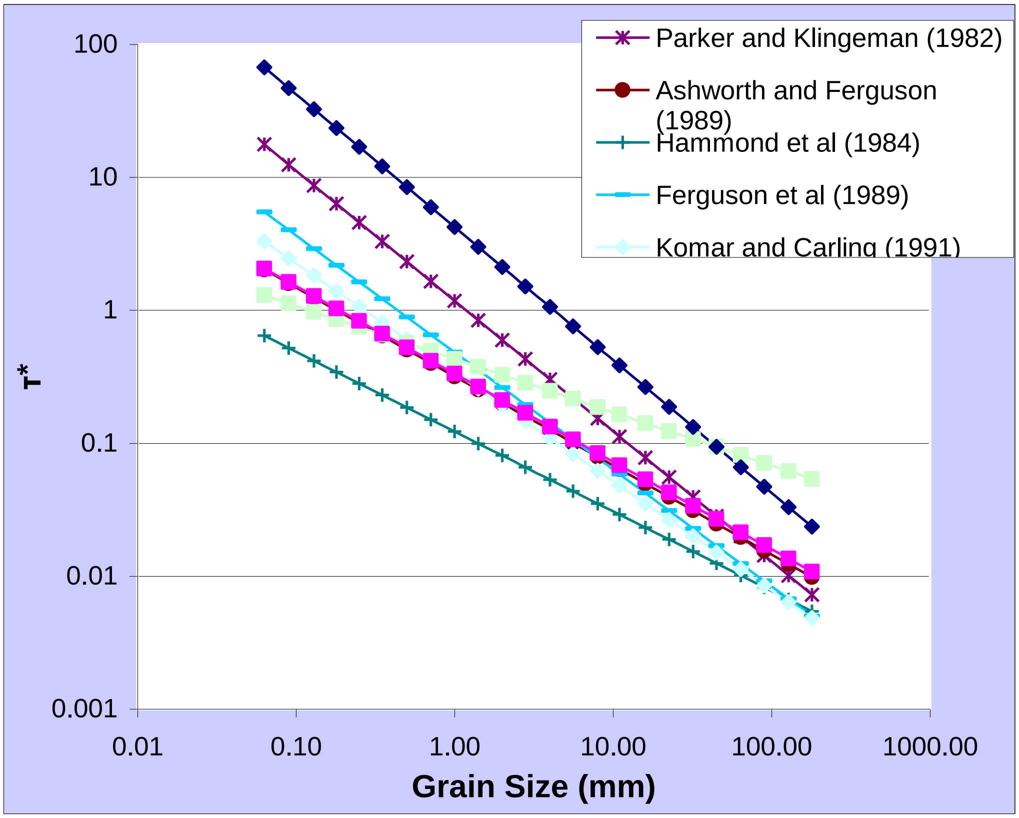

Figure 8. Theoretical bed load entrainment values per size fraction using equations in Table 1.

Mobility Frequency

The relationship between the mobility rates for different grain size was explored by calculating the mobility frequency for each grain size. That is done by using the existing transport rates and the volume of a single grain. The probable volume of a given grain size fraction is divided by the unit width, depth and time variables to obtain a transport rate. The resulting assumed volumes of one grain of each grain size fraction used in this study can be seen in Table 5.

grain size (mm)	Sphere Volume (m^3)	Cube Volume (m^3)	Average Volume (m^3)
0.063	1.309E-13	2.500E-13	1.905E-13
0.09	3.815E-13	7.290E-13	5.553E-13
0.13	1.150E-12	2.197E-12	1.673E-12
0.18	3.052E-12	5.832E-12	4.442E-12
0.25	8.177E-12	1.563E-11	1.190E-11
0.35	2.244E-11	4.288E-11	3.266E-11
0.50	6.542E-11	1.250E-10	9.521E-11
0.71	1.873E-10	3.579E-10	2.726E-10
1	5.233E-10	1.000E-09	7.617E-10
1.41	1.467E-09	2.803E-09	2.135E-09
2	4.187E-09	8.000E-09	6.093E-09
2.8	1.149E-08	2.195E-08	1.672E-08
4	3.349E-08	6.400E-08	4.875E-08
5.6	9.191E-08	1.756E-07	1.338E-07
8	2.679E-07	5.120E-07	3.900E-07
11	6.966E-07	1.331E-06	1.014E-06
16	2.144E-06	4.096E-06	3.120E-06
23	6.041E-06	1.154E-05	8.792E-06
32	1.715E-05	3.277E-05	2.496E-05
45	4.769E-05	9.113E-05	6.941E-05
64	1.372E-04	2.621E-04	1.997E-04
90	3.815E-04	7.290E-04	5.553E-04
128	1.098E-03	2.097E-03	1.597E-03
180	3.052E-03	5.832E-03	4.442E-03

Table 5. Probable grain size volumes used in this study

The average volumes from Table 5 were used with the transport rates from each sample event for each grain size fraction to yield a mobility frequency. The transport rates gathered from the sampling events are in the form of a volume per time per unit width. By setting the average volume of one grain per stream bed width equal to the transport rates, one is able to obtain a time, which is the mobility frequency of that grain size fraction during that sampling event.

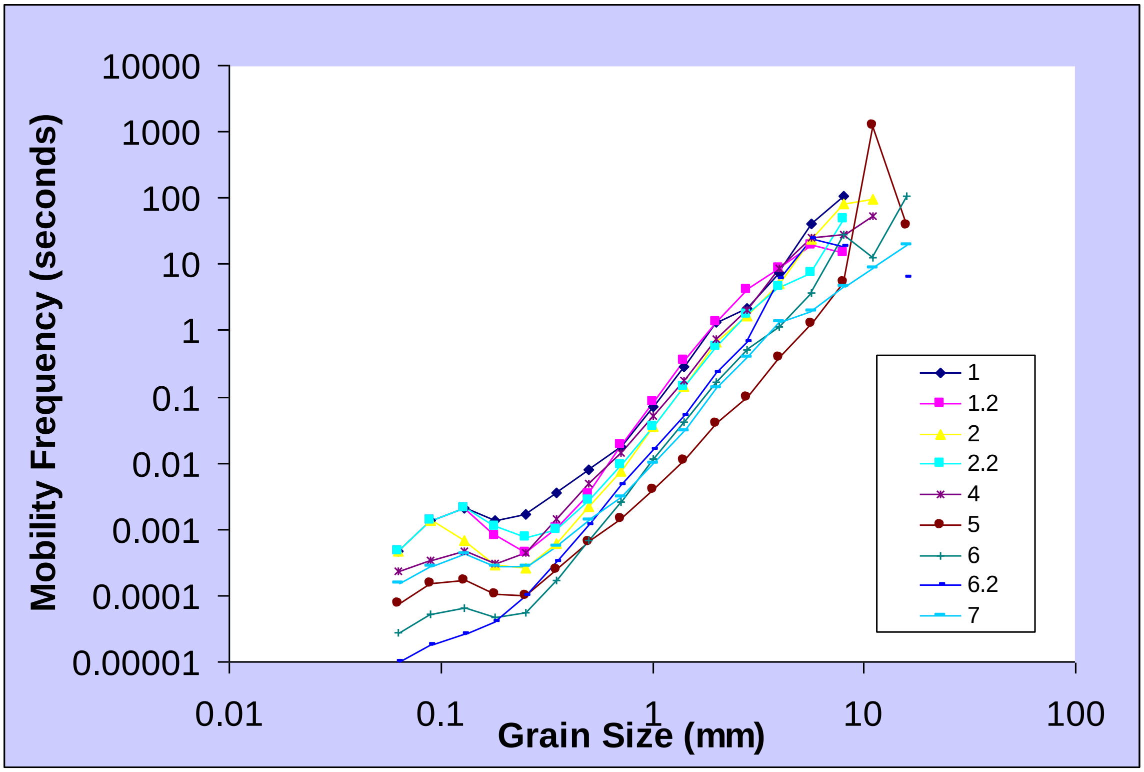

Figure 9: Mobility frequency in seconds versus bed load grain size. The different curves represent separate bed load samples, as described above.

The mobility frequency here is similar to a recurrence interval. The lowest flows produce the greatest frequencies; this is because lower flows have lower depths and corresponding lower shear stress, and thus a lesser ability to move sediments. Therefore the sediments in lower flows move sediments less frequently. If the mobility frequency curve from a sample exists higher up the y-axis that sample has a lower recurrence frequencies, meaning that there is a longer average lag time between the mobilization of each individual grain from sediments of a given size class (on the x-axis). The samples with curves lower on the y-axis are mobilizing sediment rapidly so there is a lower mobility frequency (i.e. less time in between events). For example, if one follows a single sample from the smallest grain size to the largest, the smaller size fractions are lower on the y-axis which means that the smaller size fractions are moving more often that the larger grains. As one proceeds to the larger grain sizes there is a notable break in slope. The mobility frequency stays more or less the same for the lowest grain size fractions, and then the mobility frequency decreases as the grains get larger, which is shown by an increasing slope.

Mobility frequencies shown in Figure 10 display a pronounced break in the slope at around 0.18 to 0.25 mm, depending on the sample. The break in slope represents a transition from size selective transport to equal mobility because a flat trend in the diagram (as for the finer grain size fractions) indicates that the frequency of particle entrainment is not grain size dependent, while an increasing trend (as for the coarser size fractions) demonstrates that increasingly coarser grains are mobilized with increasing rarity. This suggests that the mobility frequency decreases until a threshold is reached, in this study the threshold was about 0.2mm. The mechanics that define the transition are unclear, and this study presents too little data to tease out a relationship. This data shows the break of slope only occurring at two different grain sizes (0.18 and 0.25), for a reliable threshold relationship to be found would require the slope break to occur at many various grain sizes. The curves presented from this study are too similar for a meaningful relationship to be created based on the threshold grain size. The threshold will likely be quantified in the form of a ratio:

$$\tau^*/\ \tau^*c_i \qquad (10)$$

Where τ^* is the non-dimensionalized shear stress, and τ^*c_i is the critical Shields value for the grain size. Wilcock (1992) suggested a similar threshold for equal mobility (for all sediment size fractions):

$$\tau^*/\ \tau^*c_{d50} = 2 \qquad (11)$$

where τ^*c_{d50} is the critical Shields value for the median grain size. Future research should focus on the creation of an empirical formula that can describe the transition from equal mobility to size selective transport. Powell (1998) noted that at transport stages this high, fractional transport rates are a function of only their proportion on the bed surface, which may make it necessary to also include a variable for sorting or grain availability in the subsequent research.

By framing transport as a mobility frequency, it is possible to evaluate whether or not, and to what extent, the transport phase of equal mobility suitably characterizes the mobility of one or more grain size fractions. This formulation of the mobility frequency paves the way for further exploration of the nature of equal mobility in sediment transport, and how it changes through out a flow event. The dynamism of equal mobility within a whole transport regime is unknown. As streams undergo urbanization, and the hydrograph becomes flashier, the transition from size selective transport to equal mobility could occur at different stages and for different amounts of time. It is therefore crucial to further explore the transition to mobility frequency to full understand the urban stream evolution.

Discussion

Implications for Stream Urbanization

The trend of the relationship between initial motion and grain size is caused by armoring or the lack thereof. Whether or not the stream is armored is determined by the type of flow experienced in these locations. Armored channels are characterized by a channel in which the bed surface grains are larger on average than the underlying grains.

Natural (non-urban), perennial rivers receive a relatively more sustained flow and a subdued hydrograph (Chin 2006). The other spectrum of flow type is that of urban streams, which experience flashy hydrographs and shorter flow durations (Paul and Meyer, 2001; Chin 2006). Once a gravel stream has adjusted to natural flow conditions it typically has an armor layer that effectively reduces the total duration of transport for a given flow regime. As the armoring sediments become entrained during high magnitude flow events each size fraction may approach the condition known as equal mobility (Powell 1998).

Urban streams cannot provide armor and therefore can not achieve equal mobility in the same way. The flashiness of the hydrograph in urban streams precludes the development of channel armoring because flow increases quickly enough for the sediment to mobilize in a short period of time or the streams are able to adjust quickly enough to the rapid changes in the hydrograph, similar to ephemeral rivers found in desert settings (Cao et al. 2010).

It is worthwhile to consider the difference between the initial motion and final deposition of bed grains. While initial motion describes the movement of a predetermined amount of a certain grain size, deposition or final motion describes the last stage of the moving particles of that amount for that grain size. The deposition process sorts those grains as the flow decreases below the shear stress required to move the grains of a particular size. Selective deposition may be controlled by processes similar to those that determine particle entrainment (Powell 1998). As the hydrograph from Peavine Creek (Figure 2) shows, the rising limb of the hydrograph has the ability to selectively entrain sediments at a faster rate than the falling limb can selectively deposit the grains. Thus, begins a cycle where the deposition of an event determines the bed surface sorting which will in turn determine the initial motion thresholds for the next event. However those events may be of a significantly differing magnitude, which could cause initial motion estimates to be inaccurate. If the threshold for motion was based on a small event preceded by a larger event, that larger event would sort the bed material differently which may cause the threshold for motion to differ from that of an event preceded by similar sized events.

Curran (2007) is useful in the context of this study, in that it exemplifies the strong interaction between source material, bed surface material, and reference shear stress for initial motion. This interaction helps to explain urban stream evolution. Curran (2007) used flume studies allowed stream channel adjustment over a very short period of time. In non-experimental settings, urban streams have been observed to undergo a period of transformation (Leopold et al. 2005). This transformation consists of an initial period dominated by aggradation followed by a period of degradation. The aggradation period occurs as small sediments are introduced during earlier, higher intensity construction phases of urbanization. This aggradation of fine sediments, according to Curran (2007), effectively decreases the critical shear stress on the stream bed. This decrease in the critical shear stress could be said to occur concurrently with the peak of active urbanization. Active urbanization is the process which upsets the land in the watershed and introduces sediments. At the time when active urbanization ends, there exists a lag between end of fine sediment supply and the end of the higher transport capacities caused by the abundant fine grains already in urban streams. As the sources of the fine sediments have been largely cut off, urban stream bed may be experiencing prolonged lower critical shear stresses due to the residual fine sediments. This concurrent reduction in fine sediment sources and decrease in critical shear stress may help explain the rapid channel degradation period in urban streams (Leopold et al 2005; Chin 2006).

This description of urban stream evolution shows changes in transport regime. Theoretically, the stream begins in a nearly adjusted state, and once urbanization occurs the stream must adjust to the new hydrologic regime and sediment sources, which also change thoughout time. Because of the change in hydrograph and sediment sources, the stream changes the way it entrains sediments.

Implications for Equal Mobility

Geomorphologists have coined the term equal mobility, which one would define as the condition in which each size fraction is transported in proportion to its abundance on the stream bed (Parker et al. 1982; Powell 1998). This condition is the counterpart of size-selective transport which is the condition in which sediments are mobilized proportionally to the size of the grain (Wilcock and McArdell, 1993). These two conditions are not mutually exclusive, as shown in this study.

As streams undergo urbanization, they may evolve to an adjusted condition. An adjusted stream is defined as a stream in which sediments are being transported and deposited equally by any particular flow event. The concept of an adjusted stream may be somewhat of an ideal condition that streams may never reach, but at least in concept the sediment delivery from these stream reaches is equivalent to the sediment supply, i.e. inputs equal outputs.

A difficult task is to understand where on the spectrum of size selective transport and equal mobility a stream exists when it approximated an adjusted condition. This study shows a stream with equal mobility for the smaller size fractions and size selective transport of the larger size fractions- the threshold between transport phases appeared to be roughly 0.2 mm (Figure 8).

One must consider the differences between particle entrainment and particle deposition when evaluating the "adjusted-ness" of a stream. A hypothetical armored mountain stream that exhibits equal mobility may not necessarily be in an adjusted condition because the sediments may not be entrained and deposited at an equal rate. As the shear stress and stage falls the grains are subject to size selective deposition. On the other end of the spectrum a hypothetical stream with a flashy hydrograph that exhibits pure size selective transport will disproportionally transport and deposit the smaller grain size fractions according to the difference in duration of the rising and falling limb of the hydrograph, and therefore be unable to reach "adjusted" status. Theoretically, it seems unlikely for a stream which exhibits pure equal mobility or size selective transport to be capable of becoming adjusted. However, it is likely that most adjusted streams exist somewhere between size selective transport and equal mobility. The mobility frequency as described previously allows one to evaluate where on the spectrum a stream exists between size selective transport and equal mobility. Further study of mobility frequency could provide insight into where on the adjustment spectrum a particular stream must exists, thereby making it possible to reduce the impact of urbanization on streams and waterways.

Conclusions

Sediment mobility in urban streams is often quantitatively approached utilizing critical threshold equations developed by methodologies which are not well suited for urban streams. It is critical to understand the effects of each type of methodology on the critical values produced. The goal of this study was to contextualize some insufficiencies in current attempts to describe sediment mobility and provide a methodology which provides new insight into sediment mobility with an emphasis on urban streams. There exist many equations which describe the initial motion of sediments. These equations are used to obtain a critical threshold value for motion which is often used to characterize sediment mobility. Mobility frequencies allow a more unbiased assessment of sediment mobility in that it can describe and compare rates and patterns of transport for the entire spectrum of sediments present. Mobility frequencies provide a way to explore sediment mobility that is equally able to represent transport in any environment and across scales of magnitude.

Urban streams have very different hydrologic conditions that affect the way in which sediment is transported and deposited. Grain size fraction mobility frequencies developed in this study show, theoretically, how a stream might transition from size selective entrainment to equal mobility during a storm event. Further research is needed to understand the implication of mobility frequencies on the definitions of both size selective transport and equal mobility. Understanding the process by which the transition from size selective transport to equal mobility occurs might prove fundamental in managing streams which are experiencing rapid degradation due to urbanization.

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