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Shedding and size distributions of suspended sediments in an urban watershed

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ABSTRACT

Particle size spectra of suspended sediment eroded from the Santa Ana River, a human-impacted urban river in southern California are investigated to consider fractal behaviors in suspended sediment transport. Widespread urbanization has fueled hydrological change of the watershed over four decades, showing significant increases in storm water runoff with decreases in instantaneous suspended sediment concentration. In-site observation of particle size distributions (PSDs) during three storm studies reveals two transport regimes (flow-controlled or bed-controlled) depending on whether average particle size increase (flow-controlled) or decrease (bed-controlled) with flow rate. Despite their complexity, the observed PSDs exhibit power-law mass-size statistics, and satisfy fractal (power-law) scaling in a very robust manner. The evolution of PSD to a stable form with asymptotic behavior in suspended sediments suggests that shedding of suspended sediments in urban watershed environment system has its own self-organized characteristics wherever the sediment source come from.

Keywords: Fractal; Size distribution; Suspended sediment; Transport; Urban watershed; Storm runoff

1. Introduction

Global human migration toward the ocean has fueled urbanization of the earth's coastal regions, replacing natural landscapes (rivers, fields, forests, and estuaries) with urban civil infrastructure (canals, roadways, residential communities, and commercial land-uses). Coastal urbanization has the potential to dramatically alter the flow of material from the land into the ocean, with consequent impacts on biogeochemical cycling and the health of near shore ecosystems. The production and transport of sediment, in particular, have been changed with time in response to watershed urbanization [1,2], and may modulate terrestrial transport of organic and inorganic materials, soil and water conservation planning, geomorphic change, habitat and water quality management, estuarine and costal sedimentation.

Suspended sediments are usually understood as a collection of complex, composite, size-scaled particles. The particle size distribution arises as a result of complex geological and geophysical processes and spatio-temporal variability, which not only depends on environmental factors, such as hydrological conditions, basin characteristics, etc., but also exhibits a non-linearity of interdependent variables. In this regard, seemingly complex irregular behavior of suspended sediments could be interpreted as the fractal dimension of the distribution, which is determined by power-law dependence of number/mass on particle size [3–5].

Given the complexity of the urban watershed from which these particles were eroded, the occurrence and transport patterns of suspended particles were investigated to explain the connection between observation and conceptual erosion process with different time scales in the Santa Ana River, a highly human-impacted urban river in southern California. Field studies were carried out to measure suspended particle size distributions (PSDs) with low-angle light scattering in the runoff samples collected during three episodic storm events, and they were compared with PSDs estimated from historical sediment data to explore fractal characteristics and understand shedding patterns of suspended sediments.

2. Study area

The Santa Ana River watershed includes 6915 km^2 of land bordering the Pacific Ocean between the Cities of Los Angeles and San Diego in southern California (Fig. 1). This highly urbanized watershed is home to 10 million people, and includes the Santa Ana River drainage basin and a few small streams located near the coast, most of which drain to the ocean. With population increases, urban land had been developed by approximately 40% of the watershed in 2000 [2]. Flow in the watershed is extensively managed for flood control and drinking water supply and, except during storm water flow conditions, water in the Santa Ana River does not make it to the ocean outlet as a result of groundwater recharge effort. During storms (typically occurring between November and March), upstream discharge in the river frequently exceeds the capacity of the recharge basins, and storm water runoff from anywhere in the watershed can potentially flow to the ocean and impact water quality in the surf zone and offshore [6]. Many studies have been conducted to characterize sediment budget in the Santa Ana River [1,2,7,8], but studies on particle size distribution of sediment have remained scarce.

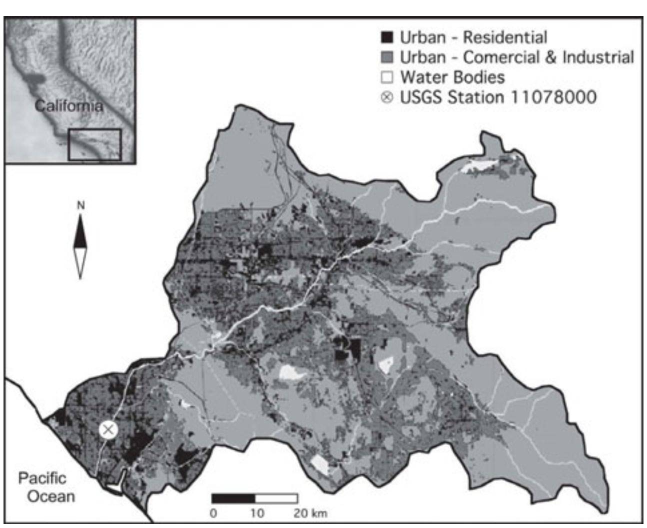

Fig. 1. Map indicating location of field site and sampling stations.

3. Data and methods

Historical discharge of water and sediment in the Santa Ana River was evaluated using data from a long-standing gauge station (USGS 11078000) (Fig. 1), which is obtained from the USGS website (http://waterdata.usgs.gov/nwis). The site represents discharge just upstream of the river mouth, as it incorporates discharge from 99.9% of the watershed. Suspended sediment samples were collected during high discharge to focus on the events responsible for the majority of sediment flux in the river, and analyzed for the suspended sediment concentration and particle size distribution by percentage of proportions by weight.

Field sampling during three storm events was carried out at the same station in the 2003/2004 wet season. During each storm, a relatively large number (n = 24 to 40) of samples were collected at frequencies ranging from four samples per hour during peaks of the hydrograph to two samples per day at the tail end of the storms. All water samples were analyzed for particle size distribution and total suspended solids (TSS). The volume-based PSD in each water sample was measured using a LISST-100 analyzer (Sequoia Scientific, Inc., Bellevue, WA) operated in batch mode. This low angle light scattering estimates particle volume resident in 32 logarithmically spaced particle size classes ranging in size from 2.5 to 500 μm. All grab samples were also analyzed for TSS using Standard Method 2540D.

The particle volume distributions recorded by the LISST-100 instrument can be represented mathematically as $\Delta V/\Delta\log d_p$, where ΔV represents the amount of particle volume (per unit fluid volume) present in one of the 32 logarithmically spaced particle diameter bins, d_p represents the median size of each particle diameter bin. The number-averaged volumetric particle size, $\langle s\rangle$ was computed from the particle volume distributions recorded by the LISST-100 as follows [9,10]:

$$\langle S\rangle = \sum_{i=1}^{32}\Delta V_i \Bigg/ \sum_{i=1}^{32}\frac{6\Delta V_i}{\pi d_{p,i}^{\,3}} \tag{1}$$

To investigate the characteristics of PSD and its relationship with the sediment sorting mechanism during suspended sediment transportation, PSD data were rendered as cumulative forms either as mass smaller than a certain diameter or as number of particles lager than a certain diameter, and then analyzed with power-law relationships and the exponents interpreted as fractal dimensions as follows [4,5,11,12]:

$$M(r < R) \sim R^{\nu} \quad (2)$$

$$N(r > R) \sim R^{-D} \quad (3)$$

where M ($r < R$) is the mass fraction of particles with a radius r smaller than R, N ($r > R$) is the number of particles per unit volume having a radius r lager than R, and D is the fractal dimension. Assuming a constant density of sediment particles, the exponent ν of the mass-based approach can be related to the exponent D of the number-based approach as $D = 3 - \nu$.

4. Results and discussion

4.1. Historical data: discharge of flow and suspended sediment

Discharge records of flow and sediment over the four-decade period of USGS suspended-sediment sampling are used to generate probability plots for monthly precipitation, instantaneous flow discharge, and suspended sediment concentration (Fig. 2). These probability curves show that the instantaneous suspended sediment concentrations have decreased whereas instantaneous flow rates have increased over four decades. This hydrological change is related to the widespread urbanization of the watershed, which largely resulted in a dilution of sediment by increases in storm water runoff due to urban impervious surfaces [2]. Since the monthly precipitation records don't show significant changes with time (Fig. 2), changes in the runoff discharge of the lower basins with time should not be reflected in an altered relationship between precipitation and sediment discharge. Thus, the percentage of precipitation that flows to nearby waterbody as overland flow appears to be significant in urban areas where much of the land area is covered with impervious surfaces.

4.2. Short-term field studies: three storm events

The temporal variability of the particle size characteristics of suspended particles may reflect the diverse patterns of behavior that may exist and the complexity of the controls involved [13]. Significant evidence can be found from the relationship between suspended particle size composition and volumetric flow discharge rate. In some natural rivers, the sediment may become coarser as flow increases, while in others, it may become finer or relatively constant in particle size composition [13–16].

Results from three field studies in the Santa Ana River highlight the considerable diversity in response to changing flow discharge (Fig. 3). The increased discharges associated with increased shear velocity permit the transport of larger particles, therefore, a positive relationship exists between water discharge and the magnitude of the coarse fraction or the average particle size (Study 1 in Fig. 3(A)). However, where the erosion dynamics of a drainage basin are such that slope erosion (fine sediment) becomes increasingly dominant over channel erosion (coarser sediment) during major storm events, or the area experiencing erosion expands into areas with finer source materials during these events, a negative relationship between water discharge and the proportion of coarse sediment or the average particle size may exist. In the latter case, expansion of the areas contributing surface runoff and sediment to the streams during times of increased flow could result in reduced delivery efficiency and, therefore, a preferential

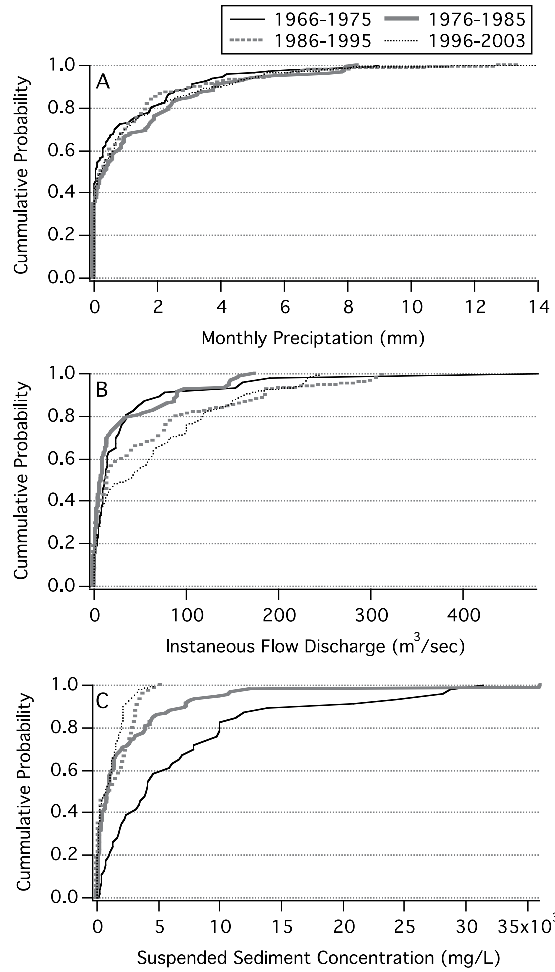

Fig. 2. Historical trends of runoff flow and suspended sediment discharge during storm events; (A) annual average rainfall, (B) instantaneous runoff discharge, (C) Total Suspended Solid (TSS) concentration.

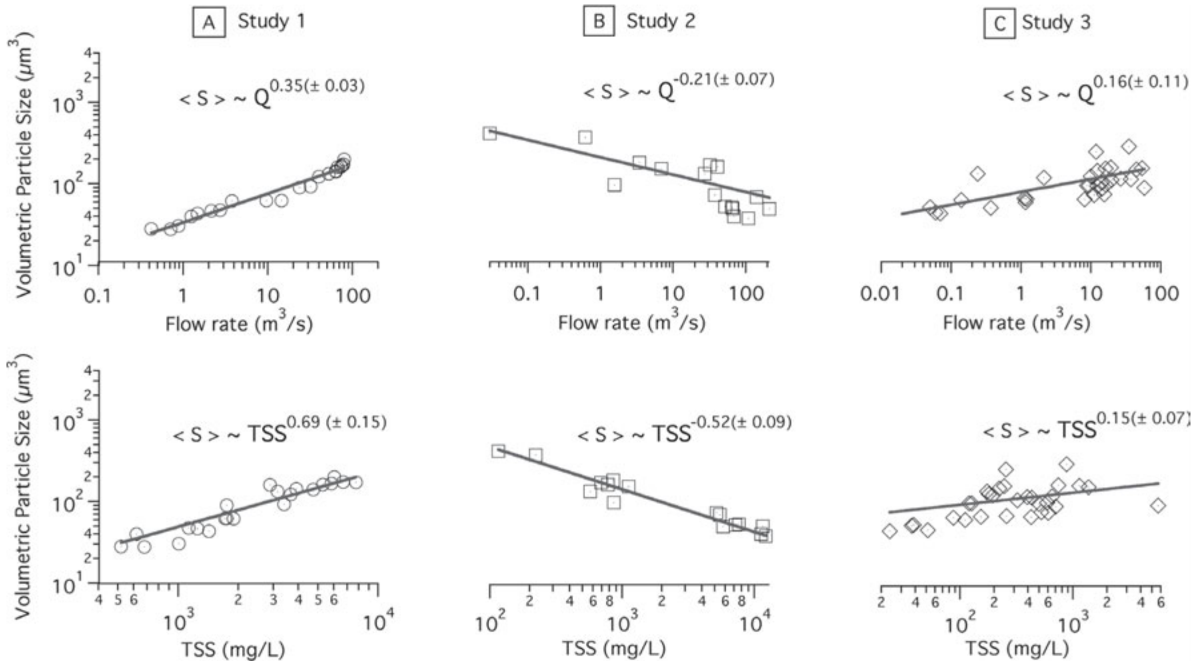

Fig. 3. Patterns of number-averaged volumetric particle size on runoff flow rate and TSS during storm events; (A) Study 1, (B) Study 2, (C) Study 3.

loss of the coarse fraction [14]. The marked increase of fine particle at high discharges in Study 2 reflects the impact of floodplain inundation and the associated preferential deposition of the coarser fraction (*see* Fig. 3(B)). However, Study 3 doesn't show the shedding relationships clearly.

4.3. Fractal dimension of suspended sediment

To investigate the characteristics of suspended sediment and its relationship with sorting mechanism during suspended sediment transportation, the PSD data are fitted by a power-law function to ascertain the physical condition under which storm water runoff generates fractal characteristic of suspended sediments (Fig. 4). The power-law exponent (fractal dimension, *D*) has some interesting hydro-geographical characteristics. Generally, it indicates the extent of dominant particle size in PSD: lower value indicates that coarser particles are dominant, while high value indicates that the finer particles are dominant [17]. Also, in the point of view of sediment transport processes, *D* values during storm may reflect a "sorting process" with along-channel transport. The *D* values determined experimentally during three storm studies have different responses to increase of volumetric flow discharge rate (Fig. 4(A)). In case of Study 1 (channel erosion or flow controlled), increasing flow (or increasing shear velocity) increases suspension of coarser particles (decreasing *D*). On the other hand, in case of Study 2 (slope erosion or bed controlled), increasing flow increases transport potential of fine particle eroded by greater dynamic contribution areas within the basins (increasing *D*).

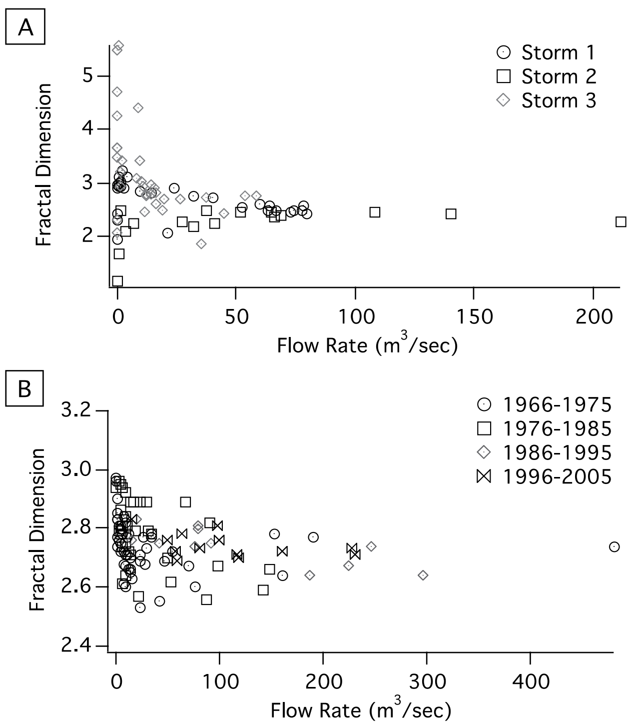

Fig. 4. Fragmentation fractal dimensions estimated from particle size distribution data (A) field study data, (B) USGS historical data.

However, at the flow rates where their associated shear velocities exceed the settling velocity of the maximum particle size over a measurement size range (~10.3 m/s), all the *D* values converge to one single value (~2.7) (Fig. 4(A)). This critical shear velocity is determined by the maximum particle size that a PSD analyzer can measure, and PSD may not be reflected a universal shedding pattern of suspended sediments until flow rate increases enough to generate a critical shear velocity. The historical PSD data also show the similar patterns of PSD as shown in Fig. 4(B). The fractal dimensions based on the mass fraction of suspended sediments are found to vary within a narrow range only, which is mainly from 2.0 to 2.25, and have a tendency to merge to a single value, which is similar to the pattern over episodic storm events at the same site.

On the other hand, the merged power-law exponent value with flow rate reflects that the environmental conditions do not significantly alter the PSD slope, although they may change the position of the PSD. The evolution of PSD to a stable form with asymptotic behavior in suspended sediments suggests that shedding of suspended sediments in watershed environment system has its own self-organized characteristics wherever the sediment source come from. This feature, the signature of scale invariance, may have their dynamic origin in the self-organization of complex system [18–21]. Physically this power scaling of PSD means that PSD exhibits self-similar over a finite range of size, and all moments of PSD will depend on sample volume and/or range over which PSD is measured (e.g., average particle size, TSS concentration, etc.).

5. Conclusions

Particle size spectra in runoff suspended sediment are presented to understand how the storm runoff from a human-impacted urban river sheds suspended sediments in different time scale. Widespread urbanization has fueled hydrological change of the watershed over four decades, showing significant increases in storm water runoff with decreases in instantaneous suspended sediment concentration. In-site observation of PSD reveals two transport regimes (flow-controlled or bed-controlled) depending on whether average particle size increase (flow-controlled) or decrease (bed-controlled) with flow rate.

Despite their complexity, the observed PSD data exhibit power-law mass-size statistics under a wide variety of conditions, and satisfy fractal (power-law) scaling in a very robust manner. The asymptotic behavior of PSD can be understood in terms of a self-similar. It would be also expected that there is a potentially interesting connection between particle size spectra and pollutant loading data from storm runoff.

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