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Parameters Influencing Sediments Resuspension and the Link to Sorption of Inorganic Compounds

Eid A. Alkhatib
Sacred Heart University, alkhatibe@sacredheart.edu

Keith Castor

PARAMETERS INFLUENCING SEDIMENTS RESUSPENSION AND THE LINK TO SORPTION OF INORGANIC COMPOUNDS

EID ALKHATIB and KEITH CASTOR

Abstract. In the aquatic environment, the accumulation of chemical contaminants by sediments poses a potential threat to endemic life forms and drinking water resources. Trace metals such as Cd, Cu, Cr, Ni, Pb, and toxic organic compounds, are among a wide variety of contaminants having an affinity for sediments. In this study, experiments were performed simulating sediment resuspension in the lower Housatonic River, Connecticut, using a Particle Entrainment Simulator. Analyses of grain size distributions, porosities and total organic contents of the sediments suggested *that these parameters influence the redistribution and entrainment of settleable solids in the water* column. These findings were established by evaluating the impact of one parameter on sediment resuspension as a function of stream flow with the other two characteristics being held constant. Total suspended solids and volatile suspended solids resuspension concentration ranged from 3.2 to 20648.3 mg L^{-1}, and 1.5 to 1823.8 mg L^{-1}, respectively, with subsequent increases in flow rates from 9 to 6 dynes cm^{-2}. The resuspension concentrations were augmented by sediment porosity (22.0 to 57.5%), percent finer grain-size distributions at 0.1 mm, and total organic content (2.7 g kg^{-1} to 29.0 g kg^{-1}). Using K_p values, and the dissolved contaminant levels of various trace metals, the particulate contaminant levels of the metals were determined under various oscillation rates. As sediment resuspension increased with increased stream flow, there was an overall general increase from 0.02 to 33.6 μg L^{-1} in the particulate contaminant levels of Cd, Cu, Cr, Ni and Pb.

Keywords: sediments, resuspension, partition coefficient, heavy metals

1. Introduction

In river systems, contaminated sediments pose a potential threat to aquatic life and drinking water sources. The United States Environmental Protection Agency's (USEPA) Assessment and remediation of Contaminated Sediments (ARCS) program (USEPA, 1994) recognized the need to conduct ecological risk assessments for evaluation of acute and chronic effects of sediment contaminants on aquatic life. Accordingly, an understanding of the nature of bottom sediments in river systems will assist in alleviating these potential risks to indigenous populations.

The entrainment of sediments into water columns is linked to various physical and chemical parameters. These parameters include river flow velocity, water content of the deposited sediments, and the composition (mineralogy, particle-size distribution and organic content) of the deposited sediments (Lee Dong-Young *et al.*, 1981). Studies have also shown that the entrainment of the settleable solids

is adversely affected through benthic processes causing aeration, mixing, fluid transports and the metabolism of organic and inorganic complexes (Arakel, 1995).

Partition coefficients define the degree of partitioning between dissolved and adsorbed phases. The partition coefficient is a very important parameter in simulating the transport dynamics of dissolved and particulate forms of contaminants. Quantitatively, the partition coefficient is calculated as

$$K_p = (p/m_1)/c$$

where

K_p = has units of L mg^{-1};
c = dissolved pollutant in μg L^{-1};
p = particulate pollutant in μg L^{-1};
m_1 = TSS in mg L^{-1}.

In a study by the USEPA (Kontaxis et al., 1982), correlation between K_p and TSS validated that K_p for metals decreases with an increase of suspended solids.

Total organic content (TOC), grain-size and porosity can be used as criteria to characterize sediment composition and the relation between particle entrainment characteristics and contaminant loads. The partitioning of nonionic organic compounds and pore water can be established with knowledge of total organic content. It can also be used to determine the availability of toxic metal concentrations (USEPA, 1994). In addition to the grain-size being utilized as a guide in determining the existence of depositional or erosional environments, it can also indicate the level of contamination within sediment loads. Porosity influences the extent to which sediments resuspend.

Resuspension characteristics of sediment were previously investigated in annular flumes. Resuspension properties of bottom sediments are now more frequently determined in portable devices known as Particle Entrainment Simulators (PES). Through the use of the PES, it is possible to evaluate bottom sediment resuspension as a function of stream flow. The data obtained from such experiments can be used in developing models for the containment and remediation of contaminated bottom sediments in rivers (Alkhatib and Castor, 1977). By correlating data on sediment resuspension with TOC, grain-size, porosity, and partition coefficient, it may be possible to adopt measures for alleviation of the adverse impacts of contaminant loads on water quality.

2. Site Specifics

The Housatonic Rivers runs from upper Massachusetts and flows about 240 km through CT to the Long Island Sound (Figure 1). Historically, the river has been
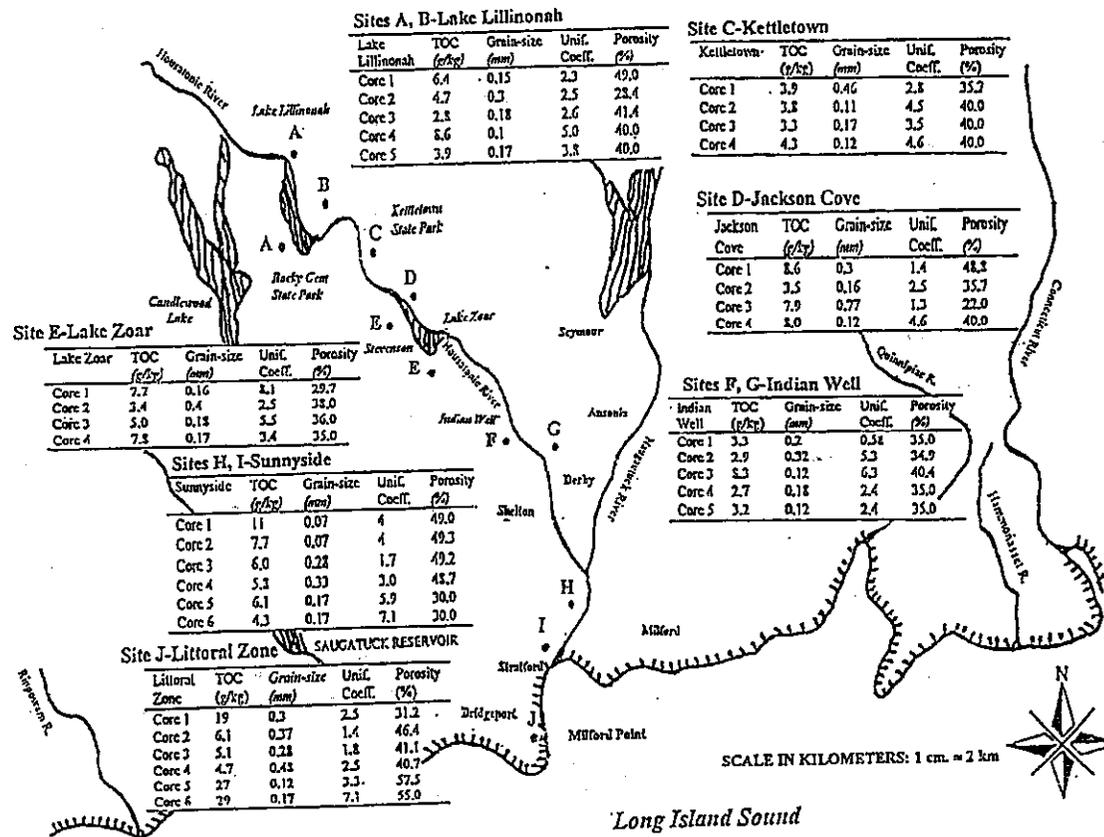
Sites A, B-Lake Lillinonah

Lake Lillinonah	TOC (g/kg)	Grain-size (mm)	Unif. Coeff.	Porosity (%)
Core 1	6.4	0.15	2.3	49.0
Core 2	4.7	0.3	2.5	23.4
Core 3	2.8	0.18	2.6	41.4
Core 4	8.6	0.1	5.0	40.0
Core 5	3.9	0.17	3.8	40.0

Site C-Kettletown

Kettletown	TOC (g/kg)	Grain-size (mm)	Unif. Coeff.	Porosity (%)
Core 1	3.9	0.46	2.8	35.2
Core 2	3.8	0.11	4.5	40.0
Core 3	3.3	0.17	3.5	40.0
Core 4	4.3	0.12	4.6	40.0

Site D-Jackson Cove

Jackson Cove	TOC (g/kg)	Grain-size (mm)	Unif. Coeff.	Porosity (%)
Core 1	8.6	0.3	1.4	48.2
Core 2	3.5	0.16	2.5	35.7
Core 3	7.9	0.77	1.3	22.0
Core 4	8.0	0.12	4.6	40.0

Site E-Lake Zoar

Lake Zoar	TOC (g/kg)	Grain-size (mm)	Unif. Coeff.	Porosity (%)
Core 1	7.7	0.16	2.1	29.7
Core 2	3.4	0.4	2.5	33.0
Core 3	5.0	0.18	5.5	36.0
Core 4	7.8	0.17	3.4	35.0

Sites F, G-Indian Well

Indian Well	TOC (g/kg)	Grain-size (mm)	Unif. Coeff.	Porosity (%)
Core 1	3.3	0.2	0.58	35.0
Core 2	2.9	0.32	5.3	34.9
Core 3	8.3	0.12	6.3	40.4
Core 4	2.7	0.18	2.4	35.0
Core 5	3.2	0.12	2.4	35.0

Sites H, I-Sunnyside

Sunnyside	TOC (g/kg)	Grain-size (mm)	Unif. Coeff.	Porosity (%)
Core 1	11	0.07	4	49.0
Core 2	7.7	0.07	4	49.3
Core 3	6.0	0.28	1.7	49.2
Core 4	5.3	0.33	3.0	48.7
Core 5	6.1	0.17	5.9	30.0
Core 6	4.3	0.17	7.1	30.0

Site J-Littoral Zone

Littoral Zone	TOC (g/kg)	Grain-size (mm)	Unif. Coeff.	Porosity (%)
Core 1	19	0.3	2.5	31.2
Core 2	6.1	0.37	1.4	46.4
Core 3	5.1	0.28	1.8	41.1
Core 4	4.7	0.43	2.5	40.7
Core 5	27	0.12	3.3	57.5
Core 6	29	0.17	7.1	55.0

SCALE IN KILOMETERS: 1 cm. ≈ 2 km

Long Island Sound

Figure 1. The lower Housatonic River and Watershed.

subjected to point source loadings of heavy metals and other toxic contaminants from many industries. Sampling of surficial and deeper sediments revealed contamination with trace amounts of PCBs (polychlorinated biphenyls), suggesting that deposition of contaminated sediments may have prevailed for several decades (U.S. Geological Survey, 1981). The river has been impounded to form major lakes, Lake Lillinonah which has a surface area of 760 ha, a drainage area of 361 000 ha and maximum depth of 30.5 m, and Lake Zoar which has a surface area of 390 ha, drainage area of 399 000 ha, and maximum depth of 22.7 m (Frink *et al.*, 1982). Large amounts of metals and other contaminants accumulated in bottom sediments and became trapped in these impoundments and other low velocity areas. These areas now act as source points for the introduction of various chemical constituents into the water column, especially during the periods of high flows. As such, contaminated sediments will inevitably be carried along the river to the Long Island Sound thereby possibly posing adverse threats to water quality.

3. Methods and Procedures

The study was conducted between May, 1997 and January, 1998. Thirty-four core samples were retrieved from seven major sites along the lower part of the river. At each site between four and six cores were extracted. These cores included samples from the intertidal zone where it meets with the Long Island Sound. In addition to TSS/VSS, the cores were analyzed for gran-size distribution, uniformity coefficient, porosity, and total organic content (Figure 1).

3.1. CORES COLLECTION

Sediment cores were retrieved by wading in the river and inserting an acrylic core barrel. The dimensions of the acrylic core barrel was selected so that cores fit precisely in the PES unit. A beveled plate with a circular groove was placed underneath the core before extracting the sediment sample with overlying river water. On the river bank, sediment cores were transferred to other sealed core barrels to prevent any leakage.

3.2. PARTICLE ENTRAINMENT SIMULATOR (PES)

The PES consists of a cylindrical chamber inside which a perforated horizontal grid oscillates vertically in the water column and creates shear stress on the sediment-water interface (Figure 2). This causes the sediment to become entrained into the water column. The PES has an aluminum drive linked to a variable speed motor. The oscillating grid is made of Plexiglas and has 42.8% porosity formed by evenly spaced holes 1.2 cm in diameter, and 1.5 cm between holes. The calibration of the PES was conducted by the analysis of cores in parallel with a USEPA PES. The USEPA PES was originally calibrated using an annular flume at the University of
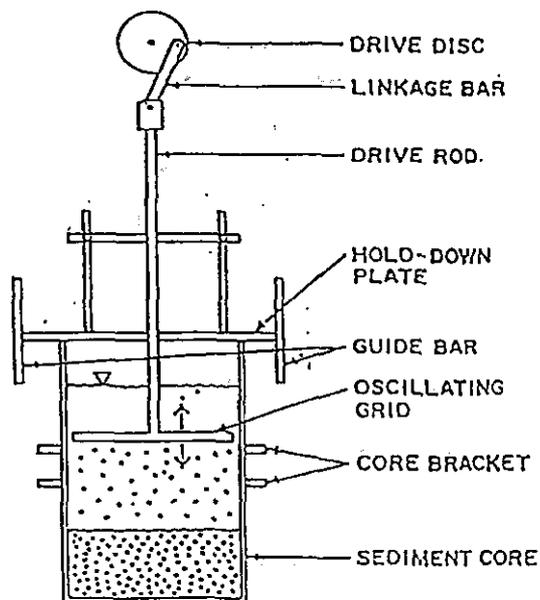
Figure 2. Particle Entrainment Simulator.

California under sponsorship from the USEPA. The calibration was determined by running the annular flume and the USEPA unit with similar sediments under the same conditions simultaneously. Through this process, the shear stress (2, 3, 4, 5 and 6 dynes cm^{-2}) of the annular flume was equated with the oscillation rate of the PES (269, 357, 455, 547 and 694 rpm).

3.3. PES TESTING

Each of the collected core samples was tested with equivalent stream flows of 2, 3, 4, 5, and 6 dynes cm^{-2}. A stroboscope-tachometer was used to set oscillation rates. The judgment of the steady state condition occurred at the end of 17 min of continued oscillation. The steady state condition was determined in a previous study that investigated the containment and remediation of bottom sediments in rivers (Alkhatib and Castor, 1997). In the study, the steady state corresponded to the condition at which the concentration of TSS remained constant irrelevant of time for a specific oscillation.

After a core sample had settled in the PES for 24 hr, it was subjected to different velocity runs. To ensure uniformity during testing, the grid of the PES was adjusted for each core-run so that the distance between the grid and sediment surface was 5.1 cm, and the distance between the grid and water-column surface, 7.6 cm.

When steady-state conditions were reached, approximately 60 mL of overlying water were drawn. For each core, six samples were collected. Total suspended

solids (TSS) and volatile suspended solids (VSS) were measured in accordance with standard methods for the examination of water and wastewater, 1995 methods 2540D (TSS) and 2540E (VSS) (Eaton *et al.*, 1995).

3.4. CORE POROSITY

For the determination of porosity, core subsamples were extracted at the collection site. Less than 2.5 cm thickness from the upper surface of the bottom sediments was retrieved for analysis. The collected samples were stored in 1 L plastic containers and transported for analysis. The following equation gives a measure of porosity:

$$n = 100V_v / V$$

where
n = porosity (%);
V_v = volume of void space in a unit volume of sediment (cm^3);
V = total volume of sediment, including both voids and solids (cm^3).

A sample of known volume is dried in an oven at 105 °C until it reaches a constant weight. The dried sample is then submerged in a known volume of water in a sealed container until it becomes saturated. The original water volume minus the volume of water in the sealed container without the saturated sample gives the volume of void space (Fetter, 1995).

3.5. GRAIN-SIZE DISTRIBUTION

The grain-size samples were sorted in the laboratory by passing a sample through nested sieves (US-Standard No. 14 – No. 230) ranging from 1.4 to 0.063 mm. The weight of each sediment fraction was determined, and the percent finer by weight versus the grain-size were plotted to yield the grain-size distribution graph.

Size-fractionating the samples also allowed for the calculation of a uniformity coefficient (C_u) for each sediment. This is described as a measure of how well or how poorly sorted a sediment is. It is the ratio of the grain-size that is 60% finer by weight, d_{60}, to the grain-size that is 10% finer by weight, d_{10} (Fetter, 1995):

$$C_u = d_{60}/d_{10} .$$

3.6. TOTAL ORGANIC CONTENT (TOC)

For the measurement of TOC, samples were dried in an oven at 105 °C for 1 hr until constant weight was achieved. After weighing the cooled samples, they were muffled at 550 °C for 20 min. The difference between the weights of the samples after drying at 105 °C, and after burning at 550 °C gave a measure of the TOC of the samples.
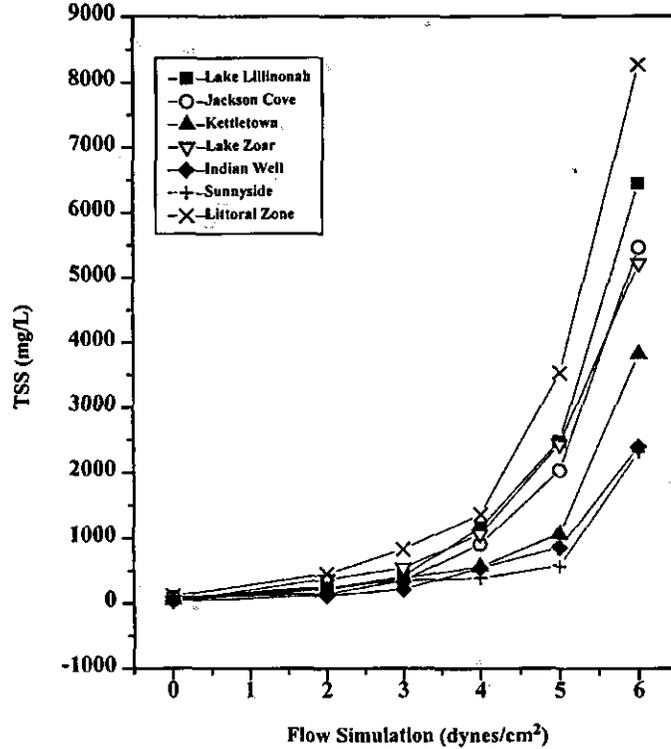
Figure 3. Average TSS concentrations in relation to increases in stream flow.

4. Results and Discussion

4.1. VARIATIONS IN TSS AND VSS RESUSPENSION

Total Suspended Solids from sampled cores ranged from 2.2 mg L^{-1} at the lowest flow simulation to 20649.3 mg L^{-1} at the highest flow simulation. For VSS, resuspension ranged from 1.5 to 1823.8 mg L^{-1}. Average TSS concentrations were related to stream flow (Figure 3). The littoral zone and Lake Lillinonah yielded the largest concentrations of TSS within the water-body whilst Sunnyside sediment's yielded the lowest within the sampled system. Similar trends were observed when VSS values were plotted.

The spatial partitioning of sediment concentrations in the lower Housatonic River does not reflect a distinct pattern. Qualitatively and quantitatively, TSS derived from the 34 cores analyzed tend to behave in accordance with site specific, and the type of sediments. Sediments in the system basically fall into two categories: fine sands and soft muds. Although fine-grained sediments are transported downstream and deposited in catchment zones under increasing flow conditions, a

few cores from upstream sampling sites yielded high concentrations of settleable solids. This can be attributed to the fact that some upstream cores were obtained from depositional areas and some were not.

4.2. IMPACT OF BOTTOM SEDIMENT'S CHARACTERISTICS ON RESUSPENSION

4.2.1. *Grain-size distribution*
Grain-size distribution curves were plotted for all cores with the curves being used to determine uniformity coefficients (C_u) and grain-size specfic finer values. Data analyses for 10% finer grain-size sediment distributions within the studied area of the river ranged from 0.07 to 0.9 mm. Cores with grain-sizes ranging between 0.07 and 0.2 mm exhibited greater resuspension of solids than cores with larger grain size. For example, core 1 from Sunnyside, which had the smallest grain-size (0.07 mm) of all cores analyzed, yielded a TSS value of 2968.8 mg L^{-1} at the highest flow rate. The structure of fine-grained sediments affords them the dominant role in the apportioning of contaminants within the water column as their extremely large surface area to volume ratio increases their sorption capacity. The uniformity coefficient is of lesser significance to grain-size in affecting sediment resuspension, and should not be used in assessing the resuspension properties of settleable solids in the water body. Uniformity coefficient measures how well or poorly sorted the sediment is whereas grain-size indicates sediment size distribution. Physical processes that will cause sediment to become entrained into the water column therefore affect grain-size. It may be more appropriate to use the corresponding percent finer by weight of all cores at 0.1 mm grain-size to investigate resuspension characteristics within the system.

In order to validate the correlation between the percentile finer at 0.1 mm grain-size and resuspension, it was important to maintain a level of consistency among the cores used for demonstrating irrelevant of their location. The representative cores chosen had fairly constant porosity ranges of 34.9–40.4%, and TOC values that ranged from 2.7 to 8.3 g kg^{-1}. Percent (%) finer than 0.1 mm was positively correlated with sediment resuspension. At moderate stream flows of 2 and 3 dynes cm^{-2}, there are increases in TSS resuspensions (Figure 4). At increased flow, the TSS concentrations increase rapidly. Total suspended solids increase from initial low concentrations to 1392.1 and 2931.7 mg L^{-1}, respectively. Resuspended VSS is also positively related to % finer than 0.1 mm. These findings suggest that the percentile finer by weight at specific grain-size does affect entrainment concentrations into the water column, and as a result can be used as a tool to predict TSS resuspension in rivers.
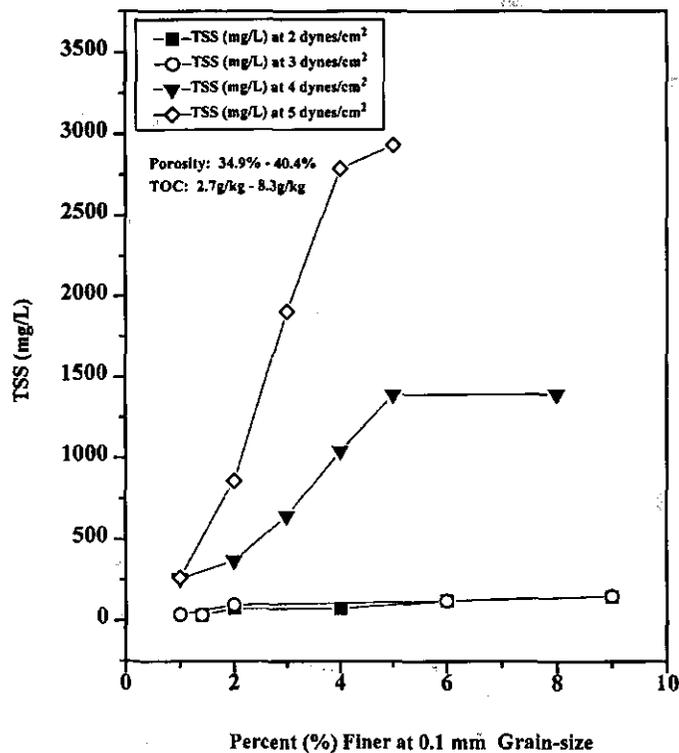
Figure 4. Impact of percent finer at 0.1 mm grain-size on TSS resuspension at varied stream flows.

4.2.2. Porosity

Bottom sediment porosity ranged from 22 to 57%. At maximum flow simulation, the majority of cores with high porosity values enhibited the greatest resuspension of solids. However, two cores with low porosity values yielded high TSS. These two cores were extracted at deposition zones that tend to retain fine-grained sediments.

The impact of porosity on TSS resuspension can be evaluated by utilizing cores with fairly uniform TOC and 10 percentile values, and assessing their relation to resuspension. To illustrate the linkage between porosity and resuspension, cores from the system with TOC values ranging from 2.7–8.6 g kg^{-1}, and grain-size ranging from 0.1–0.33 mm were employed. Results show that the larger the porosity of the core, the greater the entrainment of particulates within the water. In Figure 5, there is a moderate increase in suspended solids at a porosity range between 30 to 41%. However, at a porosity value of 49.2%, there is an extraordinary rise in TSS concentrations from an initial concentration of 183.1 to 941.5 mg L^{-1}. A similar finding occurs on extrapolating the relationship between resuspension and
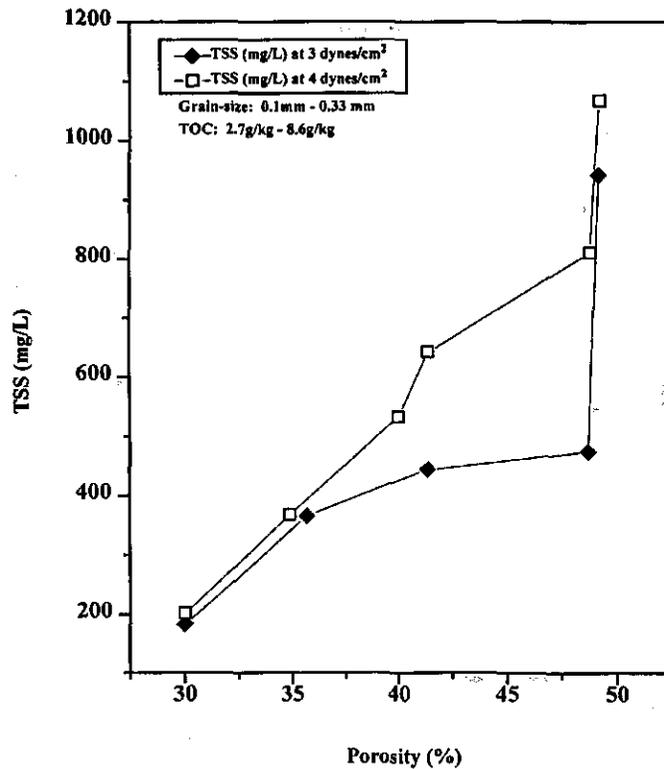
Figure 5. Impact of porosity on TSS resuspension.

porosity at a flow rate of 4 dynes cm^{-2}. TSS resuspension concentrations increase from 183.1 mg L^{-1} at a 30% porosity to 1967.2 mg L^{-1} at a porosity of 49.2% (Figure 5). The porosity of the sediment is also correlated with the entrainment of volatile suspended solids into the water column (Figure 6).

4.2.3. *Total Organic Content*

Organic materials generally have lower densities than mineral particles and therefore are more susceptible to agitation. This phenomenon was demonstrated by using cores from the system that enhibited fairly constant uniformity, and subjecting the sediment to varied levels of stream flow. The cores had grain-size distributions between 0.1 and 0.32 mm whereas porosity values ranged from 30–40%. The concentration of TSS increase rapidly with flow rate from 50.0 to 642.2 mg L^{-1} although the studied cores have fairly uniform TOCs and porosities (Figure 7). At 3 dynes cm^{-2}, TSS concentrations rise from 98.9 mg L^{-1} to 1269.0 mg L^{-1}. Similarly, VSS increases as a function of TOC at flow of 2 and 3 dynes cm^{-2}.
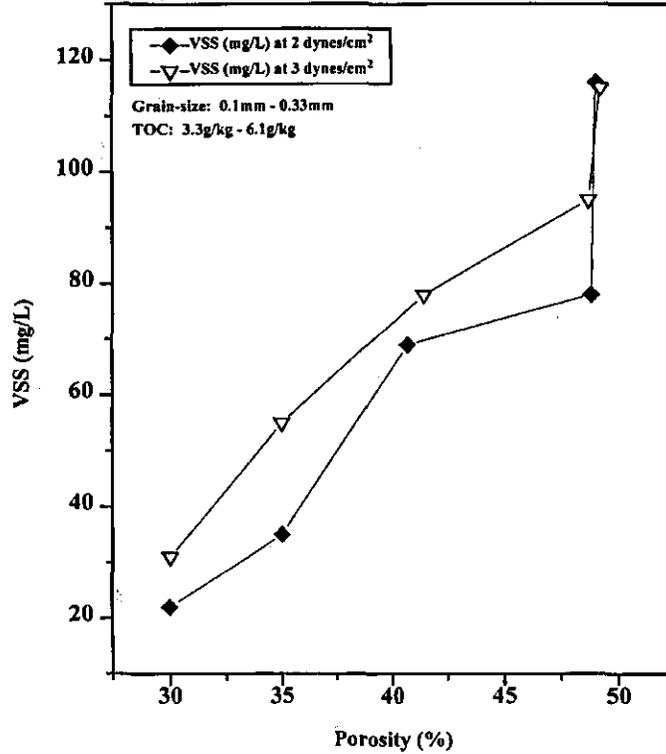
Figure 6. Impact of porosity on VSS resuspension.

4.2.4. *Link to metal partitioning*

In this study an attempt was made to link the partition coefficients (K_p) with the potential resuspension of heavy metals through dynamic simulation of the impact of flow conditions on bottom sediments. K_p values were obtained from a previous study conducted on the Blackstone River, Rhode Island (Alkhatib and Wright, 1991). Their study complemented an EPA study over a wide range of sediment resuspension concentrations which measured 5.0–600.0 mg L^{-1} TSS. K_p values for various metals including cadmium (Cd), chromium (Cr), lead (Pb), nickel (Ni), and copper (Cu) were obtained in relation to their affinity for suspended solids at various sediment concentrations. Figure 8 is an example plot of TSS versus K_p for Pb. Using these K_p values, and data obtained from the dissolved contaminant levels of various trace metals (U.S. Geological Survey, 1996), it was possible to predict the particulate contaminant concentration levels of the trace metals under six oscillation rates. Standard deviations and particulate contaminant concentrations of the five trace metals used to link the potential resuspension of heavy metals with the resuspension of bottom sediments in the lower Housatonic River are shown in
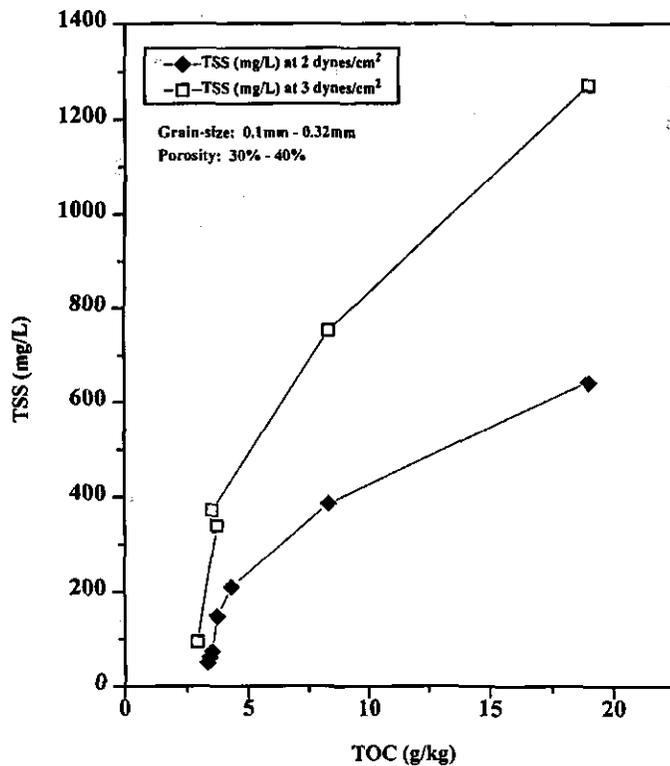
Figure 7. Impact of total organic content on TSS resuspension.

Table I. There are significant variations in particulate contaminant levels relative to variations in TSS concentrations. Of the 34 cores extracted from the system, 70% verified that the particulate concentrations of trace metal contaminants increased with increases in TSS (hence with increased stream flow) as K_p decreased. The other 30% reflected partial increases, particularly at higher stream flows. Of the five trace metals studied, Pb exhibited the greatest increase in particulate contaminant levels with increases in suspended solids. This was well illustrated in core 5 at lake Lillinonah (Figure 9).

The lead particulates increased from 1.1 μg L^{-1} at an initial TSS value of 27.4 mg L^{-1} to 28.3 μg L^{-1} at a TSS of 1886.2 mg L^{-1}. This may be attributed to the high partition coefficients of lead in relation to resuspension concentrations of suspended solids. Nickel also exhibited high particulate levels of 11.3 μg L^{-1} at a high flow simulation, and therefore at a high resuspension concentration of TSS. Particulate concentrations of Cd, Cr, and Cu were small relative to Pb and ranged from 0.18 to 3.5 μg L^{-1}. In Figure 10, the particulate concentrations of Pb in all cores within the system increased as the applied stream flow increases.
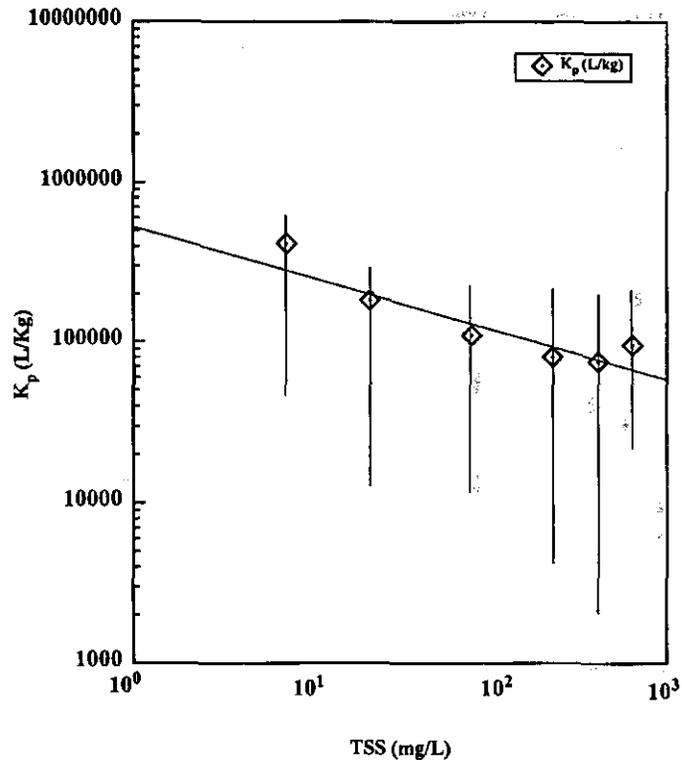
Figure 8. Relationship between partition coefficient K_p and TSS for lead trace metal in river systems.

TABLE I

Prediction of particulate metals distribution in the lower Housatonic River

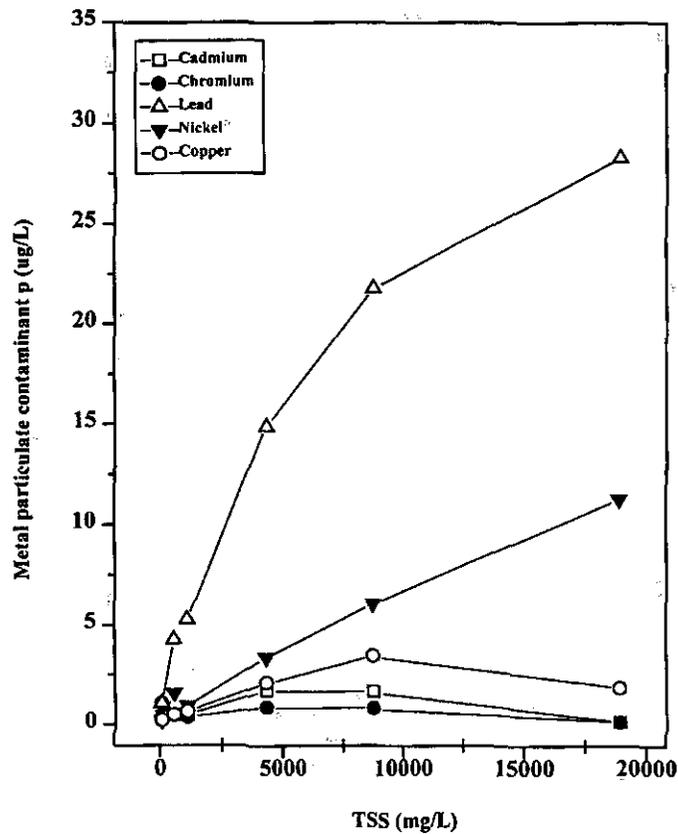| Trace metal	c	K_p range	TSS range	n	Particulate contaminant p			
					Avg.	SD	Max.	Min.
	$(\mu g\, L^{-1})$	$(L\, mg^{-1})$	$(mg\, L^{-1})$			$(\mu g\, L^{-1})$		
Cadmium	0.1	−0.001–0.8	3.2–20649.3	204	0.74	0.72	3.1	0.03
Chromium	0.1	−0.001–0.8	3.2–20649.3	204	1.03	1.50	10.0	0.10
Kead	0.1	−0.001–0.8	3.2–20649.3	204	5.00	8.50	33.6	0.03
Nickel	0.1	−0.001–0.8	3.2–20649.3	204	1.50	1.80	18.1	0.02
Copper	0.1	−0.001–0.8	3.2–20649.3	204	0.94	0.79	7.4	0.10

Figure 9. Impact of TSS on trace metal resuspension at Lake Lillinonah.

5. Conclusion

Data analyses have suggested porosity, grain-size, and total organic content influence the redistribution and entrainment of bottom sediments in the water column. Experimental results have likewise verified correlations between porosity, grain-size, TOC, and TSS/VSS. From the data obtained, it is reasonable to assume the potential for the resuspension of heavy metals in the aquatic environment is linked to an interdependence amongst these parameters. Based on these findings, it may be affirmed that the PES is an effective tool in assessing the extent to which contaminant loadings influence water quality standards. However, the lower Housatonic River represents a continuous flow of a vast body of water that is impacted by numerous impoundments. In such an expansive ecosystems, it may be necessary to study a larger more representative number of cores from more diverse sediment zones along the river to procure a comprehensive evaluation of sediment
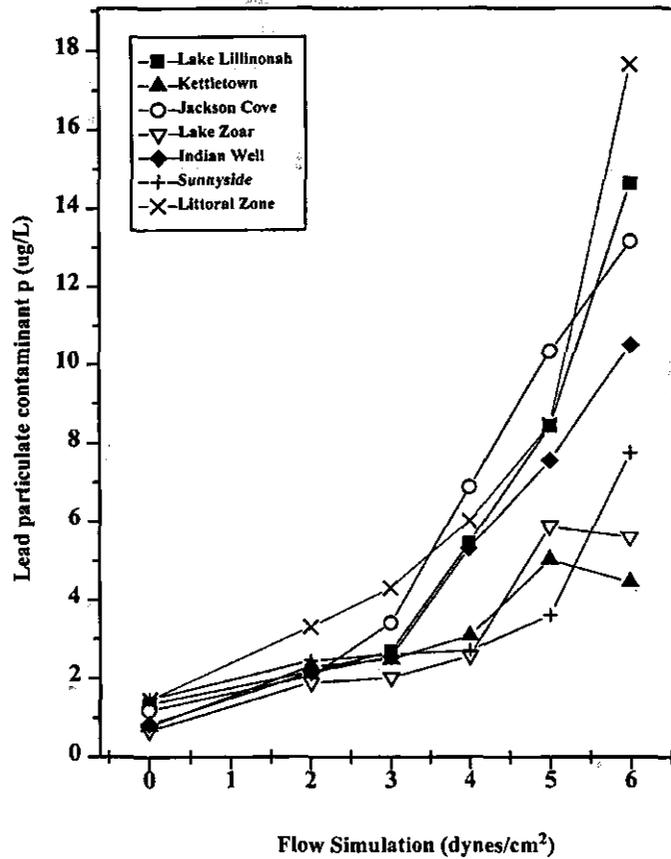
Figure 10. Impact of flow simulation on average particulate concentration of lead.

characteristics, and consequently validate the impact of the various parameters on contaminant loads.

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