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페즈(PES)를 이용한 하천의 토사 이동 시뮬레이션

Simulation of Sediment Transport in a River System Using Particle Entrainment Simulator

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Abstract

A feasibility of using Particle Entrainment Simulator (PES) to evaluate model variables describing sediment entrainment in a river system was investigated. PES in a laboratory was utilized to simulate the sediment resuspension phenomenon in the river and the subsequent relationship between shear rate and sediment entrainment was developed. The total suspended solids (TSS) data from PES was incorporated into statistical models in an effort to describe behaviors of net particle movement in the river. PES was found to be adequate for simulating particle entrainment phenomenon in a river system. Statistical analysis was used to assess propriety of PES data for predictive purposes. The results showed good relationships between PES results and system variables, such as average stream velocity and net particle movement.

Key words: particle entrainment, shear stress, river velocity, total suspended solids, sediment transport, statistical analysis.

주제어: 토사 거동, 전단응력, 하천유속, 총고형물질, 토사이동, 통계분석

1. INTRODUCTION

It has been well documented that toxic chemicals from industrial discharges, sewage treatment plant effluents, and surface runoff have a high affinity with sediment particles. Understanding of the fate and transport of particles is important, because they serve as indicators for the potential hazards associated with anthropogenic contributions from heavy metals in the aquatic environment (DiToro, 2001; Chapra, 1997; Thomann, 1987; Forstner, 1979).

These impacts may predicted by using computer models to simulate the effects from sediment transport in rivers. River water pollution can be alleviated by the help of these computer models to determine an appropriate waste load allocations for industrial and wastewater

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treatment plants. Therefore, to understand the transport of toxic substances between the water column and the sediment is crucial for determining possible impacts on the river (Jansen, 1979; Callahan, 1979; Dickson, 1982; Conway, 1982).

The settling and resuspension velocities of sediment are the most difficult parameters to be determined accurately in the quantitative analysis of sediment deposition and entrainment. They are essential for predicting the sediment transport in an aquatic environmental system, however, a cost effective and reliable method for determining the suspended solid transport rate at the sediment water interface is still under investigation. There are two available methods to determine sediment entrainment rate estimation : the one is a trial and error method from computer model application and the other is laboratory testing method.

The weakness in determining a sediment transport rate from model utilization is that the coefficient from the model becomes too specific in the specified site or reach). Modeling such a complex system is important, but difficult because particle entrainment is dependent upon current velocity, particle texture, mineralogy, water content and biological content (Salomons, 1984; Karickhoff, 1979). The calculated coefficient has a handicap because it adds an inherent amount of uncertainty to any constituent predictions, when applied to the modelling for a different river or a flow condition.

As the model application is site specific, laboratory analysis, using the annular flume, provides predictions of settling or entrainment rates for a specific sediment (MacIntyre, 1986; Lick, 1982; Tsai, 1986). Weak points with annular flume studies are the inability to mimic in-situ conditions and the cost related to calibration procedure. Sediments need to be sieved and homogenized before being placed in the annular flume, which resorts the sediment particles and causes a redistribution of the original particle bonding.

The need for a field assessment of undisturbed sediment can be fulfilled by using the Particle Entrainment Simulator (PES) (Fukuda, 1980; Lavelle, 1987; MacIntyre, 1986). PES makes it possible to determine the sediment erosion activity from relatively undisturbed field samples. Total suspended solid concentrations may be determined as a function of known shear rate over time to simulate surface sediment resuspension characteristics. This laboratory method is able to empirically bypass traditional predictive methods for determining bottom sediment velocity, such as the trial and error procedures used in modeling. The feasibility of using the PES for a quantitative analysis of resuspension phenomenon in a river system was studied in an attempt to relate PES results to physical characteristics of river that influence sediment transport.

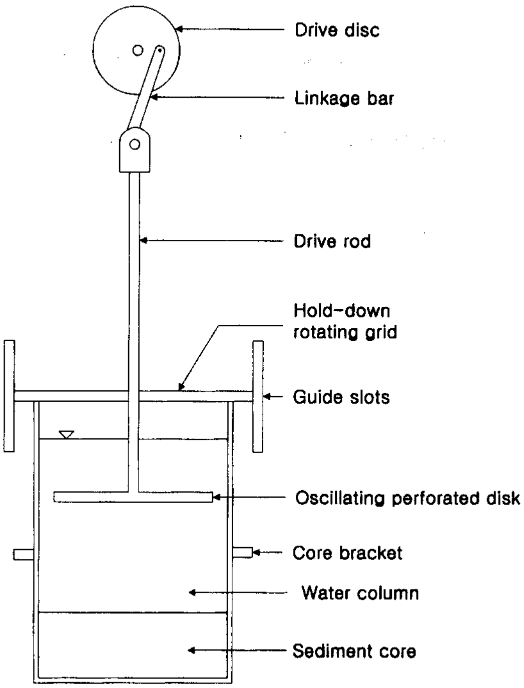

Fig. 1. Particle entrainment simulator

2. MATERIALS AND METHODS

2.1. Sampling and Analysis

Construction of PES, shown in **Fig. 1**, was completed according to the specifications from USEPA PES (MacIntyre 1986). The PES has an aluminum drive disc and linkage bar driven by a 1/8 horse power, variable speed motor. An aluminum driving rod connecting the linkage bar to the grid is kept in alignment through the use of bronze bushings. The bar is set 1.27 cm off the center of the disk to create a vertical displacement of 2.54 cm in the water column. The oscillating perforated disk is made of plexiglass and has 42.8% openings formed by evenly spaced holes of 1.2 cm diameter with 1.5 cm apart between holes.

The field work involved sediment core collection for the PES, flow monitoring and bottom topography profiles, all of which were conducted within 10 km upstream of the mouth of the Pawtuxet River in central Rhode Island, the United States. The river mouth has run-of the-river type dam, known as the Pawtuxet Cove Dam, to protect fresh river water from salt water intrusion. The first core sampling station is located 6.2 km from the Cove and the second one is located 0.77 km from the river mouth. The water quality surveys for the total suspended solids (TSS) were also conducted before and after each PES sampling. Five to six cores were sampled during each field survey for the PES at two sites. Core collection was done once a month from June through December 1999, except in November 1999. Hourly gage measurements for river stage were used from the records of the United States Geological Survey (USGS) gaging station, which is near the sampling stations. The daily average and standard deviation flow were determined from the USGS gage charts for each survey.

Samples of the river sediments were retrieved by wading into the river and inserting an acrylic core into the river bottom. The 30 cm high acrylic core has an outside diameter of 13 cm and an inside diameter of 12 cm. A 1.3 cm thick beveled plate with a 15 cm diameter was slid underneath the acrylic core before extracting the sediment sample with the overlying river water. The beveled plate has a 0.6 cm wide and 0.3 cm deep groove in it. Samples were carefully handled to capture representative surface material while avoiding any visible disturbance. On the river bank, the cores were carefully transferred to another beveled plate which has a tube of clay filled in the groove. Subsequently, each core was firmly pressed into the groove to prevent any leakage. A tube was stretched around the top wooden cover plate and the bottom plate prior to packing each core in ice for transport to the laboratory. All cores were transferred to an ice chest upon arrival at the laboratory, where they were repacked and placed on aeration. The water column in each core was slowly filled with filtered river water to prevent suspension and loss of the surface layer of sediment. The volume of water overlying the sediment was carefully monitored to maintain an undisturbed, saturated sample.

Sampling location of sediment were primarily determined by water depth and river bottom material. Cores could not be taken from the bottom over 60 cm deep under water surface because field crews could not slide the beveled plate underneath the sediment without being submerged. The characteristics of the river bottom, such as sediment composition, debris, and slopes, greatly influenced the placement of the cores during sample collection. Excessive plant growth, coarse soil and tree debris such as leaves, branches and trunks inhibited core sampling. During the core sampling for river bottom, the vertical velocity profile of the water column above the core collection site was taken using Marsh McBirney flowmeter, Model 201D. The recommended standard practice for vertical velocity profiles was followed for typical water depth of less than 60 cm. Velocity measurements were usually taken at intervals of 5 cm to accurately represent the vertical velocity profile.

River water samples for total (TSS) and volatile (VSS) suspended solids were collected with sediment core samples. Two-liter teflon buckets, which were throughly rinsed with river water, were used for surface water collection. Three one-liter bottles were used for water sampling. The average and standard deviation for TSS and VSS were determined for each station from the three samples. The temperature and conductivity were also measured using YSI SCT meter.

Each of the core samples were tested with equivalent bottom shear stresses of 2, 3, 4, and 5 dynes/cm^2 (0.08, 0.10, 0.12, and 0.16 oscillations/second of the grid). During each level of stress, the turbidity was measured using Bausch & Lomb, Spectronic 20, spectrophotometer. The turbidity samples were taken at 1, 2, 3, and 5 minutes after the initiation of a new stress and at every 5 minutes thereafter, until the concentration of suspended solids were at steady state. The sediment-water system simulated net erosion until a condition reached to the equilibrium that deposition was equivalent to erosion. We considered it as the steady state condition when the light attenuation changed less than 2% over 5 minutes. With cores which were prominently composed of coarse-grained sediments (medium sands), it took about 90 minutes to complete the experiment. With cores that were composed of fine-grained sediments (fine silts), it took up to 130 minutes.

A distilled water sample representing 100% light refraction was stored in the spectrophotometer during turbidity measurements, for reference. A total suspended solids sample was drawn from the port on the core during steady state for each shear stress and the turbidity was measured. To maintain the volume of fluid uniformly above the sediment surface throughout the experiment, an equivalent amount of filtered river water (100 mL) was added to the sediment core sample after each sampling of TSS. It was assumed that the amount of filtered water added to the core would not significantly influence the TSS sample at the next shear level. This assumption was based upon the observation that the concentrations of TSS increased exponentially with the increase of the shear rates, but dilution effects were insignificant. TSS concentrations were measured for all samples until the each steady state conditions were reached for a specific shear stress using the standard methods and Gelman A/E filter papers with 1.0 μm nominal pore size were used (APHA, 1998).

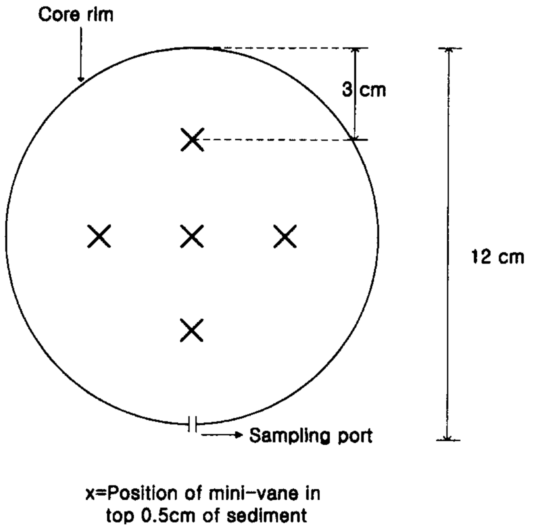

Fig. 2. Positions utilized during mini-vane shear tests.

2.2. PES Testing

Cores from the river which were placed in the PES followed the same laboratory procedure for core preparation and testing as described before. A Bausch & Lomb, Spectronic 20, spectrophotometer was used for turbidity measurement. Two conditions were modified compared with the standard procedure for testing the river corers (MacIntyre 1986): (1) Filtered river water was utilized for replacing the volume of water taken during TSS measurements, instead of unfiltered river water, and (2) Sediment cores were exposed to five shear rates instead of the typical four shear rates. The five shear rates included 0.5, 1, 2, 3, and 4 dynes/cm^2 which are equivalent to 0.02, 0.04, 0.08, 0.10 and 0.12 oscillations/second. After tests were carried out under the condition of four shear rates of 2, 3, 4 and 5 dynes/cm^2 for the preliminary two water quality survey of June and July, the lower range of 0.5 and 1.0 dynes/cm^2 were introduced and 5 dynes/cm^2 was deleted from the test conditions Since the river system is more accurately simulated using the lower shear rates than higher ones, these ranges of shear rate were adopted. Shear rates of equivalent grid oscillations were set from marks placed on the PES rheostat box before the calibration.

An average Bingham shear stress was measured at 5 positions on the sediment surface, as shown in **Fig. 2**, using a standard Brookfield recording viscometer. The standard Rheolog viscometer, Model HAT-RL4432, had a maximum torque of 14,374 dyne/cm^2.

It was operated by a 300 rpm rotor with speeds ranging from 0.5 to 100 rpm. All experiments during this study used a miniature vane with a height of 4 mm and a diameter of 8 mm. The vane shearing rotation began within 30 seconds after the vane was placed in position to avoid consolidation effects.

The basic principles of the test were to insert a four bladed miniature vane and spindle into the sediment and rotate it to measure the torque required to shear the sediment surface. The inserted vane was driven by the motor through a calibrated beryllium copper spring. The deflection in the spring by the shear stress on the vane in the sediment core made a blade within the instrument push a small air jet, which resulted in a back pressure in the air line. The changes in the line pressure were converted to an electrical signal by a pressure transducer. The electrical output was linearly related to the torque. The electrical signal output was graphically recorded using a Hewlett-Packard Model H45-7100B recorder. The maximum torque represented the shear strength of the sediment core at each testing position. The Bingham shear stress was determined using equation 1.

$$\tau = \frac{T}{\pi\,[(bD^2/2) + (D^3/6)]} \qquad (1)$$

where, τ equals to Bingham shear stress (dynes/cm^2), T is the torque required to rotate the actual vane of height, b and diameter, D.

There are several assumptions in deriving the equation to calculate bingham shear stress using a cylindrical miniature vane. These assumption are as followings:

(1) Vane insertion causes negligible disturbance to the original stress distributions.

(2) The penetration occurs across the entire surface and in the same shape and size as the cylinder of diameter, d, and height, h, formed by the vane rotation.

(3) Drainage and progressive failure do not occur in significant magnitude during the test.

(4) Sediment properties are considered isotropic.

2.3. PES Data Analysis

The standard statistical analysis were utilized to develop a simple model of the PES, TSS and shear rates (Neter, 1985). A subsequent statistical analyses were conducted to test the validity of generated regression lines. Before statistical modeling, we checked up the feasibility of model application by plotting the raw data on the graph to look over the trend of data. Figures showed various relation of the natural logarithm and inverse of TSS and shear rates. The straight line model incorporated the natural logarithm of TSS at steady state as a dependent variable and the shear rate in the PES as an independent variable. This model is shown in equation 2.

$$\ln(y) = a + bx \qquad (2)$$

where, y is TSS concentration, x is the shear rate, a is an intercept in an ordinate, and b is the slope of the line. Simple linear regression was performed using the natural logarithm of TSS for each shear rate. Tests were performed on the data from individual sediment cores in each water quality sampling station according to least square method. A student t-test was performed on all regression lines to assess the independence of the regression line and to determine whether the independent variable x, shear rates, explains a significant portion of the dependent variable $\ln(y)$, the logarithm of TSS concentrations. The hypothesis test was done in this case.

$$H_o : b = 0 \qquad (3)$$

$$H_a : b \neq 0 \qquad (4)$$

where, H_o is the null hypothesis stating that the slope, b, of the regression line is zero, and H_a is the alternative hypothesis stating that b is not zero, which means the regression line is meaningful in that the independent variable explains the significant portion of the variability of the dependent variable. A two-tailed t-test was conducted with n-2 degree of freedom.

The data which has a unusual values was checked with

Table 1. Pearson correlation matrix for TSS vs. shear rate

	Station 1		
	TSS	TSSLN	TSSINV
SHEAR	0.473	0.731	-0.648
SHEARLN	0.442	0.731	-0.698
SHEARINV	-0.369	-0.665	0.683
	Station 2		
	TSS	TSSLN	TSSINV
SHEAR	0.664	0.831	-0.411
SHEARLN	0.587	0.829	-0.499
SHEARINV	-0.470	-0.763	0.551

TSS: Total suspended solids (TSS) (mg/L)
TSSLN: Natural log of TSS
TSSINV: Inverse of TSS
SHEAR: Shear rate (dynes/cm^2)
SHEARLN: Natural log of shear rate
SHEARINV: Inverse of shear rate

the one in other observations. In order to avoid bias determination, the statistical method to find outlying observations was applied. This method tests the highest and lowest observation value for a given sample population. To test whether the largest observation, x_n, in normal samples is too large, equation 5 was used:

$$T_n = (x_n - x) / s \qquad (5)$$

where, T_n is the calculated significance with sample size n, x is the mean value of the sample population, and s is the standard deviation. Similarly, to test whether the smallest observation, x_n, in normal samples is too small, equation 6 was used:

$$T_n = (x - x_n) / s \qquad (6)$$

A table of critical value, T, was used, which lists the significance levels that cannot be exceeded to keep the data point in the population.

3. RESULTS

The graphical analysis has represented PES data as

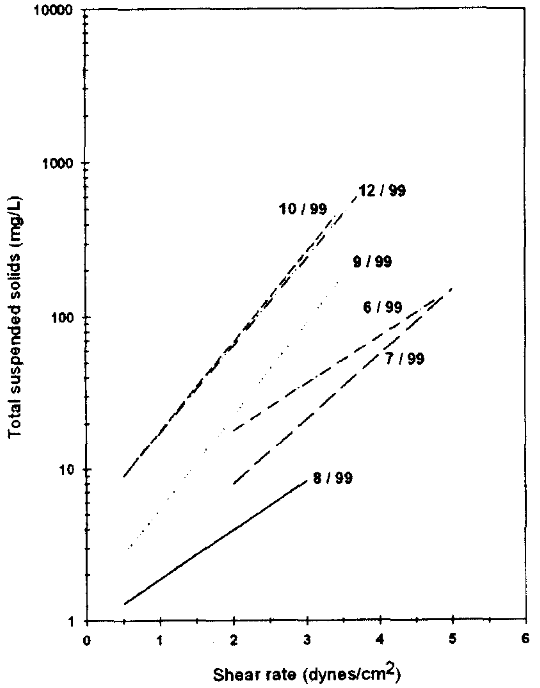

Fig. 3. Average monthly regression lines for station 1.

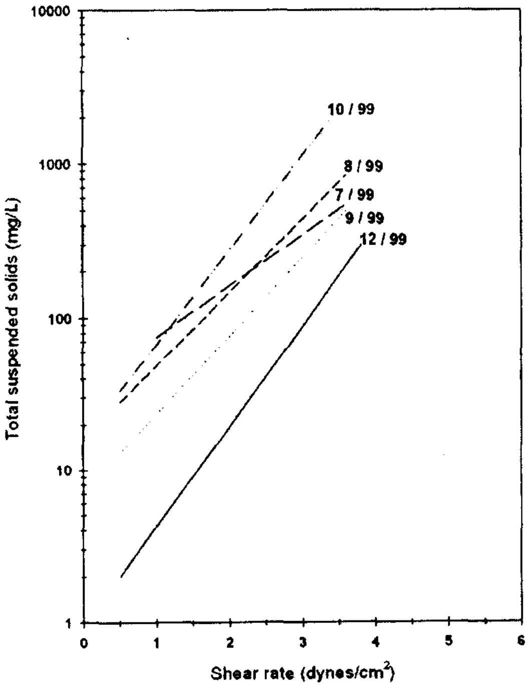

Fig. 4. Average monthly regression lines for station 2.

Table 2. Monthly linear regression results

Month	N	R^2	R	Rc	YINT	SLOPE	T	Tc
				Station 1				
June	8	0.706	0.840	0.632	1.662	0.635	3.80	2.306
July	8	0.868	0.932	0.632	0.204	0.956	6.27	2.306
August	4	0.970	0.985	0.811	0.602	0.514	8.08	2.776
September	15	0.600	0.775	0.482	0.554	1.045	4.42	2.131
October	15	0.733	0.856	0.482	1.424	1.216	5.97	2.131
December	10	0.953	0.976	0.576	1.568	1.280	12.80	2.228
				Station 2				
June	8	0.930	0.964	0.632	1.402	1.195	8.95	2.306
July	7	0.871	0.933	0.666	3.061	0.659	5.81	2.365
August	15	0.879	0.938	0.482	2.720	1.039	9.70	2.131
September	14	0.920	0.959	0.497	2.035	1.095	11.70	2.145
October	13	0.943	0.971	0.514	2.999	1.211	13.50	2.160
December	15	0.923	0.961	0.482	-0.117	1.461	12.50	2.131

LN (TSS) = YINT + (SLOPE) × (SHEAR RATE)
N: Number of samples
R^2: Coefficient of determination
R: Correlation coefficient (test statistic)
Rc: Critical R (5% significance level)
YINT: Ordinate intercept
T: Student t statistic for slope
Tc: Critical t (5% significance level with two-tail)

semi-log relationship, where the natural log of TSS was plotted against the shear rate on a normal axis to form a linear relationship. An attempt was made to check if there is a better procedure for representing the PES data as a straight line. Statistical analysis of the PES data using the Pearson product moment correlation matrix is presented in **Table 1**. There were 60 and 72 observations incorporated in the station 1 and 2, respectively, for this procedure.

Each Pearson correlation matrix indicated the natural log of TSS versus shear rate gave the highest coefficients of 0.731 and 0.831, for station1 and 2, respectively. Another significant relationship was shown between the natural log of TSS to and the natural log of shear rate, that generated the coefficients of 0.731 and 0.829 for station 1 and 2, respectively. Representing PES data as a semi-log relationship was supported by the best Pearson correlation, however, the log-log relationship also showed a meaningful results. A plots of the average monthly regression lines for the station 1 and station 2 are presented in **Fig. 3** and **4**. The average monthly regression results are shown in **Table 2**. The regression lines are proven to be valid statistically on the base that they passed student t-test and critical r value test.

River shear rates were predicted using the linear relationship between shear rate and the river velocity. This is presented in **Fig. 5**, where shear rate increases linearly as velocity increases. This is the most important relationship generated in this PES feasibility study since it relates laboratory PES results to field measurements of stream velocity. A significant dependence between shear rate on the river bottom and average stream velocity was found, generating a coefficient of determination (R^2) of 0.795. This regression line supports the fact that the sediment transport capacity is generally equal to the transport capacity of the river flow. The remainder of the coefficient of determination, 0.215, can be explained by the characteristics of bed material and flow conditions.

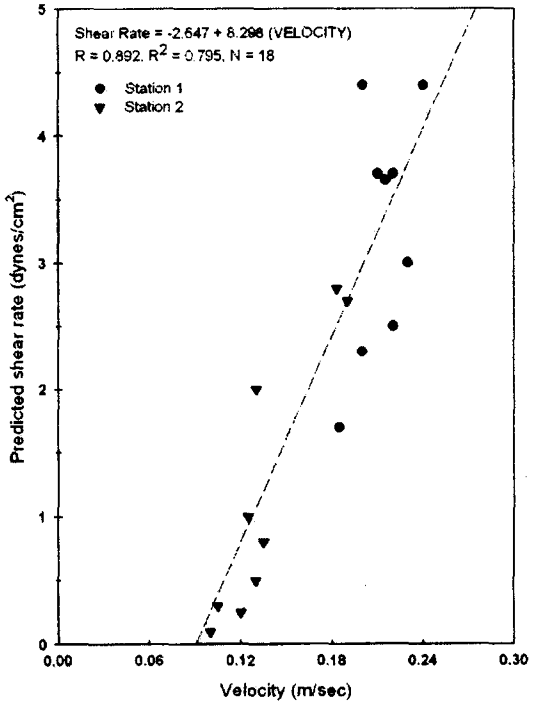

Fig. 5. Predicted river shear rate vs. velocity.

For instance, a free exchange of the bed material load with the bed is not possible in some cases due to the presence of gravel layer. In that case, the sediment transport may be smaller than the transport capacity of the river flow. The sediment transport then depends only on the sediment supply to the reach. A relatively abrupt changes of flow can also be a factor that affects the relation between shear rate and river velocity. This curve was drawn using 18 data points generated from PES data of sampling stations 1 and 2 in the flow range of 4.8-6.5 cubic meter per second, which has the range of ±1 standard deviation from the average annual daily flow. The mean, standard deviation, and 95% confidence interval of TSS at each shear rate is given in **Table 3** for each sampling location.

The semi-log relationship between TSS and river bottom shear rate was investigated using monthly PES data that are presented in **Fig. 3** and **4**. TSS was plotted against shear rate for station 1 in **Fig. 6**. The coefficient of determination was 0.617, which means bottom shear rate contributes 61.7% of TSS in the water column of the river. The rest 38.3% of TSS can be attributed to factors, such as wash load. Wash load is the concept against bed material transport, both of which contributes to sediment transport in the river (Jansen, 1979). Wash load is defined by the transport of material finer than the bed material. It has no relation to the sediment transporting capacity of the river and the wash load rate is determined by the amount which becomes available by erosion in the catchment area upstream. Since the distinction between bed load and suspended load from wash load origin cannot be defined sharply in the river, both grain size and flow condition should also be taken into account when explaining TSS with bottom shear rates. **Fig. 7** shows the relationship between TSS and shear rate for the station 2. The regression line has 62.2% coefficient of determination.

Table 3. PES TSS data at each shear rate

Shear rate (dynes/cm²)	N	Mean TSS (mg/L)	STD TSS (mg/L)	95% CI (mg/L)
		Station 1		
0.5	7	5.0	3.1	2.2-7.8
1.0	7	10.1	6.8	3.8-16.4
2.0	11	33.4	32.9	10.4-55.5
3.0	10	91.9	90.5	27.2-157
4.0	11	250	270	68.70-432
		Station 2		
0.5	9	11.9	10.5	3.9-20.0
1.0	12	35.6	27.6	18.1-53.1
2.0	13	131	116	60.7-200
3.0	14	413	380	194-632
4.0	13	847	667	445-1,250

N: Number of samples
TSS: Total suspended solids (mg/L)
STD TSS: Standard deviation of TSS (mg/L)
95% CI: 95% Confidence interval of TSS (mg/L)

In view of application of the PES to the river system, an attempt was made to relate the PES data to the net sediment transport coefficient, K_{ns}. The K_{ns} coefficient could be estimated from the solids data by combining a settling and resuspension of solids in the river, where the effect of dispersion is small in comparison with advection

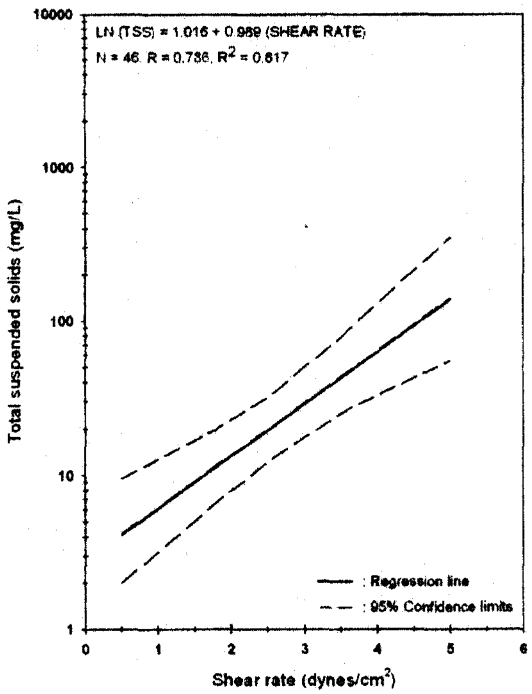

Fig. 6. TSS vs. shear rate for station 1.

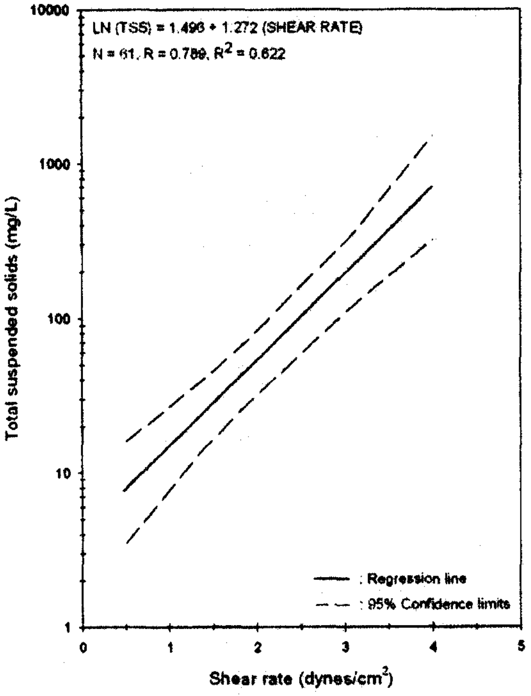

Fig. 7. TSS vs. shear rate for station 2.

Table 4. Net sediment transport coefficients (Kns) at each river shear rate

Shear Rate (dynes/cm^2)	K_{ns}
0.45	-0.70
3.94	-1.00
3.89	-1.17
3.81	-1.06
4.57	-1.30
2.49	-1.00
3.02	-0.87
2.27	-1.29
1.81	-1.52

(O' Connor 1983). This K_{ns} coefficient could be described linearly as a function of average stream velocity, U. A positive value of K_{ns} coefficient indicates a net increase of solids in the water column is due to the dominance of resuspension over settling. A negative value of K_{ns} coefficient indicates a net decrease of solids is due to the dominance of settling over resuspension. **Table 4** presents the predicted Kns coefficient versus predicted shear rate using regression line.

This means the net settling of sediment occurred in the station 1 with flow range of 4.8-6.5 cubic meter per second. Following the logic of the net sediment transport coefficient, a decrease of particles from the water column in the river would be shown as a negative coefficient due to the dominance of settling over resuspension. These results support the suitability of application of PES data for predicting a vertical sediment movement in the river system. The net sediment transport coefficient can be incorporated into a water quality computer model to predict the fate and transport of particle reactive substances, such as trace metals.

4. CONCLUSIONS

The USEPA Particle Entrainment Simulator (PES) was used to determine the relationships between shear rate and sediment entrainment in a river system. A linear relationship was developed for each PES core. Simple linear regression on the natural log of TSS vs. shear rate showed a significant coefficient of determination for all cases. The net sediment transport coefficient, which is estimated from informations on solids data, was successfully correlated to the PES data. This coefficient could be incorporated into the computer model to predict the paths of solids in the river and used as a basis to explain the solids settling and resuspension phenomena in the river. This solids movement in the river could also be applied to simulate the fate and transport of heavy metals which are subject to adsorption and desorption to the particles.

Due to the narrow range of flows observed for the water quality survey, the application of the PES for prediction purposes could only be done for a small window of data. Therefore, any seasonal variations that are associated with low to high flows from spring through fall could not be guaranteed. That is to say the PES data may be applicable to the river system within the observed stream flow range. Since the previous efforts were focused on the experiments conducted on sediments from lakes, oceans, and estuaries, these results support the fact that the PES is feasible to be used in very different aquatic systems of very different bottom soil types.

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