

Cooperating Parties Group

**LOWER PASSAIC RIVER RI/FS
NEWARK, NEW JERSEY**

APPENDIX M - ATTACHMENT C

ENTRAINMENT RATE ANALYSIS

Prepared by:



C.1 Introduction

The system understanding of sediment transport developed for the LPRSA indicates that in general, suspended sediment (SS) dynamics during normal tidal and low-average discharge conditions follow a cyclic pattern, with SS concentrations increasing during the flood and ebb tides, reaching a maximum around mid-tide and decreasing thereafter and reaching a minimum around low-water and high-water. The variability in SS concentrations scales with tidal currents on intra-tidal as well as inter-tidal time-scales, with SS concentrations increasing as velocity increases (both within the tide as well as over spring-neap cycles) and decreasing as velocity decreases. The intra-tidal variation in SS concentration and its dependence with tidal currents is indicative of a pool of easily erodible sediment termed the fluff layer overlying less erodible strata. Sediments from the fluff layer are resuspended during the flood and ebb tides with deposition from the water column around the time of low and high water acting to replenish the fluff layer. Furthermore, the system understanding of sediment transport also indicates that SS dynamics within the LPRSA are dominated by fluff layer dynamics during normal tidal and low-average discharge conditions. Therefore, the inclusion of fluff layer dynamics within the computational framework of ECOM-SEDZLJS is key to reproducing the intra- and inter-tidal variability in SS concentrations measured within the LPRSA during normal tidal and low-average discharge conditions.

The representation of the fluff layer within the computational framework of ECOM-SEDZLJS includes two separate aspects:

- The schematization of the bed structure in the model to include (1) a fluff layer, (2) the dynamics of the fluff layer under erosional and depositional regimes, and (3) the interaction between the fluff layer and the underlying less-erodible layers.
- The definition of the erosion properties of the fluff layer, in particular the critical shear stress for erosion and the erosion rate function.

The former is described in the main body of the report; this attachment describes the development of the erosion properties of the fluff layer. The erosion properties of the fluff layer have been developed from an analysis of the 2009 Fall PWCM data. The following sections describe the data used for this analysis, the formulations involved, and the results of the analysis. The resulting erosion properties for the fluff layer have also been compared against the erodibility measurements performed using the Gust Microcosm (this is described in Attachment D).

C.2 PWCM SS Concentration Dynamics

The development of the erosion properties for the fluff layer derives from certain observations from the Fall 2009 PWCM data. Figure 1 shows a two-day snapshot of the measured discharge at Dundee Dam and the tide at RM 1.4 (upper panels), the near-bottom velocity measured by the moored ADCPs at RM 1.4 and RM 4.2, and the ABS-derived

depth-average SS concentrations at RM 1.4 and RM 4.2. This period is associated with below average discharge from Dundee Dam and normal tidal conditions. Due to flood dominance in tidal currents (and therefore higher range of velocities achieved on flood than on ebb), this analysis is restricted to SS concentrations measured during the flood tide. The duration of the flood tide is indicated by the grey-shaded region (four flood tides during this two-day period).

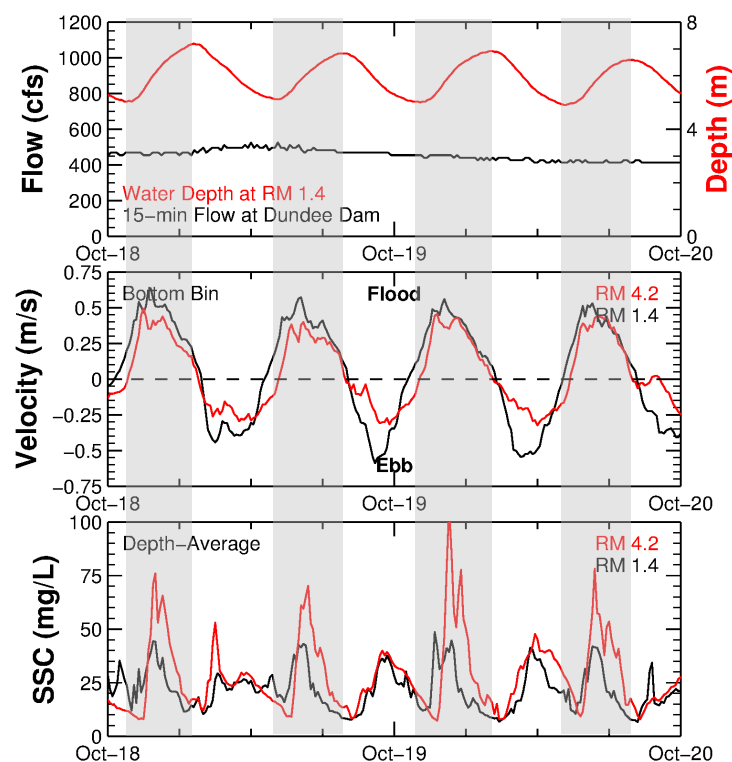


Figure 1. Time-series of discharge and tide, and near-bottom velocity and depth-average SS concentrations at RM 1.4 and 4.2 during the 2009 Fall PWCM program.

The SS concentrations show the cyclic behavior and correlation with velocity as described earlier, with concentrations increasing as velocity increases and decreasing as velocity decreases. Comparison of the SS concentrations at RM 1.4 and RM 4.2 also show that concentrations at both locations attain approximately similar values during slack water. However, during the following flood tides, SS concentrations at RM 4.2 typically reach higher values than the concentrations at RM 1.4. For instance, during the first low-water slack period on October 19, SS concentrations at both locations are approximately similar at 5-10 mg/L. During the following flood tide, concentrations increase at both locations, to ~50 mg/L at RM 1.4, and about twice as high (~100 mg/L) at RM 4.2. During this time period, the salt front and therefore the ETM are located up-estuary of RM 6.7, thereby ruling out the possibility that the additional SS concentration measured on the flood tide at RM 4.2 could reflect the up-estuary transport of the ETM. The location of the ETM up-estuary of RM 6.7, and the similarity of the slack-water concentrations at RM 1.4 and RM 4.2 during this period leads to the consideration that slack-water concentrations in the reach

between RM 1.4-4.2 may be similar to the 5-10 mg/L values measured at RM 1.4 and RM 4.2. With this assumption, the additional SS concentration measured at RM 4.2, may be considered to be associated with resuspension in the reach between RM 1.4-4.2. Restricted to the period of accelerating flood velocities, which is also the period of increasing SS concentrations, this increase in SS concentration at RM 4.2 represents gross erosion rather than net erosion between RM 1.4-4.2. This pattern of higher SS concentrations during the flood tide at RM 4.2 than at RM 1.4 is generally true during all periods when the salt front and therefore the ETM are located up-estuary of RM 4.2. Since erosion and deposition during such normal tidal and low-average flow conditions is expected to be dominated by the fluff layer dynamics, this increase in SS concentration is analyzed for an assessment of the erosion properties of the fluff layer as described in the next section. However, since this analysis uses an indirect measurement (SS concentrations) rather than a direct measurement of erosion, the results are presented in terms of the entrainment process rather than erosion. Accordingly, the term entrainment rate is used rather than erosion rate.

C.3 Idealized Schematic – Entrainment Process

The velocity and SS concentration fluctuations described in the preceding section have been used to examine the entrainment process and its dependency with tidal currents. Figure 2 shows an idealized conceptualization of the velocity and SS concentration fluctuations over the tidal cycle (in Figures 2-A and 2-B, respectively) in a Eulerian frame of reference. Low-water ($T=0$), coincides with slack water (V_0) and also the minimum SS concentration over the tidal cycle (C_0) at RM 1.4 and 4.2. As the tide starts flooding, flow velocity increases to V_1 and subsequently V_2 ; SS concentration simultaneously increases to C_1 and subsequently C_2 . This conceptualization is also depicted in Figure 2-C in a Lagrangian frame of reference. At $T=0$, concentrations in the reach between RM 1.4-4.2 are assumed to be uniform (C_0). As the tide starts flooding, at $T=1$, the first parcel of water is transported up-estuary of RM 4.2, and the second parcel of water (influenced by some erosion and entrainment) moves to RM 4.2 and associated with concentration C_1 . At the same time, the third parcel of water, located some distance down-estuary of RM 4.2, is also assumed to attain concentration C_1 . At $T=2$, the third parcel of water is transported up to RM 4.2, associated with concentration C_2 reflecting the effect of some erosion and entrainment in the time interval from $T=1$ to $T=2$. This increase in concentration in time at RM 4.2 is used to calculate the entrainment rate using Equation 1:

$$E'_t = \frac{H_t}{\rho_d} \frac{dC}{dt} \quad (1)$$

where E' = entrainment rate (L/T), C = SS concentration (M/L^3), t = time (T), H = measured water depth at RM 4.2 (L), and ρ_d = dry density for the fluff layer (M/L^3 ; assumed as 327 kg/m³, equivalent to the fluff layer density in the ST model). The entrainment rate calculation is applied to the time-series of SS concentrations measured at RM 4.2 during the Fall 2009 PWCM program. The time-variable entrainment rate is also related to the measured tidal currents to determine the threshold for initiation of motion (the critical shear stress of the fluff layer) and the variation of the entrainment rate as a function of tidal

currents (analogous to the measurements of erosion rate as a function of shear stress in the Sedflume experiments used to define the erosion rate of the less erodible layers underlying the fluff layer).

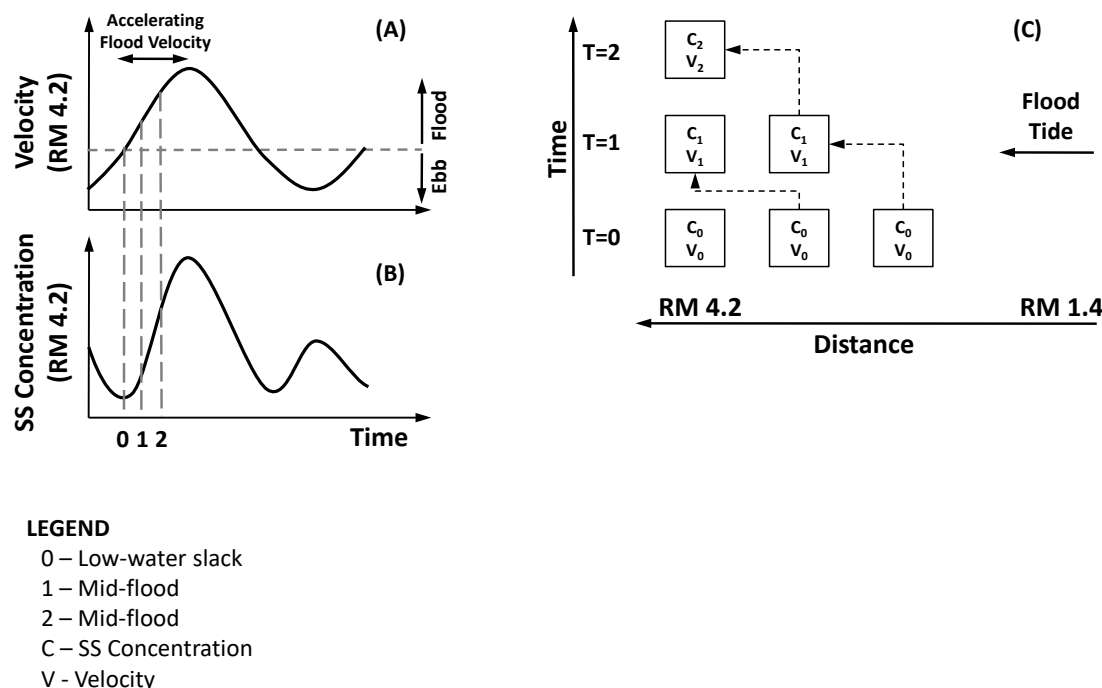


Figure 2. Idealized conceptualization of velocity and SS concentration fluctuations over the tide, and schematization of entrainment process.

C.4 Entrainment Rate – Application to Time-Series Data

The application of the entrainment rate calculation to the time-series of SS concentrations measured at RM 4.2 during the Fall 2009 PWCM program is subject to a few restrictions as described below. One restriction derives from certain phase differences between velocity and SS concentration time-series. Using the information in Figure 1 described previously, moving from low-water slack to flood, SS concentrations are typically seen to decline for some time even as flood velocities increase, reaching a minimum at some point following the initiation of the flood tide. As flood velocities increase, SS concentrations start increasing and reach a maximum after maximum flood velocities are attained. Conceptually, this increase in SS concentrations even after flood velocities have peaked may indicate the dominance of erosional processes over depositional process in this shear stress regime, and/or may indicate the influence of advection from RM 1.4 within that flood tide. Therefore, the entrainment rate calculation is performed over the duration of minimum to maximum SS concentration during the flood tide at RM 4.2 with a restriction to avoid the influence of advection from RM 1.4 as described next.

The entrainment rate calculation is conceptualized to include only the resuspension occurring between RM 1.4-4.2 on the flood tide following the period of minimum SS

concentrations. In order to avoid including the effect of erosion from locations down-estuary of RM 1.4, the SS concentration time-series was screened to exclude flow originating down-estuary of RM 1.4 and transported to RM 4.2 during the flood tide. Since the PWCM program included moored ADCPs measuring the velocity profile at RM 1.4, the measured velocities at RM 1.4 were used to calculate the distance travelled by a parcel of water located at RM 1.4 at the beginning of the flood tide and only the portion of the SS time-series at RM 4.2 not influenced by the inflow at RM 1.4 were included.

Another restriction on the time-series used for the entrainment rate calculations involves the location of the ETM. In order to avoid a SS concentration signal at RM 4.2 influenced by the tidal excursion of the ETM, the entrainment rate calculations were only performed for periods when the salt front and therefore the ETM are location up-estuary of RM 4.2. Accordingly, these periods correspond to October 11-24 and November 21-28 during the 2009 Fall PWCM program. Collectively, these periods also cover a full spring-neap cycle.

C.5 Entrainment Rate – Relation with Velocity and Shear Stress

Figure 3 shows the calculated entrainment rate for the two periods mentioned previously from the Fall 2009 PWCM program plotted as a function of the measured velocity at RM 1.4.

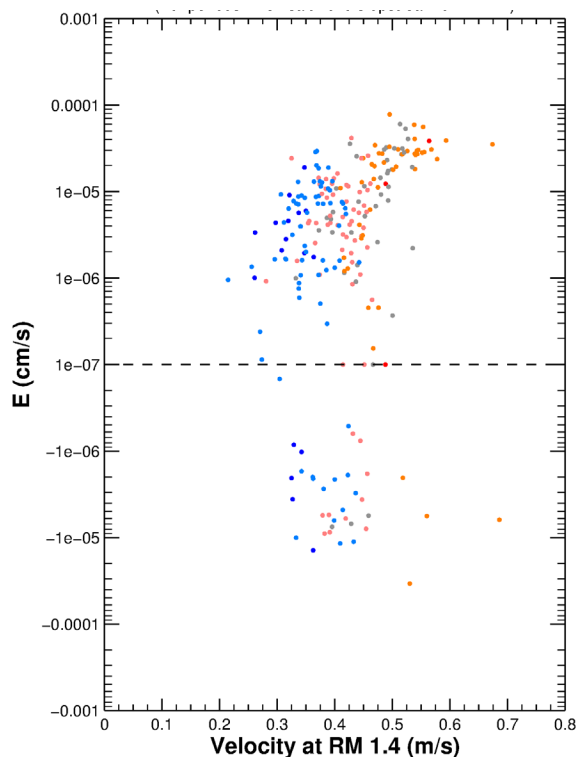


Figure 3. Entrainment rate (on Y-axis, in cm/s) versus measured near-bottom velocity at RM 1.4

Given the availability of high-frequency SS concentration data, the entrainment rate is calculated every 12 minutes within the tidal cycle for the two periods mentioned previously. In this case, the entrainment rate is plotted against the near-bottom velocity measured by the ADCP at RM 1.4 for illustration purposes. The near-bottom velocity can be taken as a surrogate for bed shear stress. Since the entrainment rates were calculated from high-frequency SS concentration measurements, they are susceptible to variability in the SS concentrations. However, the effect of this variability in SS concentrations (as judged by the range of entrainment rates as well as negative entrainment rates) is restricted to a relatively small subset (15%) of the entire dataset. The negative entrainment rates also occur mostly towards the lower end of the velocity range (between 0.3 and 0.45 m/s) over which the entrainment rate analysis is performed. Examination of Figure 1 shows that this is also the range of flood velocities occurring immediately after slack water when SS concentrations reach minimum values (after ebb) before showing the characteristic increase on flood. In other words, the negative entrainment rates occur mainly during the lower velocities (occurring after slack water) when SS concentrations are relatively low compared to other periods within the accelerating flood tide. The entrainment rate data also show a relationship with velocity, increasing as velocity (and shear stress) increases. Functionally this is similar to the relationships measured in the Sedflume erosion experiments.

C.6 Model Parameterization – Fluff Layer Erodibility

The entrainment rates were paired with shear stress using the approach described in Mathew and Winterwerp (2017). Briefly, the entrainment rate (which is calculated using the SS concentration data from one instant to the next at RM 4.2), is assumed to be reflective of the erosion and entrainment experienced by given parcel of water traveling to RM 4.2 over corresponding time period. In other words, the entrainment rate calculated over a certain time period (and associated with given parcel of water) is considered to be a function of the Lagrangian shear stress experienced by that parcel of water over corresponding time period.

The Lagrangian shear stresses were estimated using high-frequency outputs of the depth-average velocity and shear stress calculated by the HD model along the thalweg of the LPR. The depth-average velocity fields were used to calculate the flow path (typically a distance of less than 0.3 miles down-estuary of RM 4.2) during the time period associated with a given entrainment rate measurement, and thus estimate the Lagrangian shear stress. The approach to calculate the Lagrangian shear stresses involves a number of approximations and assumptions as described in Mathew and Winterwerp (2017). As shown in Figure 4, the resulting pairs of entrainment rate and shear stress were examined in a manner analogous to the data from Sedflume erosion experiments. The entrainment rate data were also binned over shear stress intervals of 0.2 dynes/cm² and used to develop a functional relationship similar to the Sedflume erosion rate formulation shown in Equation 2 below:

$$E = A\tau^n \quad (2)$$

where E = erosion rate in cm/s, τ = skin friction in dynes/cm², and parameters A and n are empirically determined from the data by a least-squares fit to the binned shear stress-entrainment rate pairs. Note that the negative entrainment rates were excluded from the binned shear stress and entrainment rate pairs.

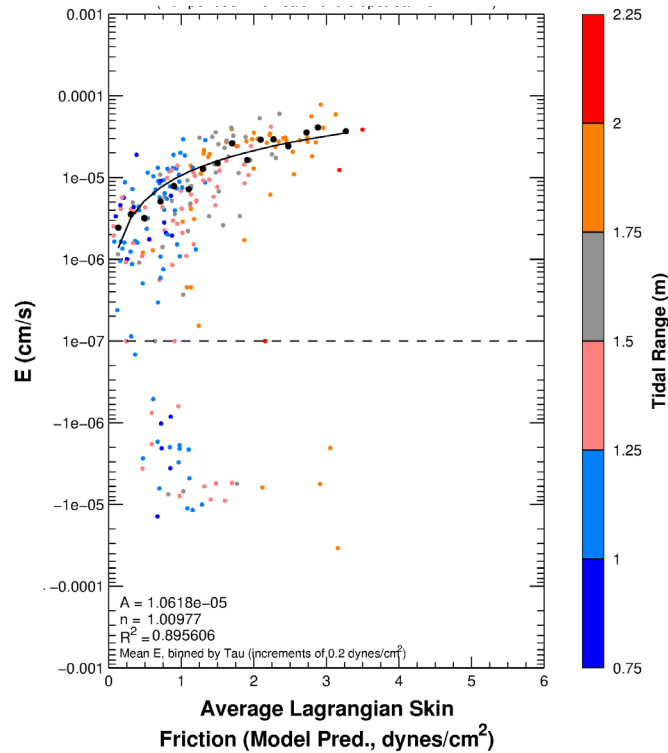


Figure 4. Entrainment rate (on Y-axis, in cm/s) versus model calculated skin friction along the thalweg between RM 1.4 and 4.2. Filled black circles represent entrainment rate data binned in shear stress increments of 0.2 dynes/cm². Negative entrainment rates excluded before binning.

The relationship fit using Equation 2 is approximately linear ($n=1.01$), with binned erosion rates ranging from $\sim 2 \times 10^{-6}$ to $\sim 3 \times 10^{-5}$ cm/s over the entire range of tidal shear stresses. Another important erosion property apparent from Figure 4 is the threshold for resuspension or the critical shear stress for erosion; appreciable entrainment is noted to occur at shear stress greater than ~ 0.25 dynes/cm² which suggests the critical shear stress for the fluff layer within the LPR/NB ST model framework. This critical shear stress is also comparable to measurements for the fluff layer at other sites (0.5 dynes/cm² reported by Wang 2003; 0.25 - 0.5 dynes/cm² reported by El Ganaoui et al. 2004; 0.5 dynes/cm² reported by Maa et al. 1998). The erosion rates ranging from $\sim 2 \times 10^{-6}$ to $\sim 3 \times 10^{-5}$ cm/s over the range of normal tidal conditions also overlap with reported values for other sites (constant 10^{-6} cm/s reported by Wang et al. 2003; 10^{-7} – 8×10^{-6} cm/s reported by El Ganaoui et al. 2004 over the same shear stress range).

The results of the entrainment rate analysis were used to define the erosion properties for the fluff layer in the LPR/NB ST model – the critical shear stress for erosion was defined as 0.25 dynes/cm² and the erosion rate (in cm/s) was defined as a power function of the skin friction with coefficient $A=1.06 \times 10^{-5}$ and exponent $n=1.01$.

C.7 Entrainment Rate Analysis, Validation

In an attempt to assess the impact of the variability inherent in the entrainment rate data on the resulting fluff layer erosion parameters, a sensitivity analysis was performed by sub-sampling the entrainment rate dataset. The overall entrainment rate dataset shown in Figure 4 consists of data from October 11-24 and November 21-28, 2009. This period covers a full spring-neap cycle and comprises 39 separate flood tides. These were segregated into low, medium, and high tidal-range subsets with data from 13 tides in each group. The sub-sampling was performed by randomly selecting 3 separate tides from each of these groups (to characterize the full range of shear stresses over the spring-neap cycle), for a total of 9 tides per sub-sample, and the erosion parameters A and n in Eq. 2 were calculated by least-squares optimization.

The sub-sampling and optimization procedure was implemented a large number of times ($n=10,000$) to characterize the range of variability in the erosion parameters. Figure 5 shows the results of this exercise. The individual values of A and n calculated for the sub-sampled datasets are shown as a cumulative probability distribution (filled squares). The parameter estimates developed from the entire dataset (shown in Figure 4) are shown for comparison with a horizontal solid line. The probability associated with the median and one standard deviation on either side of the median are shown with dashed grey lines; 68% of the distribution occurs within one standard deviation of the median. The range of values for erosion coefficient A in the sub-sampled data, as judged by one standard deviation on either side of the median, is relative small, ranging from about 8×10^{-6} to 1.1×10^{-5} . The value of the A derived from the entire dataset ($A=1.06 \times 10^{-5}$) is within one standard deviation and also within about 10% of the median from the sub-sampled data ($A=9.4 \times 10^{-6}$). In comparison, the erosion exponent n is somewhat more variable; one standard deviation around the median is associated with $n=0.83$ to $n=1.32$. However, the median value from the sub-sampled dataset ($n=1.06$) is very close to the estimate derived from the entire dataset ($n=1.01$).

The sub-sampling of entrainment rates from the overall dataset allows for an assessment of the potential variability in the estimates of erosion parameters A and n . As expected, with the sub-sampling procedure, due to the smaller dataset of entrainment rate and shear stress pairs, the resulting parameter estimates of A and n tend to be more variable. However, the median values of A and n derived from the sub-sampled dataset are similar (within about 10%) to the values derived from the overall dataset. This suggests that the parameter estimates derived from the overall dataset are more or less representative of the average or median erosion properties and are suitable for use in parameterizing the relevant process in the model, i.e. the erosion properties of the fluff layer.

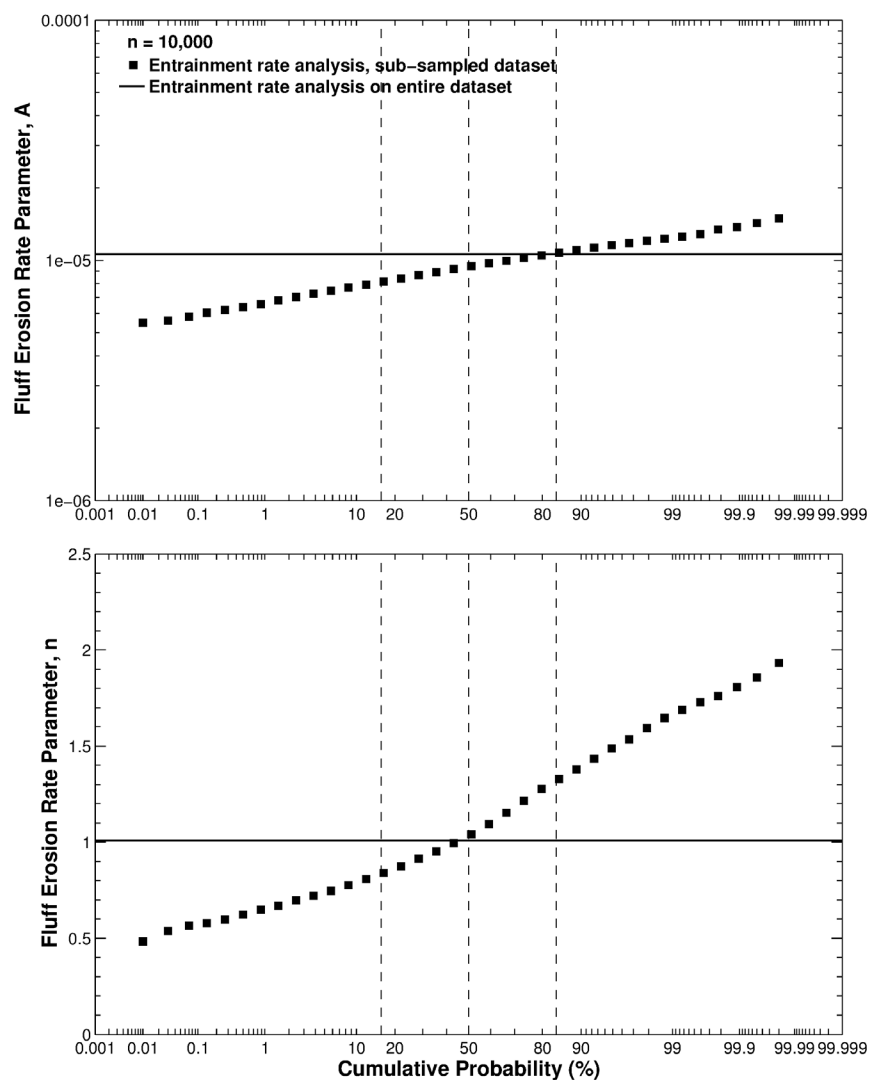


Figure 5. Probability distribution of the erosion parameters A and n in Eq. 2 calculated by sub-sampling the entrainment rate dataset.

C.8 References

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