Fluvial Transport of Suspended Solids

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Introduction

The fluvial transport of suspended solids is of great interest to living communities. It has been known for a very long time that the deposition of fine sediments on flood plains increases the fertility of farmlands.

In urban areas, high suspended sediment concentrations adversely impact the quality of drinking water and increase the operation cost of water treatment plants. During floods, the excessive suspended sediment concentrations can also cause major sedimentation problems resulting in aggradation, river navigation problems, and changes in river morphology. On the other hand, riverbed degradation from a lack of fine sediment in suspension can also undermine the stability of bridges and river protection structures.

Equilibrium Transport of Sediment Suspensions

There are two types of sediment sizes that contribute to the suspended sediment load of a river: (1) wash load and (2) bed material load. The difference between wash load and bed material load depends on whether the size fractions can be found in large quantities in the bed. The size fractions that are found in large quantities in the bed are referred to as bed material load. In practice, all size fractions that are finer than the d_{10} of the bed material will be considered wash load. The wash load does not depend on the sediment transporting capacity of the flow, but depends on the supply of sediment from upstream sources or from the river bank.

The quantity of wash load can only be determined from field measurements. Suspended sediment sampling is usually done with a point sediment sampler of the type P-61 or P-63. Point sediment samplers are designed to collect sediment through time at a given point along the stream vertical. The sampler weight is the primary difference between the P-61 (100 lb) and P-63 (200 lb) and heavy samplers must be used in deep and fast-flowing rivers. Figure 1 shows a P-63 sampler on the Mississippi River.

The bed material load in suspension requires basic knowledge of the properties of the flow and of the transported sediment. In a very simplified form, two main properties describe suspended sediment transport in rivers: (1) the shear velocity of the flow and (2) the settling velocity of the bed material. The shear velocity $u_* = (ghS)^{0.5}$ is approximately equal to the square root of the product of gravitational acceleration g, flow depth h, and friction slope S.

The settling velocity is a property of the particle in its surrounding fluid. It can be directly calculated from the dimensionless particle diameter d_*, which is defined from the particle diameter d_s, the specific gravity G of sediment, the kinematic viscosity of the fluid v, and the gravitational acceleration g, as

$$d_* = d_s \left[\frac{(G-1)g}{v^2} \right]^{1/3} \quad [1]$$

Simplified calculations are obtained with the grain diameter (m), the kinematic viscosity ($v = 1 \times 10^{-6}$ m^2 s^{-1}), g (9.81 m s^{-2}), and G (2.65). The settling velocity ω (m s^{-1}) of a sediment particle in clear water is then calculated from

$$\omega = \frac{8v}{d_s} \left\{ \left[1 + \frac{d_*^3}{72} \right]^{0.5} - 1 \right\} \quad [2]$$

The ratio of shear velocity u_* to settling velocity ω determines the primary mode of sediment transport. The bed material can be subdivided into three zones describing the dominant mode of transport: bed load, mixed load, and suspended load. In most rivers, bed load is dominant at values of u_*/ω less than about 0.4. Note that incipient motion corresponds to $u_*/\omega \cong 0.2$, which means that the bed material does not move when $u_* < 0.2\omega$. A transition zone called mixed load is found where $0.4 < u_*/\omega < 2.5$ in which both the bed load and the suspended load contribute to the total load. When $u_*/\omega > 2.5$, most of the sediment load is transported in suspension. Field measurements are necessary to determine the rate of sediment transport.

The concentration of suspended sediment in rivers varies with depth. The suspended sediment concentration C at an elevation z above the bed for the suspended load can be calculated from the Rouse equation as

$$C = C_a \left[\left(\frac{h-z}{z} \right) \left(\frac{a}{h-a} \right) \right]^{\omega/\kappa u_*} \quad [3]$$

where C_a is the concentration at an elevation a above the bed, h is the flow depth, and κ is the von Karman constant ($\kappa \cong 0.4$). The exponent of this equation is called the Rouse number $Ro = \omega/\kappa u_*$, which varies with u_*/ω. The near-bed concentration can be obtained from point sediment concentration measurements near the bed, or in the lower part of the water column. The Rouse number can be experimentally obtained as the slope of the linear fit to the concentration profile obtained after a logarithmic transformation, as shown in Figure 2.

The sediment flux per unit area is the product of the flow velocity and sediment concentration. For instance, the volumetric flux of sediment is obtained from the product of the volumetric sediment concentration, the flow velocity, and the unit area. Because the flow velocity and sediment concentration vary with depth and width, it is necessary to integrate the velocity and concentration profiles along the vertical and across the entire width of a river to determine the sediment flux. This integral is very complex and is discussed in detail in Julien (1995). The depth integral of the sediment flux describes the unit sediment discharge or amount of sediment being transported per unit channel width q_{tx}. It represents a volume of sediment per unit width.

Figure 1 Suspended sediment sampling on the Mississippi River.

Nonequilibrium Transport of Sediment Suspensions

As rivers approach reservoirs, lakes, and estuaries, the reduced sediment transport capacity in the backwater areas causes deposition of the suspended sediment load. Owing to the continuity of sediment, the equation of conservation of mass determines the changes in vertical elevation from settling when there is a decrease in sediment transport in the downstream direction. This equation of conservation of mass shows that the settling sediment flux in the z direction causes a change in bed surface elevation z_b:

$$\frac{\partial z_b}{\partial t} = -\frac{T_E}{(1-p_0)}\frac{\partial q_{tx}}{\partial x} \qquad [4]$$

The porosity p_0 depends on the specific weight of sediment deposits and is approximately 0.43 for sand-bed rivers. The trap efficiency T_E describes the fraction of sediment that would deposit in a given river reach of length X. It is therefore a measure of how much sedimentation could take place in backwater flow conditions. Trap efficiency is a function of the reach length X, the river width W, the flow discharge Q, the mean flow velocity V, and the settling velocity ω as

$$T_E = 1 - \exp\left(-\frac{X\omega}{hV}\right) = 1 - \exp\left(\frac{-WX\omega}{Q}\right) \qquad [5]$$

This relationship for the trap efficiency of sediment can be useful. At a given flow discharge, the trap efficiency remains very small for very short reaches and for very fine sediment particles (low ω). Under

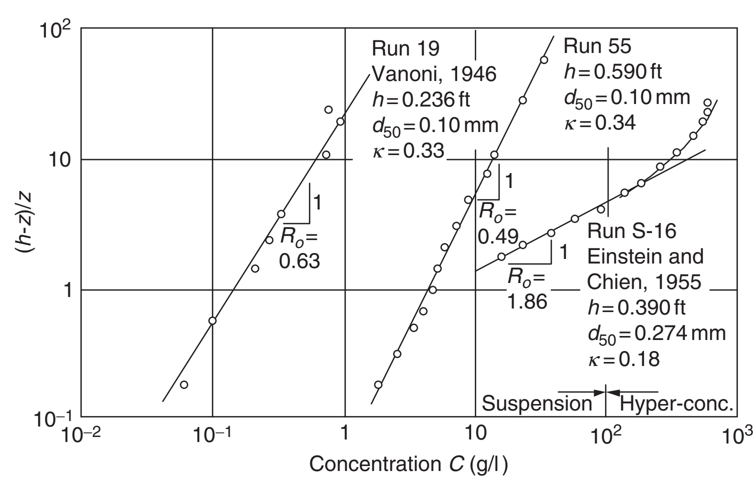


Figure 2 Examples of sediment concentration profiles (from Julien, 1995).

changes in sediment transport capacity in the downstream direction, the trap efficiency describes a greater potential for coarse sediment to deposit. It is also interesting to note that the trap efficiency at a given reach length and flow discharge increases with increasing sediment size ω and channel width W. It is therefore noticeable at a given discharge that river widening will induce settling of suspended sediment (Julien, 2002).

When calculating the trap efficiency of silt and clay particles in backwater areas like reservoirs and estuaries, careful consideration must also be given to density currents and possible flocculation. Flocculation of silts and clays is a complex subject, but in its essence, the settling velocity of floc of silts and clays is typically around 0.6 mm s^{-1}. The settling velocity of flocs increases with floc size but will rarely exceed 5 mm s^{-1}.

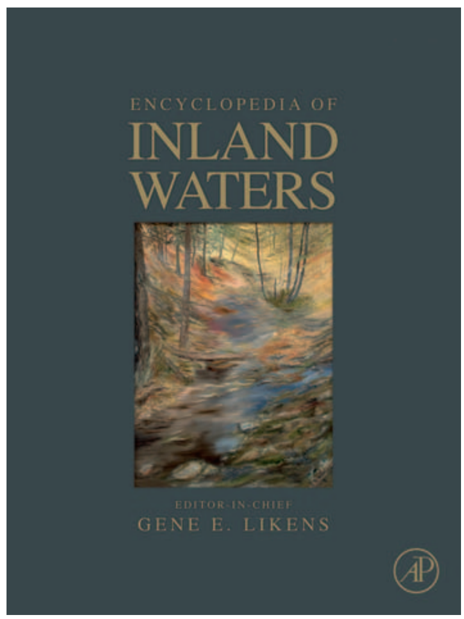
As an example to illustrate the concepts covered in this article, consider the Rhine River data from Julien (2002). The flow depth is approximately 10 m, the main navigable channel constrained between a series of dikes is about 260 m wide, the mean flow velocity is 1.68 m s^{-1}, and the friction slope 13.2 cm km^{-1}. The sediment concentration at mid depth is 38 mg l^{-1}, and the near-bed concentration is 400 mg l^{-1} at a distance of 0.5 m above the river bed. If the grain diameter of the sediment in suspension is 0.2 mm, the following parameters can be calculated from the methods covered in this article: (1) the shear velocity obtained from $u_* = (ghS)^{0.5}$ is approximately $u_* = 0.11$ m s^{-1}; (2) the dimensionless particle diameter is approximately 5 from eqn [1] and the settling velocity from eqn [2] is $\omega = 0.027$ m s^{-1}; (3) the ratio $u_*/\omega = 4.2$, and the Rouse number is 0.59 assuming $\kappa \cong 0.4$, thus most of the sediment is transported in suspension; (4) the suspended sediment concentration 1 m below the free surface is 19 mg l^{-1} obtained from Ca = 400 mg l^{-1} at $a = 0.5$ m, $h = 10$ m, and the concentration at $z = 9$ m from eqn [3]; and (5) the trap efficiency over a reach length of 500 m from eqn [5] is $T_E = 0.55$, which means that about half the suspended sediment load would deposit within half a kilometer if the transport capacity of this river would be suddenly reduced.

This example is quite instructive because most of the suspended sediment load would deposit very rapidly despite the fact that most of the sediment is fine and transported in suspension. The high T_E indicates that most of the sediment would also easily be trapped on the flood plain within short distance of the main channel during major floods. This river would be very dynamic and could change morphology if it were not constrained with a series of dikes. Finally, the suspended sediment concentration near the free surface is only 19 mg l^{-1} compared with 400 mg l^{-1} near the bed, and water intakes should definitely be located near the free surface.

Further Reading

Julien PY (1995) *Erosion and Sedimentation*, 280p. New York: Cambridge University Press.

Julien PY (2002) *River Mechanics*, 434p. New York: Cambridge University Press.



Julien P Y. (2009) Fluvial Transport of Suspended Solids. In: Gene E. Likens, (Editor) Encyclopedia of Inland Waters. volume 1, pp. 681-683 Oxford: Elsevier.