Hydrology Journal, **30**(3-4) July-Dec 2007

Transport of fines/ wash load through channels – A review

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Abstract :*A lot of wash load comes to the streams during the rainy season due to the erosion of soil form the catchment and known to flow practically without settling on the streambed. The presence of wash load is known to affect the resistance to the flow. The effect of its presence on transport of bed-material load is not well known. The present paper is devoted to a review of the studies regarding concept of wash load, changes in resistance to flow due to the presence of wash load, the effect of presence of fines in suspension on the transport of bed-material. The presence of excessive amount of fines in the stream bed adversely affect the spawning of salmon and other species of fish. So, the literature is also reviewed regarding deposition/infiltration of fine sediments within the pores of a coarse bed channel and the wash load carrying capacity of rigid and alluvial bed channels. The review brings out clearly the areas in which the research should be carried.*

INTRODUCTION

The study of flow in alluvial streams has attracted the attention of hydraulic engineers for a long time. Knowledge of the mechanism of entrainment of sediment and its subsequent transport is required for handling many problems like design of stable channels, reservoir sedimentation, bed level variation *etc.* When the shear stress acting on the bed of a channel exceeds a certain minimum value, defined as the critical tractive stress, sediment movement starts. The sediment particles may move by rolling, sliding or saltating along the bed of the channel. Sediment load carried by these modes of transport is known as bed load. At higher shear stresses, a part of the transported sediment goes into suspension and is maintained in a state of suspension by the turbulent fluctuations within the flow. Sediment load transported in this way is termed as suspended load. The sum of bed load and suspended load is termed as the total load. If all of the transported material is related to the bed material, it is called bed-material load. Suspended load sometimes consists of significant quantity of sediments that are not found in appreciable quantity in the bed and banks of the stream. This part of the suspended load is conventionally termed as wash load. The wash load mainly comes from the catchment into the stream during period of high rainfall and known to flow practically without settling on the streambed. It is generally believed that the wash load is not related to the discharge carried by the channel but is dependent on the erodibility of the soil within the catchment, *i.e.* the catchment characteristics, and hence is difficult to predict. However, the presence of wash load is known to affect the resistance to the flow. The effect of its presence on transport of bed-material load is not well known. The present paper is devoted to a review of the studies regarding concept of wash load, changes in resistance to flow due to the presence of wash load, effect of presence of wash load on bed-material transport. Additionally, the literature is also reviewed regarding deposition/infiltration of fine sediments within the pores of a coarse bed channel and the wash load carrying capacity of flow in rigid and alluvial bed channels. Accordingly, the review of the literature has been presented under the following headings:

1. Concept of wash load
2. Effect of wash load on flow resistance
3. Limiting capacity of wash load transport
4. Deposition/Infiltration of fines or wash load within the pores of coarse bed streams
5. Effect of wash load on transport of bed-material load

CONCEPT OF WASH LOAD

Einstein *et al.* (1940) were among the first to introduce the concept of wash load. They defined it as the sediment load of the size fractions not present in significant amounts in the stream bed and banks and which is easily washed away by the flow. Its rate of transport was considered to depend upon the upstream supply rate from the catchment and could not be related to the flow rate.

The Subcommittee on Sediment Terminology of the American Geophysical Union (Lane, 1947) defined the wash load as that part of the sediment load of a stream which is composed of particle sizes smaller than those found in appreciable quantities in the shifting portions of the stream bed.

Einstein (1950) recommended that the limiting size for the wash load might be arbitrarily taken as that particle size for which 10 per cent of the bed material is finer. Einstein and Chien (1953 a) contradicted the common belief that wash load is not deposited in the channel bed. From their experiments they found that fine material does temporarily settle on the channel bed. Thus, both the bed-material and the wash load settle out on the channel bed. According to Einstein and Chien (1953 b), a small proportion of wash load in the bed is related to a very large quantity of this material in the flow, whereas for bed material, a fairly large quantity of this material in the bed is related to large quantities of this material in motion. According to them the wash load can be predicted by using Einstein's bed load function when the surface composition of the channel bed is known.

Shen (1970) defined wash load as the sediment size for which the sediment supply rate is less than the sediment transport capacity of the channel for given hydraulic conditions. As per this definition, the size of wash material cannot be constant but should increase with increase in the discharge.

According to Partheniades (1977), the actual wash load may consist of two distinct types of sediment which may coexist. The first type has a bed load function for a limited range of discharge. For higher discharges it behaves as wash load without deposition of particles in the bed, whereas for discharges lower than that range it simply deposits. The second of above type can never have a bed load function; in alluvial channels it is either carried in suspension without leaving any traces in the bed or it deposits in the estuarine reaches of the channel or in reservoirs in zones of sufficiently low shear stresses. He concluded that in alluvial channel only the second type of wash load meets the requirement of independence from flow conditions and absence from the bed composition. According to Woo *et al.* (1986), it is not possible to stipulate the size limit for the wash load though many engineers assume the limiting size of wash load to be approximately 0.0625 mm which corresponds to silts and clays. In the coarse bed streams with steep slope, sands and fine gravels can also be considered as wash load so long as the sediment transport capacity remains larger than the availability of the sediment. For sandy streams with flat slopes the wash load may be in the clay and silt range.

Thus, the definitions of wash load presented above and the explanation of its behavior implies that even the sediment sizes transported as wash load can have a bed load function. Any sediment can be considered as wash material provided its supply rate is less than the transport capacity of the channel. Also the available definitions of the wash load are mainly based upon the information collected through sampling for bed material composition made after the passage of the flood wave.

EFFECT OF WASH LOAD ON FLOW RESISTANCE

Vanoni (1946) and Vanoni and Nomicos (1960) found that the value of Manning's roughness coefficient n and von Karman constant κ were smaller in sediment-laden flows than in corresponding clear-water flows. The decrease in the value of n was attributed to the damping of turbulence caused by the presence of suspended sediment in the flow.

Einstein and Chien (1955) found that in supercritical flow for the same depth, slope and bed material sizes, the resistance is less when it carries sediment in suspension. They also stated that, because of the damping of turbulence and the resulting smaller internal friction of the flow, the velocity increases in the presence of suspended load.

From their study in a 2.4 m wide flume with 0.48 per cent to 2.83 per cent of bentonite clay in suspension, Simons *et al.* (1963) found a decrease in friction factor on both the ripple bed and the dune bed and an increase in friction factor in antidune bed regime.

Yano and Daido (1964) carried out experiments in supercritical flow using 0.0088 mm sediment in suspension and found that friction factor increases with the increase in sediment concentration in suspension.

Through analysis of the turbulence energy equation, Gyr (1967) has concluded that frictional resistance in a sediment-laden flow should be smaller than that in the corresponding clear–water flow.

Muller (1967) conducted experiments with sediments of size 0.11 mm and relative density 1.35 to study the variation in the size of the eddy with increase in suspended sediment concentration in the flow. He measured turbulence in clear-water flow and sediment-laden flow at concentrations of 0.26 per cent to 0.86 per cent and found that the size of the smallest eddy increased with increase in suspended sediment concentration in the flow. The work of Muller thus substantiates the results of the mathematical model of Gyr (1967).

Kikkawa and Fukuoka (1969) conducted experiments in a flume with bed material of size 0.18 mm and wash material of sizes 0.05 mm and 0.015 mm. From the data presented by them it can be seen that in the dune bed regime the friction factor decreased with increase in concentration of wash material of size 0.015 mm at Froude number 0.58, whereas no change occurred in the flat bed and antidune regime at Froude number of 1.05 and 1.34 respectively. They also observed a change in bed configuration *i.e.* from dune bed to flat bed at Froude number of 0.7 and from flat bed to antidune bed at Froude number of 1.2, by the addition of wash material of size 0.05 mm and a consequent variation in channel resistance.

Ippen (1973) has reported that in all studies carried out at Massachusetts Institute of Technology on smooth bed channels, the resistance to flow in sediment-laden flows was greater than that for the clear-water flow. He argued that an initially smooth bed is modified by the addition of sediment in suspension because of typical longitudinal streaks and bands of sands in motion on the bed and it always gives a higher friction factor than that for the clear-water case. He further stated that decrease in channel resistance might occur with fine sediments due to change in flow properties and filling of interstices between larger grains present in the bed.

UPIRI (1974) in their field study has reported a decrease in the resistance to flow with increase in concentration of suspended sediment in flow. Part of this sediment load is likely to be wash load.

Imamato *et al.* (1977) found that the resistance to flow increases with increase in concentration of suspended sediment in the supercritical flow regime. They found an increase in 13 per cent of the resistance coefficient at a concentration of 10,000 ppm for sediment of size 0.152 mm and relative density 2.65.

Pullaiah (1978) performed experiments in a rigid-boundary channel and found that friction factor for sediment-laden flows increases over its values for clear-water flow when $\frac{\sqrt{\overline{v'^2}}}{\omega} < 100$ and decreases when $\frac{\sqrt{\overline{v'^2}}}{\omega} > 200$. No data was available in the range of $\frac{\sqrt{\overline{v'^2}}}{\omega}$ between 100 and 200. Here v is vertical fluctuation of turbulent velocity and ω is the fall velocity of the sediment.

Itakura and Kishi (1980) found that friction factor in sediment-laden flows is less than that in clear-water flows. They also attributed this to reduced turbulence in sediment-laden flow.

By using the general velocity distribution for sediment-laden flow and the experimental evidence presented by Coleman (1981), Lau (1983) has shown that the flow resistance must decrease in the presence of suspended sediment.

Arora *et al.* (1986) have shown that friction factor for sediment-laden flows compared to its values for clear-water flow increases when value of $\frac{C\,\omega}{U\,S}$ is more than 1200 and decreases when this value is less than 1200. Here U is the mean velocity of flow C is the volumetric sediment concentration in ppm and S is the slope of the channel.

Parker and Coleman (1986) developed a depth averaged perturbation model for sediment-laden flows based on conservation equations, supplemented by a mean energy balance equation. This model predicts friction factor f in sediment laden flow to be a decreasing function of the parameter $(s-1)\frac{C_T\,\omega}{U\,S}$, where s is the relative density of the sediment in suspension. Here C_T is the volumetric concentration of suspended sediment.

Lyn (1991) compared the friction factor in a sediment-laden flow with the friction factor in an equivalent clear-water flow determined for the Reynolds number of the sediment-laden flow and a roughness size equal to the mean diameter of the sediment. He showed that the presence of suspended sediment resulted in an increase in flow resistance. The flow resistance increased upto 40 per cent for the sediment-laden flow.

Wang *et al.* (1998) have studied the variation of resistance to flow over smooth, gravel and stone beds due to clay in suspension. They used 0.0018 mm size clay as wash load and found that for sediment-laden flow the friction factor reduced by more than 50 per cent over the gravel bed as compared to clear-water flow at the same discharge and energy slope. According to them the resistance to flow is affected by suspended sediment in two ways *i.e.* by damping of the turbulence, which causes reduction in resistance, and by increasing the viscous resistance. Due to this, over rough boundaries, the resistance decreases due to damping of turbulence and over smooth boundary no drag reduction takes place as the two effects tend to compensate each other.

Cellino and Graf (1999) performed experiments in a rectangular flume using 0.14 mm size sediment. The bed of the flume was made rough by cementing 4 mm size sediment on it. Their data showed that the average flow velocity increased with an increase in suspended sediment concentration indicating that the resistance to flow decreased with increase in sediment concentration.

Peng *et al.* (2001) used Micro Acoustic Doppler Velocimeter for the measurement of turbulence in sediment-laden flow. They have found that for sediment size of 0.034 mm, there was no noticeable change in turbulence intensity for different concentrations of suspended sediment, whereas for sediment size of 0.09 mm, the mean velocity of flow increased indicating a decrease in the value of friction factor for the flow.

Khullar *et al.* (2002) carried out experiments in a 0.2 m wide and 30 m long flume using coarse uniform and nonuniform sediments as bed material and 0.064 mm fine sediment as wash material and pointed out that in the absence of any change in bed features the resistance to flow due to the presence of different concentration of wash load decreases in closely packed non-alluvial and alluvial bed channels and increases as well decreases in rigid bed channels. Khullar (2003) has proposed predictors for finding out the resistance to flow for different concentrations of wash load through such channels. According to him the friction factor for closely packed non-alluvial and alluvial bed channels can be computed from the following relationship

$$1-\frac{f}{f_o}=10^{-5}(s-1)\frac{C\,\omega}{U\,S} \tag{1}$$

Here f_0 is friction factor for clear water flow. For rigid bed channels the friction factor in the presence of different concentration of wash load for the value of $C^{1/8}\left(\frac{u_* \, d}{\upsilon}\right) \geq 0.65$ can be computed by

$$\frac{f}{f_o}=e^{8\times10^{-6}(s-1)\frac{C\,\omega}{U\,S}} \tag{2}$$

Here u_* is shear velocity. For the value of $C^{1/8}\left(\frac{u_* \, d}{\upsilon}\right)<$ **0.65 its** value can be computed from

$$1-\frac{f}{f_o}=10^{-12}\left[(s-1)\frac{C\omega}{US}\right]^3+10^{-8}\left[(s-1)\frac{C\omega}{US}\right]^2-5\times10^{-5}\left[(s-1)\frac{C\omega}{US}\right] \tag{3}$$

From above it is clear that the resistance to flow may decrease due to decrease in turbulence in the presence of wash load and may increase due to increase in form resistance due to change in bed features. But there is no unanimity about the conditions under which the resistance will increase or decrease. More research is required to be done on the aspect of resistance of flow in the presence of different concentration of wash load of different sizes to arrive at a definite conclusion.

LIMITING CAPACITY OF WASH LOAD TRANSPORT

Depending on the flow, the fluid, the sediment and the channel characteristics, there exists an upper limit for sustenance of fine sediment in suspension. The concentration of suspended sediments when increased beyond such limit shall result in deposition of sediment on the bed. The knowledge about such a limit is very important in the design of lined channels, sediment extractors, sediment excluders *etc.*

Using the general laws of physics, Bagnold (1966) has derived a transport function for suspended load transport for sediment size less than 0.04 mm. His relation for suspended load transport in the absence of bed load is given as

$$C_T = 0.015 \frac{\gamma_f \, U \, S}{\gamma_s \, \omega} \left(\frac{\rho_s}{\rho_s - \rho_f} \right) \tag{4}$$

Here γ_s is unit weight of sediment, γ_f is unit weight of fluid, ρ_s is the unit mass of sediment and ρ_f is the unit mass of fluid.

Itakura and Kishi (1980) carried out experiments by using two sediment sizes to find out the condition for the initiation of deposition of suspended sediments in an open channel with rough bed having roughness height equal to 3.3 mm. They found that the limiting condition for deposition is attained at flux Richardson number R_{fc} equal to 0.02.

Arora (1983) carried out experiments to find wash load carrying capacity of rigid-boundary channels of semicircular, trapezoidal and rectangular shapes having smooth and rough beds using coal and natural sand with size ranging from 0.082 mm to 0.147 mm as the sediment. Based on analysis of the data collected by Arora (1983) and the data of Pullaiah (1978), Coleman (1981) and Taggart *et al.* (1972), Arora *et al.* (1984) proposed a graphical relationship for finding the limiting concentration of wash load transport through rigid-boundary channels.

Westrich and Juraschek (1985) investigated the hydraulic criteria for incipient deposition of suspended sediment in an open channel flow with a rigid-boundary and proposed a relationship for the suspended load transport capacity of a channel on the assumption that the turbulent energy generated by the flow is used to keep the sediment in suspension. By integration of the two dimensional transport equation for the turbulent kinetic energy over the depth of flow they obtained the following equation for suspended sediment transport capacity

$$C_T = k_1 \frac{\tau_o \, U}{(\rho_s - \rho_f) \, g \, h \, \omega} \tag{5}$$

Here k_1 is a constant which represents an efficiency coefficient for suspended sediment transport, h is the depth of flow, g is the acceleration due to gravity and τ_o is total shear stress. On the basis of experimental data using fine sediments of size 0.026 mm to 0.11 mm and of relative density 2.65, they found the value of k_1 to be 0.0018.

According to Wiuff (1985) the suspended sediment transport capacity of a channel is given as

$$C_T = 0.016\,(\frac{\rho_s - \rho_f}{\rho_f})\frac{q\,S^2}{d_m\,\omega} \tag{6}$$

where q is discharge per unit width and d_m is mean size of the particle in suspension.

Celik and Rodi (1991) proposed a relationship for the transport capacity of suspended sediment in an open channel based on the assumption that the energy needed to keep the sediment particles in suspension is proportional to the production of turbulent kinetic energy. Their relationship for the transport capacity is given as

$$C_T = 0.034\left[1-\left(\frac{k_{s1}}{h}\right)^{0.06}\right]\frac{U\,S}{(s-1)\omega} \tag{7}$$

where k_{s1} is equivalent resistance parameter and is equal to the bed roughness height. The above relation is derived for sediment particles having median size in the range 0.005 mm to 0.6 mm and sediment concentration in the range 10^{-4} per cent to 10 per cent.

Nalluri and Spaliviero (1998) carried out regression analysis of suspended sediment transport data at limit deposition in rigid-boundary channels. The data cover a wide range of volumetric concentrations (37–48542 ppm) and sediment size (0.006-0.37 mm) under different hydraulic conditions. They proposed a relationship for the suspended sediment transport in rigid-boundary channel at limit deposition condition as

$$\frac{U_{sc}}{\sqrt{g\,(s-1)\,d_{50}}} = 3.32C^{0.12}\left(\frac{d_{50}}{h}\right)^{0.28} f^{-0.14} \tag{8}$$

Here U_{sc} is self-cleaning velocity for no deposition. The value of friction factor f for sediment-laden flow can be computed by using the relationship given by Nalluri *et al.* (1994) as

$$f = 0.88\, C^{0.01} \left(\frac{b}{h}\right)^{0.03} f_o^{\,0.94} \tag{9}$$

Here b is the width of the channel.

Ota and Nalluri (1999) studied the importance of sediment size and gradation on limit deposition. According to them, the transport capacity of graded sediment C_{vg} is given as

$$C_{vg} = C_v \sigma_g^{0.35} \tag{10}$$

where C_v is the limiting capacity in ppm by volume of uniform sediment having sediment size equal to d_{50} of graded sediment and $\sigma_g = \sqrt{d_{84}/d_{16}}$ is the geometric standard deviation of sediment. Here d_{84} and d_{16} are the particle sizes such that 84 per cent and 16 per cent of the material is finer than these sizes respectively. The value of the limiting capacity in Eq. (7) for uniform sediment can be obtained from any of the existing equations.

Khullar (2006) also studied the limiting capacity transport of wash load using fine sediment of size 0.064 in laboratory flume having coarse sediment as bed material and proposed a criterion for limiting condition of wash load transport through such channels. According to him the method of Arora *et al.* (1984) can be used to find out the limiting capacity of wash load transport through alluvial channels. He proposed analytical relationships for finding out the limiting capacity of wash load transport as under:

(i) For $0.43 \le q^* \le 2.0$

$$C = 125.8\left(q^*\right)^{1.945} \tag{11}$$

(ii) For $2.0 < q^* \le 6.0$

$$C = 180.21\left(q^*\right)^{1.458} \tag{12}$$

(iii) For $6.0 < q^* \le 63$

$$C = 0.0441\left(q^*\right)^3 - 6.885\left(q^*\right)^2 + 483.28\left(q^*\right) - 177.87 \tag{13}$$

Here q^* is defined as $q^* = \dfrac{q\, S_c^{2.5}}{\upsilon f^2 (\omega d/\upsilon)^{0.6}} \left(\dfrac{D}{h}\right)^2$ and D is hydraulic depth of flow.

Most of the methods reviewed above are intended for finding the limiting capacity of wash load transport in rigid-boundary channels. Not much work is, however, done so far for the determination of the limiting capacity of wash load transport in alluvial channels using different sizes of wash load.

INFILTRATION / DEPOSITION OF FINES IN COARSE BED STREAMS

The presence of excessive amount of fines in the stream bed could adversely affect the spawning of salmon and other species of fish (Einstein, 1968 and Diplas and Parker, 1992). It has been observed by several investigators that fines infiltrate and deposit within the pores of the coarse stream bed over a definite top thickness of the coarse bed termed herein as the active bed layer. As more fines are added they saturate the active bed layer of the coarse bed and start appearing on the stream surface layer. Subsequent clear-water flows over such beds result in entrainment of fines from the pores of the active bed layer.

Simons *et al.* (1963) conducted experiments in a recirculating flume by using uniform sand as the bed material and clay as wash material. They found that the concentration of clay in suspension decreased with time and that the clay was deposited on the floor of the flume even though the dune trough never scoured upto the flume floor, suggesting that the clay particles had infiltrated upto the stream bed.

Einstein (1968) studied experimentally the process of infiltration of fines into the pores of a gravel bed. He conducted experiments in 18 m and 30 m long recirculating flumes with gravel as bed material and silica flour (0.0035 – 0.03 mm) as fine material. He noted that the concentration of fines in flow decreased with time due to intrusion of the particles into the pores of the gravel bed. The fine particles gradually reached the bottom of the flume and then filled the pores in the bed from the bottom up. The rate of infiltration/deposition was found to be proportional to the local concentration. This study by Einstein indicates that fine particles intrude into the pores of the coarse bed during their routing through the coarse bed streams. However, Diplas and Parker (1992) noted that the main deficiencies of the experiments conducted by Einstein (1968) were the lack of existence of a pavement layer, the absence of bed load motion and pool-and-riffle structure, and the great size difference between the coarse and fine sediment phases. The first factor may be crucial in the creation of seal within the substrate whereas the last factor is the most significant for the mode of deposition of fines. The second and third factors may provide important mechanisms for cleaning the gravel bed of fines (Alonso *et al.*, 1988; Lisle, 1989).

According to Sowers and Sowers (1970) fine soil particles in flow infiltrate into coarse stream bed and the mode of deposition of these fines is mainly controlled by the relative size of the settling fines and the voids of the gravel bed. According to them, to prevent soil particles from moving through the filter, the effective pore diameter of the filter must be smaller than d_{85} of that soil and to allow free drainage, the effective pore diameter of filter must be larger than the d_{15}

of that soil. Here d_{85} is defined as the particle size for which 85 per cent of the particles are finer and d_{15} is the particle size for which 15 per cent of the particles are finer. The effective pore diameter of a good filter is taken as 0.2 d_{15}.

According to Milhous (1973), a surface bed layer called pavement layer exists in gravel bed streams. This layer is coarser than the subsurface material. This layer acts as a sink for the suspended sediment, which tends to deposit between the bottom of the pavement and the top of the subsurface called the silt reservoir. As such, the role of the pavement layer is very important in the deposition and retention of fines in bed. At high shear stress when the flow has insufficient fines, the fines deposited in the bed are entrained by the flow. As such, the proportion of fines in the bed reduces. The long-term average proportion of sediment of size less than 2 mm in the Oak Creek substrate was found to be about 12 per cent, which suggests that there is some sort of balance in the stream and the catchment on a long-term basis.

Beschta and Jackson (1979) performed experiments using 15 mm well-sorted gravel as bed material and 0.5 mm and 0.2 mm size sand as fines. Fine sediments were fed at the upstream end of the flume. The experiments were performed below incipient condition for the gravel bed. They observed that for the finer sand the gravel pores got filled from the bottom up where as for the coarser sand it resulted in a sand seal. The depth of deposition increased with increase in Froude number. They have suggested values of thickness of the seal ranging from $2.5d_{90}$ to $5d_{90}$. Here d_{90} is the particle size for which 90 per cent of the particles are finer.

From their field study Adams and Beschta (1980) found that the proportions of fines of sediment less than 1 mm size within the streambed varied between riffle areas in the same stream, and within the same riffle. It was also mentioned that the variation across the channel is typically more pronounced than it is along the channel. They observed spatial and temporal variability of the fines in the substrate. They attributed the spatial variability of fines to differences in the size of the gravel substrate and fines, the supply rate of fines and the hydraulic condition of the flow in the stream. The temporal variability of fines is attributed to the flushing of fines which takes place mainly during high flows when the bed is set in motion.

Dhamotharan *et al.* (1980) carried out a preliminary study on the transport of fine sand of size 0.12 mm through a gravel bed flume at equilibrium stage of bed load transport. The experiments were performed at discharges large enough to cause entrainment of the coarsest gravel in the bed material and the fine sediment was capable of moving in suspension. It was found that these fine particles deposits in the subpavement and pavement of gravel bed and caused 33 per cent reduction in the bed load transport rate when compared with the corresponding experiment in the absence of fines. The reduction in transport rate was believed to be due to packing effects caused by the fines in the bed.

Carling (1984) studied the infiltration/siltation rate of sand into gravel bed (d_{50}=15.6 mm) in a laboratory flume. Three sands having median size 0.15 mm, 0.19 mm and 1.4 mm were used as fine material. The experiments were performed below incipient conditions for gravel bed. He observed that the coarsest sand was the only one to form a seal. According to him the initial concentration of sand was the only mean flow parameter that correlated well with the siltation rate. He also observed that the siltation rate was high even at low flow concentrations, and that the surface bed layer remained free of sand.Frostick *et al.* (1984) found that the amount and type of fines infiltrating into the pavement of Turkey Brook were influenced by the presence of coarser surface bed layer and bed load transport. Flows that caused movement of bed sediment resulted in higher amounts and larger size of fines going into the bed. The infiltrating fines exhibited spatial variation, with higher proportion in pools compared to bars. The fines deposited in the bed were flushed from the bed upto a depth of $2d_{90}$ during the period of high flows.

O'Brien (1987) found that the gravel bed of a stream can be cleaned of fine particles present in it upto a depth close to the median size of the bed in the absence of gravel movement.

Alonso *et al.* (1988) carried out a field study to calibrate a computer program that simulates the deposition of fines in coarse gravel matrices. They observed that the infiltrating fines did not create a seal within the bed subsurface which was contrary to the findings of other investigators. They also observed that the proportion of fines in the bed was directly related to suspended sediment transport rate. The different depositional behavior of fines infiltrating the Tucannon River substrate was mainly due to large difference in size between the gravel framework and the matrix material, a situation that is not commonly encountered in natural streams.

Jobson and Carey (1989) pointed out that alluvial streams can extract fine sediment from flow and store them in their bed when the incoming concentrations are high and release the sediment to the flow when the incoming concentrations are low. The mechanism of storage in the stream bed depends upon the relative size distribution of the suspended sediment particles and bed material, as well as the flow hydraulics. Alluvial flow tends to segregate the deposited material according to size and density of the particles. Some of the storage locations are temporary, while some can store the fine sediment for very long periods of time.

Lisle (1989) studied the process of sedimentation of fines in gravel bed streams in North California by burying cans filled with gravels below the pavement. The amount of fines deposited into the cans and the depth of their infiltration was measured. He observed that fines infiltrated into the bed with silt and fine sand reaching the bottom of the can and coarse particles being caught near the top and forming a seal. The depth of seal increased with increase in the flow energy.

Diplas and Parker (1992) conducted experiments for modeling gravel-bed-streams and to study the deposition of fines into and their releases from the channel bed. Silica flour having d_{50} of 0.08 mm and 0.11 mm were used as fines. As soon as the fines were introduced into the channel they started to deposit on the bed and infiltrating below its surface (See Fig. 1 to 4). According to Diplas and Parker (1992) the fines infiltrated into the bed in two different modes; the first one was characterized by unobstructed settling through the voids of the framework material and in the second mode the fines were inhibited from settling freely due to bridging of the gaps among particles of the gravel bed, thus creating a seal that limits any deeper penetration of fines. The depth of infiltration depended on the difference in size between the penetrating grains and the coarser bed material and the dimensionless boundary shear stress. Both type of fines used created a seal within the substrate which was deeper for fines of size 0.08 mm and shallower for the other sizes. The seal was more in depth in the areas of higher dimensionless shear stress. According to them, the amount of fines that could ultimately be deposited within the subpavement layer was independent of the boundary shear stress and other flow parameters. As long as there were fines in the channel flow moving in suspension, they kept infiltrating into the bed until they had saturated the subpavement layer. The fines that settled in the surface layer did interact with the flow. According to Diplas and Parker the amount of fines deposited in the bed depends on the dimensionless boundary shear stress, the fall velocity of fines, the particle Reynolds number and the mean flow concentration of fines.

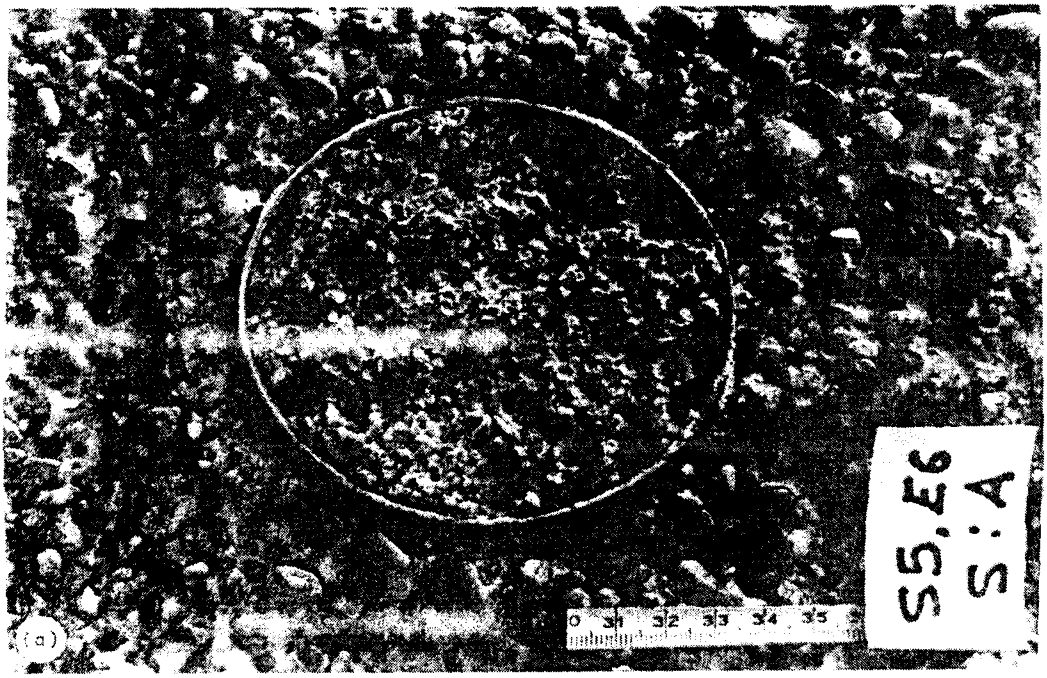

Figure 1. Photograph of the pavement and sub-pavement layers from run S5:E6 (Diplas and Parker, 1992)

Figure. 2. View of well developed ripple bed at the end of run S6:E7 (Diplas and Parker, 1992)

Diplas and Parker (1992) further found that when the amount of fines deposited in the bed was about 5 per cent of the subpavement material, the bed load transport rate started to decline. The observed reduction in the bed load transport was upto 57 per cent in the presence of fines when compared to the corresponding transport in clear-water.

Diplas and Parker (1992) also found that higher amounts of fines were deposited at the bar tail (downstream end of the bar) and in the pool area. During their field tests, Frostick *et al.* (1984) also found larger quantities of fines deposited in the pool compared to the deposition in the bar head.

Diplas (1994) studied deposition and removal of fines from the gravel bed and found that fines coming into a gravel bed stream were deposited within the pavement. The siltation was more pronounced in the pool and in the bar tail. During the cleaning process the fines were first removed from the bed at bar head and subsequently from the pool and bar tail. The extent of removal of fines was related to the flow strength. According to Diplas (1994) fines could be removed from the channel bed upto a depth of $4d_{90}$ during the flood simulating event.

Khullar (2003) carried out experiments in a 0.2 m wide and 30 m long flume using coarse uniform and nonuniform sediments as bed material and 0.064 mm fine sediment as wash material and found that wash load infiltrates into the pores of the coarse bed during the process of routing of the wash material through the channel upto limiting state of wash load transport and there after deposit on the surface of the bed (See Fig. 3 to 5). The channel bed tries to clear itself of wash material during the clear water flow through it. He also developed a mathematical model to study this process.

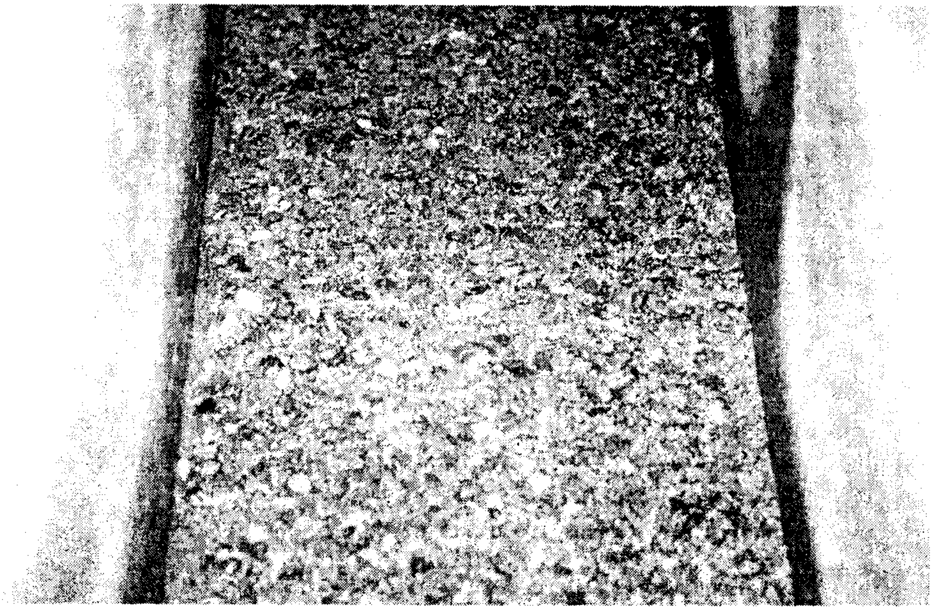

Figure 3. Photograph of bed surface for run *MW*22 (*C*=836 ppm; nonuniform bed material, d_{50}=2.1 mm)

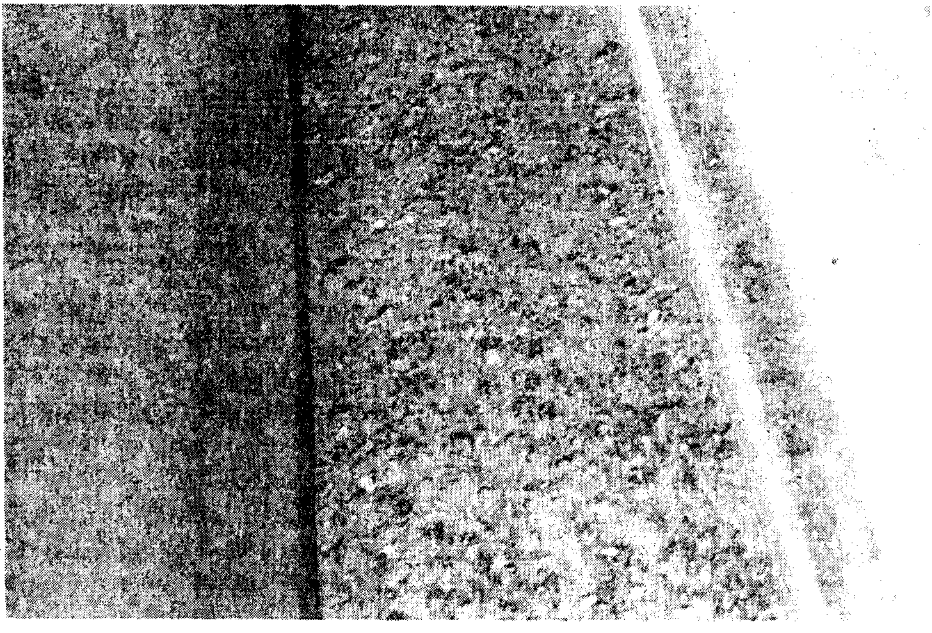

Figure 4. Photograph of bed surface for run *MW25* (*C*=2459 ppm; nonuniform bed material, d_{50}=2.1 mm)

Figure 5. Photograph depicting close view of ripples of wash material on channel bed for run *MW26* (*C*=3115 ppm; nonuniform bed material, d_{50}=2.1 mm)

From the above review it is clear that if there are no fines in the bed of a coarse bed stream and wash load enters the stream, the fines will always infiltrate into the coarse bed irrespective of the size of fines in the flow. The rate and mode of deposition of the fines is intimately connected with the near-bed concentration of wash material in flow, relative size of wash material, the bed material and the bed shear stress. The mathematical modeling of this process has not been carried out.

EFFECT OF WASH LOAD ON TRANSPORT OF BED-MATERIAL LOAD

Colby (1964) carried out investigations on highly concentrated flows with both fine sediments and sands and proposed an empirical method for estimating total sediment discharge in hyperconcentrated flows which account for the effect of fine sediment concentrations upto 200000 ppm. He assumed that the fine sediment affects the relationship between sediment discharge and average flow velocity through change in fluid viscosity.

Kikkawa and Fukuoka (1969) carried out experiments in 8 m long and 0.4 m wide flume, using 0.18 mm sand as bed material and silt of sizes 0.05 and 0.015 mm as wash material. They found that the transport rate of bed material increased with increasing concentration of wash load. The tractive force on the bed increased with increasing concentration of wash load. They found that the behavior of wash load is almost the same as that of the suspended load. They also found that velocity gradient in the very thin layer near the bed becomes steeper in the presence of wash load. In a few runs the bed configurations also changed due to the presence of wash load.

Wan (1985) carried out experiments in a closed rectangular conduit with bentonite clay as fine particles and plastic beads of relative density 1.29 as coarse particles. He found that particles settle more slowly in the presence of bentonite suspension as compared to clear-water condition. Also the coarse sediments were found to move at a value of flow intensity higher than that governed by Shields' criterion. Due to larger threshold velocity and smaller settling velocity, the bed load was found to be smaller and the suspended load larger than that in case of transport without wash load. As a result the total load was smaller in the low flow intensity region and larger in high flow intensity region.

Woo *et al.* (1987) tested the applicability of Einstein's (1950) and Colby's (1964) sediment transport formulae for predicting the total bed sediment discharge in flows having clay suspensions. Using Simons' *et al.* (1963) data having bed material size 0.47 to 0.54 mm; they found that the total transport rate of bed material was more than that given by the two methods mentioned above.

Khullar (2003) and Khullar *et al.* (2007) found out that the bed load transport increases in the presence of increased concentration of wash load transport through the alluvial channels. According to them, the bed load transport in the presence of wash load can be computed by using the method of Patel and Ranga Raju (1996) for uniform and nonuniform sediments provided the changes in resistance due to presence of wash load in suspension is taken care of.

Thus, while it is clear that the presence of wash load in suspension affects the transport rate of bed material, quantitative information on the same is still inadequate. So there is need to study the effect of different concentration of wash load of different sizes on sediment transport in alluvial streams.

CONCLUSIONS

The critical review presented herein brings out the fact that resistance to flow and transport of the bed-material load in alluvial channels is affected by the presence of wash load. However, no definite relations for resistance to flow and transport rates are available under these scenarios. The criterion for determining the limit deposition condition in coarse bed alluvial channels and the method for determining the limiting capacity of wash load transport in alluvial channels needs to be verified by additional data with different sizes of wash load. The process of deposition/infiltration of fines/wash load within the pores of coarse bed stream has been studied extensively. Mathematical modeling of such a process, however, has not been attempted as yet.

ACKNOWLEDGEMENT

I wish to express my deep sense of gratitude to Dr. KG. Ranga Raju, Retired Professor, IIT Roorkee and Dr. U. C. Kothyari, Professor, Department of Civil Engineering, IIT Roorkee for their invaluable guidance, fruitful suggestions and encouragement during the course of my research and their motivation to me to write this review paper.

REFERENCES

Adams, J.N. & Beschta, R.L. (1980) Gravel bed composition on Oregon coastal streams. *Can. J. Fishery and Aquatic Sci.* **37**(10), 1514-1521.

Alonso, C.V., Theurer, F.D. & Zachmann, D.W. (1988) *Tucannon River offsite study: sediment intrusion and dissolved-oxygen transport model.* US Department of Agriculture, Agricultural Research Service, Hydro-Ecosystems Research Group, Fort Collins, Colorado, USA.

Arora, A.K. (1983) *Velocity distribution and sediment transport in rigid-boundary channels.* Ph.D thesis, University of Roorkee, Roorkee.

Arora, A.K., Garde, R.J. & Ranga Raju, K.G. (1984) Criterion for deposition of sediment transported in rigid boundary channels. *Proceedings of International Conference on Hydraulic Design in Water Resources Engineering Channel and Channel Control Structures*, Southampton, U.K. 3-45 - 3-55.

Arora, A.K., Ranga Raju, K.G. & Garde, R.J. (1986) Resistance to flow and velocity distribution in rigid boundary channels carrying sediment-laden flow. *Water Resour. Res.* **22**(6), 943-951.

ASCE Task Committee on Sediment Transport and Aquatic Habitats. (1992) Sediment and aquatic habitat in river systems. *J. Hydraul. Eng.*, ASCE. **118**(5), 669-686.

Bagnold, R.A. (1966) *An approach to the sediment transport problems from general physics.* Professional Paper 422-I, United States Geological Survey, Washington, D.C.

Beschta, R.L. & Jackson, W.L. (1979) The intrusion of fine sediments into a stable gravel bed. *J. Fishery Res. Board Canada.* **36**, 204-210.

Carling, D.A. (1984) Deposition of fine and coarse sand in an open gravel bed. *Can. J. Fishery and Aquatic Sci.* **41**, 263-270.

Celik, I. & Rodi, W. (1991) Suspended sediment transport capacity for open channel flow. *J. Hydraul. Eng.* ASCE. **117**(2), 191-204.

Cellino, M. & Graf, W.H. (1999) Sediment laden flow in open channels under non capacity and capacity condition. *J. Hydraul. Eng.* ASCE, **125**(5), 455-462.

Colby, B.R. (1964) *Discharge of sands and mean velocity relationship in sand bed streams.* Professional paper no. 462-A, United States Geological Survey, Washington, D.C.

Coleman, N.L. (1981) Velocity profiles with suspended sediment. *J. Hydraul. Res.* IAHR. **19**(3), 211-229.

Dhamotharan, S., Wood, A., Parker, G. & Stefan, H. (1980) *Bed load transport in a model gravel stream. Project Report No. 190.* St. Anthony Falls Hydraulic Laboratory, University of Minnesota.

Diplas, P. (1994) Modeling of fine and coarse sediment interaction over alternate bars. *J. Hydrol.* **159**, 335-351.

Diplas, P. & Parker, G. (1992) *Deposition and removal of fines in gravel bed streams. Dynamics of Gravel bed Rivers.* John Wiley and Sons Ltd. 313-329.

Einstein, H.A. (1950) *The bed load function for sediment transportation in open channel flows.* United States Department of Agriculture, Technical Bulletin No. 1026.

Einstein, H.A. (1968) Deposition of suspended particles in a gravel bed. *J. Hydraul. Eng.* ASCE. 94(5), 1197-1205.

Einstein, H.A. & Chien, N. (1953 a) *Transport of sediment mixtures with large range of grain sizes.* Institute of Engineering Research, University of California, Berkeley, California, USA. Missouri River Division, Series No. 2.

Einstein, H.A. & Chien, N. (1953 b) Can the rate of wash load be predicted from the bed load function"? *Trans. of Am. Geophy. Union.* **34**(6), 876-882.

Einstein, H.A. & Chien, N. (1955) *Effects of heavy sediment concentration near the bed on the velocity and sediment distribution.* Institute of Engineering Research, University of California, Berkeley, California, USA. Series No. 33, Issue No. 2.

Einstein, H.A., Anderson, A.G. & Johnson, J.W. (1940) Distinction between bed load and suspended load in natural streams. *Trans. of Am. Geophy. Union.* **21**.

Frostick, L.E., Lucas, P.M. & Reid, I. (1984) The infiltration of fine matrices into coarse-grained alluvial sediments and its implications for stratigraphical interpretation. *J. Geol. Soc.*, London. **141**(6), 955-965.

Gyr, A. (1967) The behavior of turbulent flow in a 2-D open channels in the presence of suspended load particles. *Proceedings of 12th Congress of IAHR, Fort Collins.*

Imamato, H., Asano, T. & Ishigaki, T. (1977) Experimental investigation of a free surface shear flow with suspended sand grains. *Proceedings of 17th Congress of IAHR*, Baden, A-4.

Ippen, A.T. (1973) Transport of suspended sediment. *Proceedings of International Seminar on Hydraulics of Alluvial Streams*, IAHR, New Delhi, India.

Itakura, T. & Kishi, T. (1980) Open channel flow with suspended sediments. *J. Hydraul. Eng.*, ASCE. **106**(8), 1325-1343.

Jobson, H.E. & Carey, W.P. (1989) Interaction of fine sediment with alluvial stream beds. *Water Resour. Res.* **25**(1), 135-140.

Khullar, N.K. (2003) *Effect of wash load on transport of uniform and nonuniform sediments*. Ph.D thesis, Indian Institute of Technology Roorkee, Roorkee.

Khullar, N.K. (2006) Limiting capacity of wash load transport in channels. *ISH J. Hydraul. Eng.* **12**(1), 73-86.

Khullar, N.K., Kothyari, U.C. & Ranga Raju, K.G. (2007) Bed load transport in the presence of wash load transport. *ISH J. Hydraul. Eng.* **13**(1), 106-122.

Khullar, N.K., Kothyari, U.C. & Ranga Raju, K.G. (2002) Effect of suspended sediment on flow resistance. *Proceedings of the 5th International Conference on Hydro-Science and Engineering* (ICHE-2002), Warsaw, Poland. Paper No. 302.

Kikkawa, H. & Fukuoka, S. (1969) The characteristics of flow with wash load. *Proceedings of 13th Congress of IAHR.* **2**, 233-240.

Lane, E.W. (1947) Report of the subcommittee on sediment terminology. *Trans. Am. Geophy. Union.* **28**.

Lau, Y.L. (1983) Suspended sediment effect on flow resistance. *J. Hydraul. Eng.* ASCE. **109**(5), 757-763.

Lisle, T.E. (1989) Sediment transport and resulting deposition in spawning gravels, north coastal California. *Water Resour. Res.* **26**(6), 1303-1319.

Lyn, D.A. (1991) Resistance in flat bed sediment laden flows. *J. Hydraul. Eng.* ASCE. **117**(1), 94-114.

Milhous, R.T. (1973) *Sediment transport in a gravel bottomed stream*. Ph.D. thesis, Oregon State University, Corvallis, Oregon, USA.

Muller, A. (1967) Measurements of the influence of suspended particles on the size of vortices. *Proceedings of 12th Congress of IAHR*, Fort Collins, Vol. **4**, D-12.

Nalluri, C. & Spaliviero, F. (1998) Suspended sediment transport in rigid boundary channels at limit deposition. *Water Sci. and Tech.* **37**(1), 147-154.

Nalluri, C., Ghani, A.A. & El-Zaemey, A.K.S. (1994) Sediment transport over deposited beds in sewers. *Water Sci. and Tech.* **29**(1-2), 125-133.

Nikora, V. & Goring, D. (2000) Flow turbulence over fixed and weakly mobile gravel beds. *J. Hydraul. Eng.* ASCE. **126**(9), 679-690.

O'Brien, J.S. (1987) A case study of minimum streamflow for fishery habitat in the Yampa River. *Sediment Transport in Gravel bed Rivers*, Thorne, C.R., Bathurst, J.C. & Hey, R.D. (Eds), Wiley, New York, 921-942.

Ota, J.J. & Nalluri, C. (1999) Graded sediment transport at limit deposition in clean pipe channel. *Proceedings of XXVII Congress of IAHR*, Graz.

Partheniades, E. (1977) Unified view of wash load and bed material load. J *J. Hydraul. Eng.* ASCE. **103**(9), 1037-1057.

Parker, G. & Coleman, N.L. (1986) Simple model of sediment laden flows. *J. Hydraul. Eng.* ASCE. **112**(5), 356-375.

Patel, P.L. & Ranga Raju, K.G. (1996) Fractionwise calculation of bed load transport. *J. Hydraul. Res., IAHR*, **34**(3), 363-379.

Peng, L., Chen, L. & Huang, J. (2001) Study the structure of flow in open channel with suspended sediment. *Proceedings of XXIX Congress of IAHR*, Beijing, China, 319-323.

Pullaiah, V. (1978) *Transport of fine suspended sediment in smooth bed channels.* Ph.D thesis, University of Roorkee, Roorkee, India.

Shen, H.W. (1970) *Wash load and bed load. River Mechanics*, Ed. & Published by H.W. Shen, Fort Collins, Colorado. Vol. I, Chapter II.

Simons, D.B., Richardson, E.V. & Haushid, W.L. (1963) *Some effects of fine sediments on flow phenomenon.* Water Supply Paper No.1498G, United States Geological Survey, Washington. D.C.

Sowers, G.B. & Sowers, G.F. (1970) *Introductory soil mechanics and foundations.* 3rd Edition, Macmillan, London.

Taggart, W.C., Yermoli, C.A., Montes, S. & Ippen, A.T. (1972) *Effects of sediment size and gradation on concentration profiles for turbulent flow.* M.I.T. Report No. 152.

UPIRI (1974) *A study of permissible aggradation in Ganga Canal. U.P.* Irrigation Research Institute, Roorkee, India. T.M. 44, RR(H_2 -12).

Vanoni, V.A. (1946) Transportation of suspended sediment by water. *Trans. ASCE*, Paper No. **2267**, 67-133.

Vanoni, V.A. & Nomicos, G.N. (1960) Resistance properties of sediment laden streams. *Trans. ASCE*, Paper No. **3055**, 1140-1175.

Wan, Z. (1985) Bed material movement in hyperconcentrated flow. *J. Hydraul. Eng.* ASCE. **111**(6), 987-1001.

Wang, Z.Y., Larsen, P., Nestmann, F. & Dittrich, A. (1998) Resistance and drag reduction of clay suspensions. *J. Hydraul. Eng.* ASCE. **124**(1), 41-49.

Westrich, B. & Juraschek, M. (1985) Flow transport capacity for suspended sediment. *Proceedings of 21st Congress of IAHR*, Melbourne, Australia, Vol. 3, 590-594.

Wiuff, R. (1985) Transport of suspended material in open and submerged streams. *J. Hydraul. Eng.* ASCE. **111**(5), 774-792.

Woo, H.S., Julien, P.Y. & Richardson, E.V. (1986) Wash load and fine sediment load. *J. Hydraul. Eng.* ASCE. **112**(6), 541-545.

Woo, H.S., Julien, P.Y. & Richardson, F. (1987) Transport of bed sediment in clay suspensions. *J. Hydraul. Eng.* ASCE. **113**(8), 1061-1065.

Yano, K. & Daido, A. (1964) *Fundamental study on mud flow (i) to (ii).* Bulletin of the Disaster Prevention Research Institute, Kyoto University, Kyoto, Japan.