2.3 Bed Load Transport

Bed load transport is the movement of sediment by saltation, rolling, or sliding in the bed layer (Simons and Senturk, 1977) or may be described as the instantaneous transport of the bed-material in the bed layer zone (i.e. kg/s, m^3/s) (Carson and Griffiths, 1987). Bed load transport in coarse bed rivers is initiated most commonly during runoff events. Miller (1958) observed that bed load transport in gravel bed rivers is not continuous as often the case of sand bed rivers but is episodic. In typical gravel-bed rivers the bed may be stable for all but a few days or a short season each year. This is because the bed-material sizes are large enough to withstand tractive forces applied by the flowing water most of the time (Matin, 1993).

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2.3.1 Transport Characteristics

The proportion of bed load in the total sediment load depends upon the coarseness of the bed material. As bed-material gets coarser, normally its proportion increases. It also depends upon the bed material modality i.e. whether its unimodal or bimodal. Simons and Senturk (1977) stated that for larger sand bed rivers (with unimodal particle size distribution) bed load proportion varies from 5-25% of the suspended load. This proportion of bed load transport may rise up to 10 to 50 % in case of boulder bed streams (Lauffer and Sommer, 1982; Ergenzinger and Custer, 1983; Bathurst et al., 1987). Jones and Seitz (1980) during a field study recorded that bed load ranged from 2 to 10% of the suspended sediment load and averaged about 5%, both for the Clearwater and Snake Rivers which have bimodal bed grain size distribution.

Transport of bed load sediment depends upon the source of sediment i.e. catchment area's geological formation, contribution of banks, type of load (i.e. abrasion or through-put load). It also depends upon the flow event period. For large flow events a large proportion of the bed material is immobile, even at bankfull discharge. Thus, for lengthy periods, bed load transport is negligible or restricted to the finer size particles.

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For bimodal bed material particle size distribution (sand and fine gravel) bed load may move in threads between the cobbles and boulders (Bathurst et al. 1987, Carson and Griffiths 1987).

2.3.2 Factors Affecting (Inherent Pattern) Bed load Transport

2.3.2.1 Snow melt and Rainstorm

Østrem et al. (1971) described that rivers having a water supply source as 'snow' carry more sediment in the early period of snow melt, because of the availability of sediment being deposited in the winter season. In the later months bed load supply will be relatively less, until some changes take place. Newson (1980) and Moore and Newson (1986) while quoting the example of the Roaring River (Colorado, USA) mentioned that a rainfall flood is likely to carry more bed load sediment than a flood caused by the snow melt, since the former one carries sediment eroded from the upland catchment areas.

2.3.2.2 In-Channel Deposited Sediment

A huge volume of sediment is stored in the river channels, usually, in the form of bars. This sediment volume can be ten times the average annual particulate sediment exported from the catchment area (Swanson et al. 1982). Therefore, any change in this storage of sediment could results in a significant change in the sediment yield. Sediment present in the channel can also affect the movement of sediment waves (i.e. to delay and make intensity thinner) resulting from upland areas.

2.3.2.3 Flood Stage

If a flood is occurring after a long interval then in-channel accumulated material will be transported by the first flow event of the flood. The transport of bed-material will be proportional to the increase in water stage up to the maximum stage limit, in other words it can be said that the rising limb pattern of flood hydrograph and sediment hydrograph will coincide with one another (VanSickle and Beschta, 1983). When accumulated bed-material is depleted there will be a sudden fall in sediment transport rate, therefore, flow and sediment hydrographs will not coincide with one another on the falling limbs. If the bed has an armour layer then the rise in stage will not make the sediment transport increase until the armour layer breaks, that usually breaks at the peak flows. When an armour layer breaks, large volume of sediment are released and this flow will continue even during the falling stage, until stream power reduces to one third of the power required to initiate the sediment transport (Klingeman and Emmett, 1982; Reid et al. 1985). The pattern of flow is shown in Figure 2.1

2.3.2.4 Unsteady Flow Conditions

It has been observed that bed load transport rate in unsteady flow conditions increases faster to that expected during the equivalent steady flow conditions (Graf and Suszka, 1985). Since bed load transport mostly occurs during unsteady flow conditions, therefore, it is also likely to be unsteady. This unsteadiness in sediment transport takes place even with the same flow in a small interval of time (Jackson and Beschta, 1982; Klingeman and Emmett, 1982; Tacconi and Billi, 1987). Jackson and Beschta (1982) stated that the sudden variation in bed load transport over a small interval of time may be due to the disruption of armour layer and scour or fill connected with riffle/pool systems sequence. Reid and Frostick (1984) and Reid et al. (1985) etc. described it as a result of sporadic break-up of clusters of sediment particles.

2.3.3 Indeterminacy of Bed Load Transport

Numerous studies carried out during the last decade proved indeterminacy in the bed load transport inherent pattern (bed load rating curve). Investigations conducted at Turkey Brook suggested that there is no simple relationship between instantaneous gravel transport rate and flow parameters, in-contrast to what was originally assumed. For example, bed load transport rates and water depths recorded at Turkey Brook (Reid et al. 1985) (depicted in Figure 2.2), for two flood events, clearly show the suppression of bed load transport rates at peak of the floods, whereas theoretically at flood peaks bed load transport rates should be the maximum.

Reid and Frostick (1986) highlighted the suppression of bed load transport at peak flow stages and stated that transport rate abruptly ceases on the rising limb (of flow hydrograph) as Y/D (water depth/particle size) approaches 70 and only resumes again at the same value on the falling limb, however the authors did not provide any reason for this feature. On the other hand Carson (1986b) found that the conclusions of Reid and

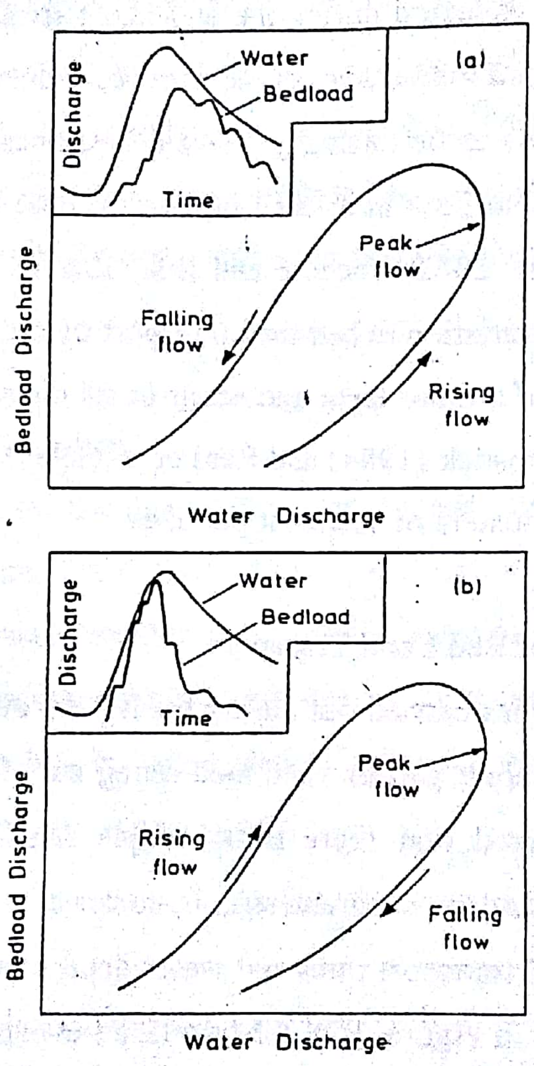

Figure 2.1: Variation of bed load transport with water discharge through a flood hydrograph: (a) where sediment becomes available during the falling limb; (b) where sediment supplies are depleted during the rising limb. Water and bed load discharge hydrographs are inset (after Bathurst 1987b).

Frostick (1986) do not agree with the flume data of Williams (1970) in which bed load showed a direct relationship with bed grain stress for Y/D = 20 -150.

The deviation of bed load transport from its inherent pattern (as shown in Figure 2.1) has also been observed by Samide (1971) and Hudson (1983) during the flume and studies on the Elbow River, Canada. Results of Hudson and Samide depicted in Figures 2.3 and 2.4 indicate that (in gravel bed streams) bed load moves in waves. During a study of Kariri river Griffiths (1979) observed the same wave pattern as Samide (1971) and Hudson (1983). Hysteresis between the rising and falling limbs of a hydrograph are also visible from Figure 2.5, a data plot of East Fork River, having bimodal particle size distribution (i.e. sand and gravel). Bagnold (1980) noted the pronounced scour of bed-material immediately upstream during the rising stage and deposition during the falling stages for East Fork. Similar views have also been presented by Leopold and Maddock (1953), frequently quoted in the literature.

What ever the causes are for this deviation from the inherent pattern of bed load transport, these results suggest the need for more research to make a closer inspection how coarse bed-material does move and to collect data for model development based on the real field conditions rather than depending upon those semi-empirical formulae, based on flume studies result, plane-bed formation assumptions (with uniform bed-material) and mean parameters for the channels.

2.3.4 Bed Load Transport Theories

Simons and Senturk (1977) while describing the bed load transport concept said that in a movable bed stream when hydraulic conditions exceed the threshold conditions of motion of bed-material, sediment will start to move. If this movement of sediment particles is of the saltating, sliding or rolling type, in the bed layer zone, then such type of sediment transport is commonly called bed load transport.

DuBoys (1879) was the first investigator who initiated the idea of bed shear stress (tractive force) in the analysis of bed load. Since then a large number of bed load transport formulae have been developed, relating the bed load discharge, flow condition and composition of bed load-material. Mostly, these formulae have been developed assuming steady flow and thus are applicable for this condition but in-reality transport of

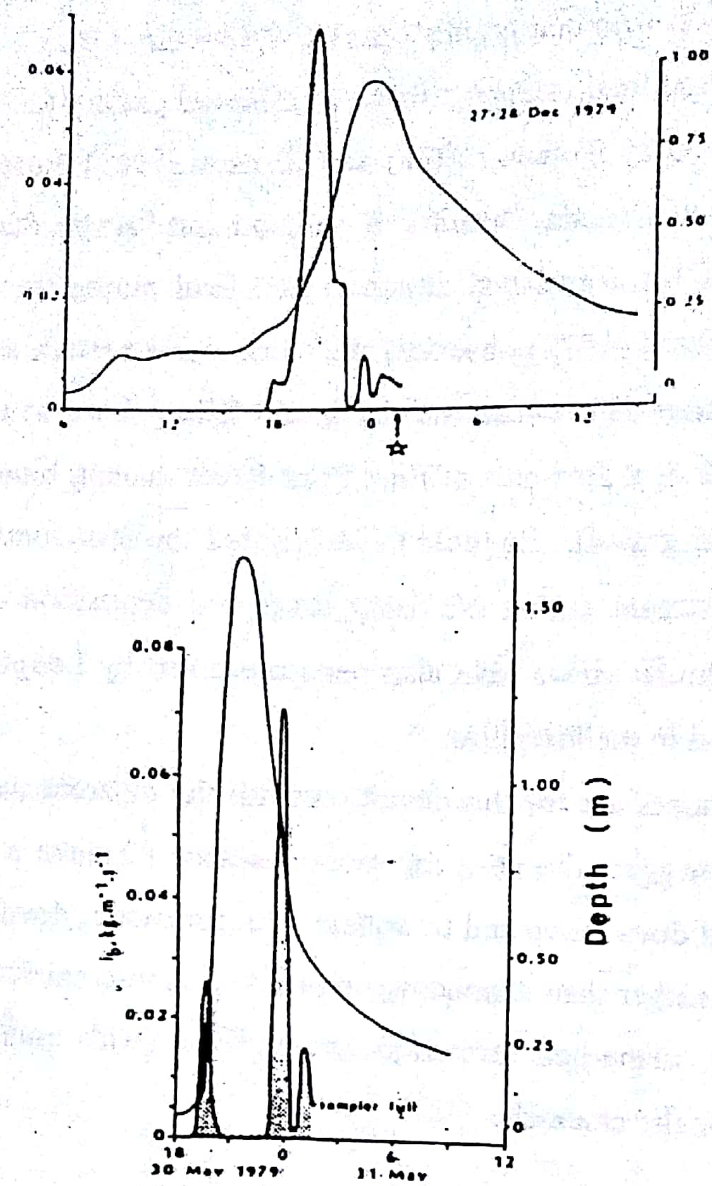

Figure 2.2: Bed load transport rates and water depth for two floods on Turkey Brook, UK (after Reid et al., 1985).

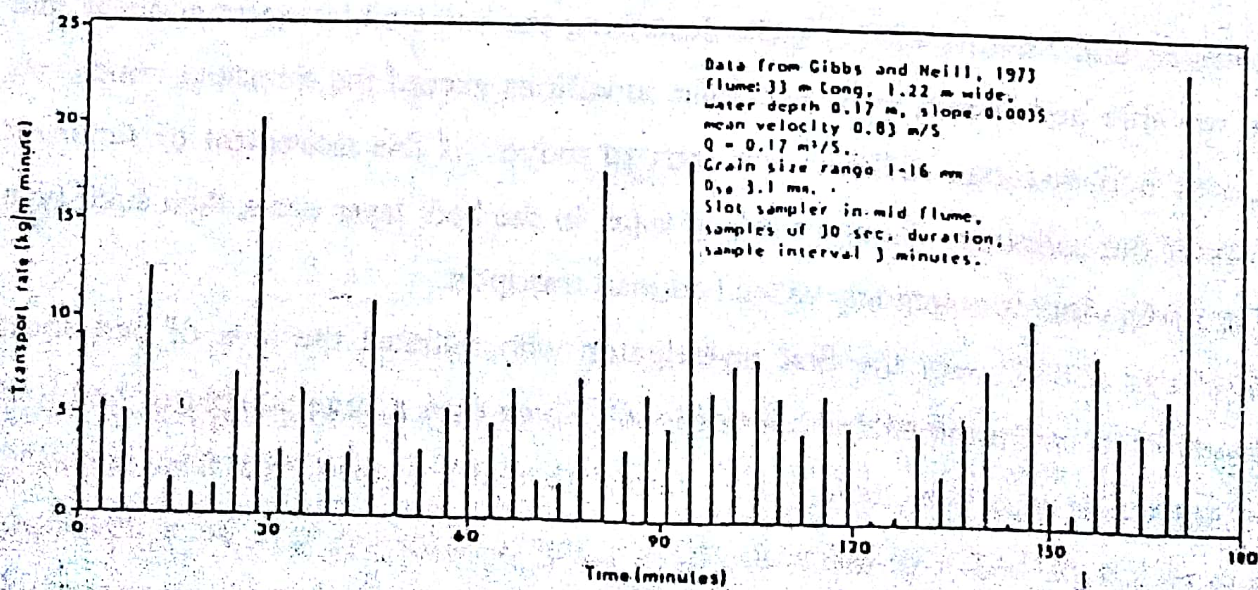

Figure 2.3: Bed load transport rate variations over time in a large gravel bed flume (after Hudson 1983).

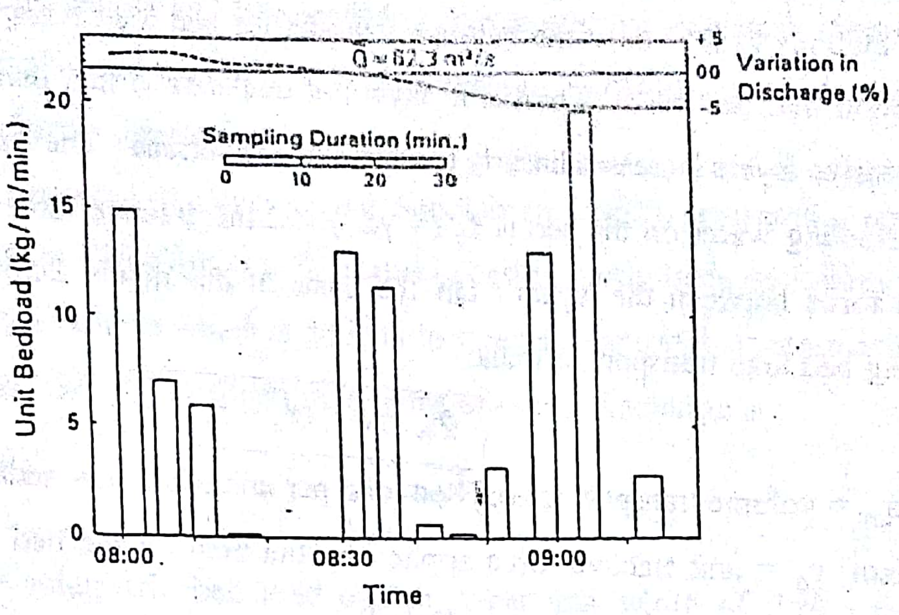

Figure 2.4: Bed load transport rate variations over time at Bragg Gauge, Elbow River (after Samide 1971 and Hudson 1983).

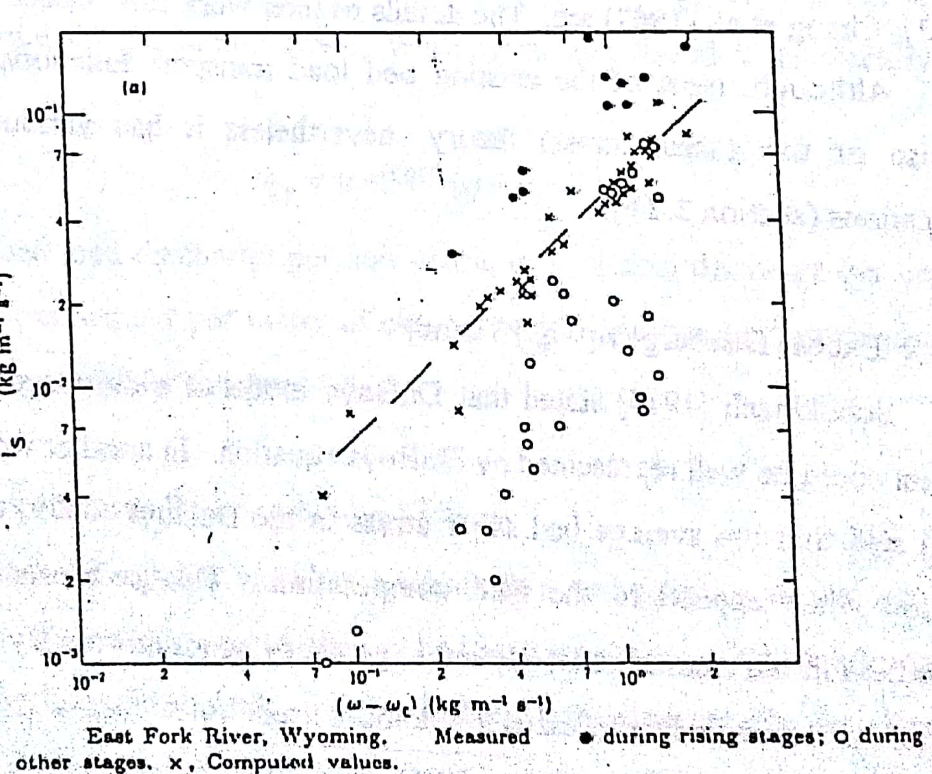

Figure 2.5: Hysteresis in relationship between bed load transport rate (i_s) and excess unit power on rising and falling stages of floods (after Bagnold 1980).

sediment is unsteady and non-uniform. The existing bed load transport formulae, generally, have been developed by using the following theories.

2.3.4.1 Excess Shear Stress (τ_o - τ_c) Theory

Duboys (1879) used the bed-layer model for bed load transport study with the assumption that bed-material moves in layers of thickness 'd' and that the mean velocity of successive layers increases linearly toward the bed surface. The tractive force applied by the flowing water on the bed is τ_o (= γdS) and this tractive force is balanced by the friction force between the layers. On the basis of this model DuBoys developed the following bed load transport formula:

$$q_{bv} = k\tau_o(\tau_o - \tau_c) \qquad (2.20)$$

where q_{bv} = volume transport rate of bed load per unit width; k = sediment characteristic coefficient, τ_o = unit tractive force applied by the flow on the bed of a wide channel (kg/m^2); and τ_c = critical shear stress (kg/m^2).

Lot of work has been done on this theory (more than any other theory) by various investigators including O'Brien and Richard (1934), Shields (1936), Kalinske (1942), Chang et al. (1967) etc. The details of their work can be seen in standard texts.

Although, most of the existing bed load transport functions are based on the premise of this (shear stress) theory, nevertheless it has various problems in its applications (section 2.2.6).

2.3.4.2 Excess Discharge (q - q_c) Theory

Schoklitsch (1914) stated that DuBoys' model of sliding layer was incorrect but his data could be well represented by DuBoys equation. In another work he (Schoklitsch 1930) said that the average bed shear stress in the DuBoys (1879) equation is a poor criterion when applied to the field computation. This is because the shear stress distribution in the channel cross-section is generally non-uniform. By replacing τ by q in the DuBoys' equation he expressed it in a more useful form; that is

$$q_{bw} = \frac{7000}{D_s^{1/2}} S^{3/2}(q - q_c) \qquad (2.21)$$

where q_{bw} = bed load discharge by weight per unit width per unit time; D_s = particle size; S = slope; and

$$q_c = 1.94 \times 10^{-2} \frac{D_s}{S^{4/3}} \tag{2.22}$$

The basis for Equation 2.21 is that bed-material begins to move at some critical discharge and that the bed load discharge is proportional to the rate of work done by the tractive force in excess of that needed to overcome the resistance along the wetted perimeter (Schulits and Corfitzen 1937). Later on, MacDougall (1934) and Schoklitsch (1934, 1950) further developed this theory.

In this process of development Schoklitsch (1962) presented a new version of bed load function. This function is relatively better, partly because it does not explicitly involve depth, a variable which is difficult to measure accurately in steep and rough flows (Bathurst et al. 1987). His function in terms of excess discharge is

$$q_{bv} = \frac{2.5}{\rho_s / \rho} S^{\frac{3}{2}} (q - q_c) \tag{2.23}$$

where q_{bv} is volumetric bed load discharge per unit width of flow, ρ_s and ρ are densities of sediment and water respectively and q_c = critical discharge per unit width and can be computed by Equation 2.3.

Recently, Milhous (1989) modified the Schoklitsch (1962) function and checked its performance for Tucannon River, Washington and found it satisfactory. Milhous function is

$$q_s = 0.07 S^{3/2} (q - q_c)^2 \tag{2.24}$$

where q_s = bed load discharge per unit width; q_c = critical discharge per unit width (in cubic meters per second per meter of channel width) and can be computed by Equation 2.5; S = energy slope of the river.

2.3.4.3 Excess Stream Power $(\omega_o - \omega_c)$ Theory

To relate energy (or work) of a stream flow and quantity of sediment transport to the flow is a recent theory in the field of bed load transport. This theory was (first time) introduced by Bagnold in 1966, for fine bed-material streams. He described the rate of doing work as the product of available stream power (τV) and efficiency (e). The bed load work rate is the product of bed load transport rate expressed as submerged weight per unit width per unit time and tan α. From a physical view point the available stream power supplies the energy for the transport of sediment. Thus;

$$\left(\frac{\gamma_s - \gamma}{\gamma}\right) q_{bw} \tan\alpha = \tau V e_b \tag{2.25}$$

where q_{bw} = bed load discharge by weight per unit width per unit time; α = coefficient of dynamic solid friction; e_b = bed load transport efficiency which considers that part of stream power available for bed load transport. Later on, Bagnold (1980) by using the same concept as he did for the fine bed streams developed an expression for coarse bed channels, which is

$$q_{bw} = (q_{bw})_* \left[\frac{\omega_o - \omega_c}{(\omega_o - \omega_c)_*}\right]^{3/2} \left[\frac{Y}{Y_*}\right]^{-2/3} \left[\frac{D}{D_*}\right]^{-1/2} \tag{2.26}$$

where

q_{bw}= bed load transport rate per unit width per unit time (kg/m.sec); $(q_{bw})_*$ = reference value of q_{bw}; ω_o= stream power per unit bed area (kg/m.sec); ω_c = threshold value of ω_o at which bed load movement starts; D = mode of size of bed material; D* reference value of D; Y = mean flow depth; and Y* = reference value of Y. Bagnold derived these reference values (i.e. $(q_{bw})_*, (\omega_o - \omega_c)_*, Y_*, D_*$) by using Williams' (1970) data.

Using the same theory of excess stream power different investigators developed their bed load transport expressions. Significant among them are Ackers and White (1973) and Yang (1984).

Although this theory has been used by the well known investigators, nevertheless it incorporates all the disadvantages associated with the shear stress and velocity methods, as stream power is the product of shear stress and mean velocity (i.e. $\omega = \tau V_m$).

2.3.4.4 Excess Velocity (V - V_c) Theory

Although some investigators made successful efforts to develop bed load transport relations for fine bed rivers by using excess velocity theory, nevertheless, no appreciable work has been carried out to develop bed load transport functions for coarse bed-material channels, except some introductory type work by Hjulstrom (1935), Isbash (1936) and Lane (1955). Isbash (1936) developed a function for determining the critical mean velocity at cessation of bed load transport and Lane (1955) while designing stable channels determined the critical mean velocity values for different bed-material sizes, varying from 5 mm to 200 mm. Consequently, just one bed load transport formula is available for coarse bed rivers (i.e. developed by Levi 1957), whereas for fine bed-material channels, Barekyan (1962) and Colby (1964) developed bed load and total load equations, respectively.

Use of the vertically averaged velocity as a predictor of bed load transport has been limited, because of the problem that critical mean velocity for scour is less for a given sediment in shallower streams. However, similar problems are associated with other approaches (i.e. tractive stress and stream power).

2.3.5 Calculation Approaches for Determining Bed Load Transport

The suitability of an approach for a given application depends on how well it can describe the dominant physical processes in the river system. The choice of approach (i.e. deterministic, probabilistic etc.) for a particular study depends on the requirements of the study and the availability of data. This section, therefore, deals with different approaches that have been used by the investigators for the development of sediment transport functions.

2.3.5.1 Uni-Sized Bed-Material Transport

All the work done in the beginning of bed load transport history, laboratory or field studies, was based upon the assumption that channel beds comprise material having uni-size (uniform) formation. In uni-size bed-material transport it is assumed that all particles of bed-material will start their movement as soon as flow stress or shear stress exceeds a critical limit. Likewise, particle movement will cease when the flow stress falls below a critical limit. In order to develop bed load transport functions investigators followed different approaches for the optimal solution of the problem. Generally, available bed load functions have been developed by using the following calculation approaches.

2.3.5.1.1 Empirical Approach (Regression Approach)

This approach is used mainly to obtain empirical relations between sediment discharge rates and some flow and sediment parameters. This approach like other approaches has some advantages and disadvantages. An advantage of using this approach is that it can give quick site-specific relations provided reliable data are available. A disadvantage is that it does not provide much physical meaning or explanation of the sediment discharge process. Using this approach Meyer-Peter et al. (1934) developed an empirical model for gravel sizes, ranging from 5.05 to 28.6 mm diameter. Later on, Meyer-Peter and Mueller (1948) made modifications in their original empirical model and presented a new version in metric units:

$$q_b = \frac{\gamma}{\gamma_s - \gamma}\left[\frac{(\frac{Q_s}{Q})(\frac{K_s}{K_r})^{\frac{3}{2}} dS - 0.047\left\{\left(\frac{\gamma_s - \gamma}{\gamma}\right)\right\}D}{(\frac{0.25}{\gamma})(\frac{\gamma}{g})^{\frac{1}{3}}}\right] \quad (2.27)$$

where

$$K_s = U / d^{\frac{2}{3}} S \qquad K_r = 26/D_{90}^{1/6}$$

and

U = mean velocity, d = flow depth, γ = specific weight of water, γ_S = specific weight of sediment, Q_S= water discharge proportion to the bed, Q = mean water discharge, Q_s/Q = 1 for wide channels, and K_S/K_r = 1 for smooth channels.

Likewise, Hey (1982) used data from 66 UK sites and developed two empirical type functions for the computation of bed load in gravel bed rivers. He used regression analysis technique in the development of his functions.

Other significant important investigators/agencies who developed the empirical models/relations include Paintel (1971), Wang (1975), Pazis and Graf (1977), Bagnold (1980, 1986). A model developed from this technique can only be applied to the conditions which are similar to those used in obtaining the empirical model.

2.3.5.1.2 Probabilistic Approach

In this approach prediction of sediment transport rate is based on the prediction of particle motion, are derived from a statistical basis. Functions to define the beginning and ceasing of sediment motion, as well as the rate of sediment discharge can be formulated. Einstein's (1942, 1950) bed load function is the most prominent function based upon this approach. He had two ideas which broke with the concepts used in the past by DuBoys (1879) and Schoklitsch (1934) in their functions. His two ideas are: (1) the critical criteria for incipient motion was avoided, because it is difficult to define; and

(2) the bed-load transport is related to the turbulent flow fluctuation rather than to the average value of forces the flow exerts on sediment particles. Consequently, the beginning and ceasation of sediment motion is expressed with the probability concept, which relates instantaneous hydrodynamic lift forces to the particle's submerged weight. This approach afterward was followed by Brown (1950), Toffaleti (1969) and Wang (1975) for the development of bed load transport functions.

2.3.5.1.3 Dimensional Analysis Approach

When scientists understood the complexity of the sediment transport process then they extensively relied on dimensional analysis. The usual approach is to correlate sediment concentration or a dimensional transport rate with a principal, and perhaps other, dimensional parameters. Examples of principal dimensionless parameters are the mobility number of Ackers and White (1973) combining shear stress and grain shear stress, and the unit stream power of Yang (1973, 1984) which combines velocity and slope.

Pioneering work in this regard was done by Shields (1936) and afterward extended by Rottner (1959) who used dimensional analysis technique in the development of sediment transport functions. While working on uniform sediment transport in a flume study, Garde and Ranga Raju (1985) also relied on this technique.

Parker et al. (1982) and Diplas (1987) also depended upon the dimensional analysis technique, though for mixed size sediment. Diplas used this technique to avoid the concept of equal mobility being introduced by Parker et al (1982).

2.3.5.1.4 Semi-theoretical Approach

Apart from the approaches described above, some attempts have also been made to tackle the bed load problem from a theoretical viewpoint. These investigations are based on some form of an analytical model based on principles of statistics and fluid mechanics. However, in no case is the solution completely theoretical; experimental data have been extensively used to obtain the constants involved in the derivation.

Einstein (1942) was the first to attempt a semi-theoretical solution to the problem of bed load transport. However, the relationship presented by him in 1942 did not include the effect of bed forms on the bed load transport. He therefore presented a modified and more detailed solution to the problem in 1950.

Using this approach Luque and Beek (1976) developed a function for uniform bed-material (size varying from 0.9 to 3.3 mm) transport. During their experiments the critical shear stress value was taken as less than that of the Meyer-Peter and Mueller's dimensionless shear value (i.e. 0.047). The developed function is:

$$Q_B = 5.7\left(\tau^* - \tau_c^*\right) \tag{2.28}$$

There are many other investigators who worked on this approach and developed bed load transport functions. Some important examples are Kalinske (1947), Bagnold (1956), Engelund and Fredse (1976), Nakagawa and Tsujimoto (1976) and Yalin (1977).

2.3.5.2 Mixed-Size Bed-Material Transport

The movement of grains in a sediment mixture is affected by the other particles since small grains can be sheltered by the larger, and the largest particles have greater exposure to the flow. As a result, each size fraction will have its individual transport rate which depends on the total distribution of sizes available for transport. Thus the grain size of an individual size fraction in a mixture has two effects, one absolute and the other relative, on the transport rate of that fraction. For a given grain density and shape, the absolute size determines the mass of the grain and the area of grain surface exposed to flow. The size of each grain relative to others in the mixtures controls the variation from fraction to fraction of both the value of bed shear stress acting on individual grains and the resistance of those grains to movement. Because smaller grains in a mixture are more hidden from the flow and also more impeded in their motion than coarser grains, the relative-size effect counteracts the absolute size effect by decreasing the mobility of the finer fraction and increasing the mobility of the coarser fractions. Wilcock and Southard (1988) stated that the reality of the underlying phenomenon of mixed-size sediment transport problem lies in the balance between these two grain size effects.

Because of the pivotal role of relative grain size in mixed-size sediment transport three approaches have been used to incorporate its effects, on the mixture, in the development of sediment transport functions/models.

2.3.5.2.1 Reference Particle Size Approach

In this approach, a single grain size, called reference particle size (or characteristic diameter, commonly D_{50}) has been used to represent the relative size effects of the mixture. The particles of reference size are unaffected by the hiding/exposure effects and behave as if present in a bed of uniform material (Cecen and Bayazit 1973). Models developed before Einstein's (1950) seminal work, when he introduced the hiding function (x), belong to this category. A well known example of this category is the Meyer-Peter and Mueller (1948) model (section 2.3.5.1.1). Work on such models is still going on. It has been stated that there was little improvement in the computed load by subdividing the bed-material into different size classes rather than relying on the reference particle diameter. In this regard the findings of Andrews (1983) are important as they indicate that the threshold tractive stress for particles of different size in a given reach varies very little: that is, essentially, all particles start to move at one time when there is widespread instability of the cover layer. However, subsequent mobility of these particles is not so invariant with size. Several studies suggest that particles close to the median diameter (or just larger) are the most mobile. Smaller ones get trapped more easily and stay locked in the bed for longer periods of flood flows; larger ones are simply more difficult to keep moving, not withstanding their greater exposure, because of their mass. However, none of the data sets so far available indicates substantial differences in mobility with size, that for D_{50} being no more than 30% different from that for D_{16} or D_{84}, at least for typical log-normal grain size distributions found in natural channels (Meland and Normann 1969; Laronne and Carson 1976).

This general conclusion that, in a gravel-bed rivers, the overall mobility of the particles in the channels bed is basically much the same irrespective of size, so that, in effect, total bed material transport rates computed on the basis of a single representative particle diameter are comparable with those integrated for different size fractions, has also received support from Parker and Klingeman (1982) using data for Elbow River and Oak Creek. Of course, if finer throughput material is present this will move at flows less intensive than that needed to activate the main bed surface.

2.3.5.2.2 Hiding Function Approach

Einstein (1950) was the first to use this approach. He attempted to incorporate the effect of relative grain size on the fractional transport rates. Einstein defined several empirical correction functions in terms of mixture properties but only one of these , the hiding function x was defined as a function of relative grain size. Although the exact derivation of x is not clear, it was apparently computed as a final empirical correction between predicted and measured fractional transport rates. It is defined as a function of D_i/X, where X is an empirical quantity intended to represent the largest grain size in a mixture that experiences hiding effects. The value of the hiding function decreases for $D_i < X$ and becomes constant at $D_i \geq X$ (Figure 2.6). This function is included in the transport model as a multiplicative correction factor. In this approach Einstein tried to account for the effect of relative grain size, but only partially, as he did not consider the exposure effect of the large particles. However, Parker et al. (1982) reasonably proved that the hiding function of Einstein was not correct.

In another study Egiazaroff (1965) incorporated the relative-grain size effect, for mixed-sized sediment, in a function. The relative-size variation was introduced in terms of the flow velocity acting on different fractions. Ashida and Michiue (1972) stated that Egiazaroff function (depicted in Figure 2.6) may be slightly modified in the form of multiplicative correction function.

Misri et al. (1984) and Samaga et al. (1986) made advancements in this field and the former investigator developed a conceptual model for the effect of a particular size of sediment on the transport rates of the other particles, for mixed-size sediment. This model comprises a coefficient known as the sheltering and exposure coefficient which takes into account the relative grain size effects.

2.3.5.2.3 Particle Size Fraction Approach

In this approach bed load is computed on a fractional transport basis. The fractional transport rate is computed as if that fraction formed a uniform bed. The total transport rate was then computed as a sum of the fractional transport rates weighted by the proportion of each fraction present in the bed. Models developed during the preliminary stages of this approach did not incorporate the relative grain size effect, in the computation of transport of each size fraction. A well known example of such models is that of the Parker et al (1982) substrata-based model. The models developed using the particle size fraction approach can be classified into two categories: with equal mobility hypothesis and without equal mobility hypothesis. Both categories are explained below.

a) With Equal Mobility Hypothesis

Parker et al. (1982) developed a bed load function (substrata-based) for a stream of mostly gravel and coarser materials. He divided the bed-material into ten grain size fractions to get a representative bed load transport function. He used the equal mobility hypothesis, according to which once the pavement is broken essentially all grain sizes, including the D_{90} of the pavement, roughly will begin to move. In the development of his function the equations were empirically fitted using field data from several streams, with median size ranging from 18 to 28 mm. The Parker et al. function is

$$q_{bi} = \frac{W_i^* P_i (gDS)^{\frac{1}{2}} DS}{(s-1)} \tag{2.29}$$

where

$$W_{i=50}^* = 0.0025 \exp\left[14.2(\Phi_{50}-1) - 9.28(\Phi_{50}-1)^2\right] \qquad \text{For } 0.95 < \Phi_{50} < 1.65$$

$$W_{i=50}^* = 11.2\left(1 - \frac{0.822}{\Phi_{50}}\right)^{4.5} \qquad \text{For } \Phi_{50} > 1.65$$

$$\Phi_{50} = \frac{DS}{(s-1) d_i \tau_{ri}^*}$$

$$\tau_{ri}^* = 0.0876\left(\frac{d_{50}}{d_i}\right)^{-0.982}$$

As clear from the equation the value of τ^*_{r50} (reference Shields stress associated with the D_{50} of the subpavement) was taken equal to 0.0876. Parker et al. said since the correlation coefficient, R^2 was 0.9997 for the above mentioned equation, therefore, this equation (which is Equation 9(a) of the Parker et al.) can be accurately replaced by the following equation, taking the exponent value -0.982 equal to -1.

$$\tau_{ri}^* = 0.0876 \frac{d_{50}}{d_i}$$

which is a simplified form of the equation 9(b) of the Parker et al. Other investigators

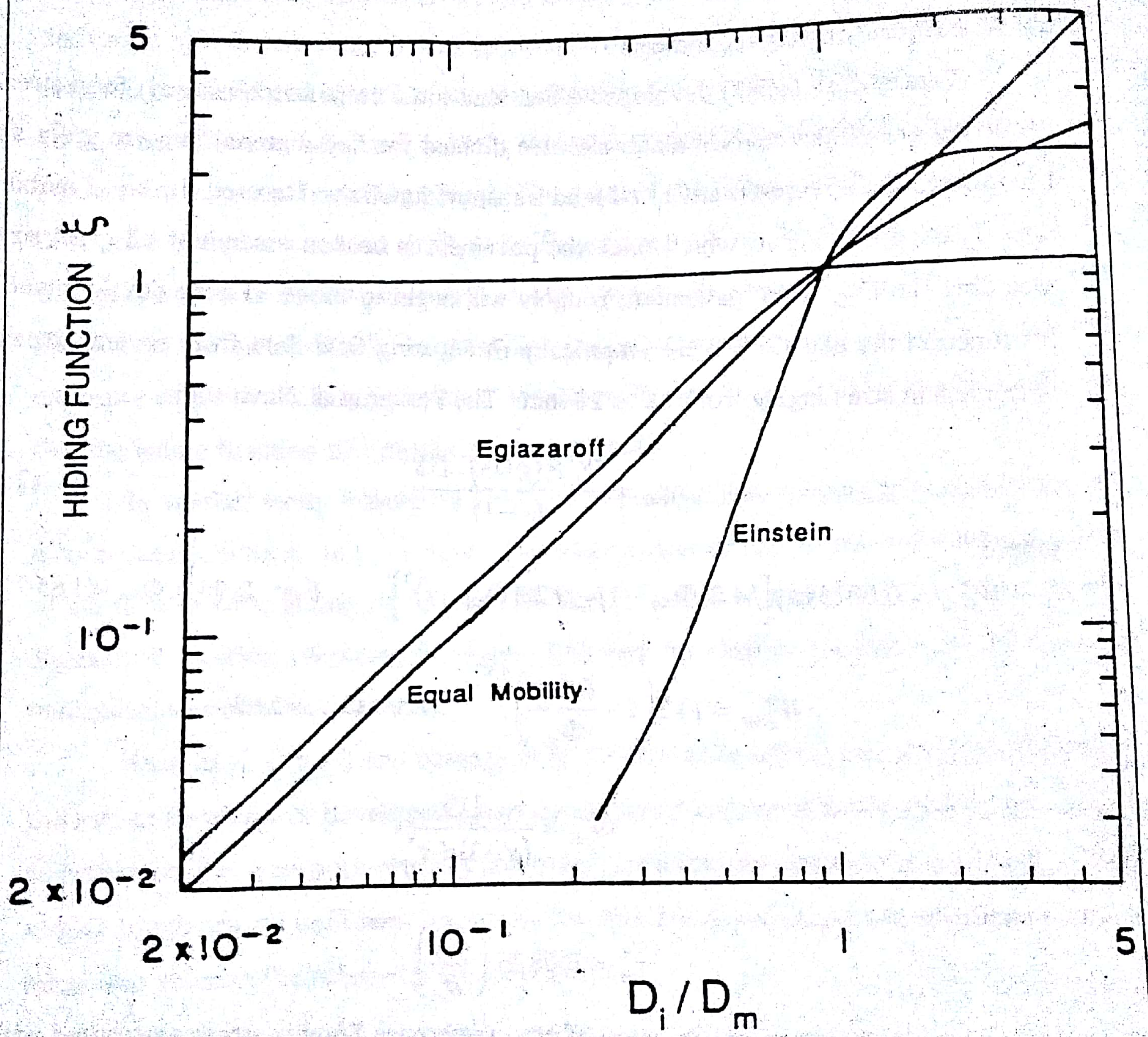

Figure 2.6: Hiding functions of Einstein and Egiazaroff (after Andrews and Parker 1985). The Einstein Hiding Function assumes rough flow, $X = D_{65}$, and $D_{65}/D_m = 2$. The Egiazaroff relation is from Ashida and Michue 1972).

including Diplas (1987), Ashworth and Ferguson (1989), Ashworth et al. (1992), Wilcock (1992) and Wathen et al (1995) found that the value of τ^*_{r50} (= 0.0876) taken by Parker et al. is a site specific value and that it could significantly vary for other streams. Later, Parker (1990) transformed his subsurface grain size distribution based equation (Parker et al 1982, Equation 2.29) into a surface layer grain size distribution based equation. The performance of the latter equation has not yet been sufficiently tested/confirmed. Therefore, Equation 2.29 (Parker et al. 1982) is selected in this study for testing purposes as it is well known, although it is based on the concept of equal mobility which may not hold for other streams.

So far as the equation parameters are concerned q_{bi} is bed load discharge per unit width for the ith. grain size fraction of the bed-material; D = stream depth; S = slope of energy gradient; s = specific gravity; P_i = a size fraction; and W^* = dimensional transport rate.

b) Without Equal Mobility Concept

Diplas (1987) in a study used data of Oak Creek (collected by Milhous 1973) and developed a bed load transport function for gravel bed streams, which is valid for the whole range of Shields stress (ϕ_{50}). This function incorporates the effect of hiding and is independent of the concept of equal mobility. The hiding function used by Diplas depends on ϕ_{50} and D_i/D_{50}. He stated that its dependence on ϕ_{50} suggests that the use of a single grain size to describe the mobility of a mixture is inappropriate and therefore, knowledge of the complete size distribution of the bed-material is necessary to calculate the bed load transport rate of poorly sorted material for a wide range of ϕ_{50} values. In developing this function he used dimensional analysis and a new similarity approach.

In an experimental study with a recirculating flume Wilcock and Southard (1988) found that at equilibrium the transport rates of all fractions were not equally mobile. Based upon the study results they developed a bed load transport function with a grain size distribution of the bed load similar to the grain size distribution of the bed-material. With this function fractional transport rates are computed as

$$q_{bi} = \left(\frac{p_i}{f_i}\right) q_b \tag{2.30}$$

where p_i is the proportion of each fraction in transport, f_i is its proportion in the bulk bed sediment mix, and q_b is the total transport rate.

Later on, Parker (1990) transformed his substrata-based gravel transport model (Parker et al., 1982) into a surface-based model. His new model includes the concept of hiding, according to which coarser surface grains are intrinsically less mobile than finer surface grains. This model stands independent of the concept of equal mobility, even though the concept was used as a convenient approximation in developing it. Recently, Cui et al. (1996) used this model successfully (along with the transfer function of Toro-Escobar et al. 1996) in the development of numerical model for bed aggradation of heterogeneous sediment to study downstream fining of gravel in rivers.

2.3.5.2.4 Grain Size Distribution Approach

It relies on the Rosin distribution and how its parameters depend on the flow discharge and bed stress. Shih and Komar (1990) first employed this approach on Oak Creek data (collected by Milhous, 1973) and concluded that the grain size distribution of bed load gravels in Oak Creek follows the Rosin distribution at flow stages which exceed that necessary to initiate break-up of the pavement in the bed-material. The distributions systematically vary with flow discharges and bed stress, such that at higher flow stages the grain sizes are coarser while the spread of the distribution decreases. Based upon these result they formulated a differential bed load transport function for individual grain-size fractions. During the development of this function they utilised the dependence of two parameters (i.e. k and s) in the Rosin distribution upon the two flow stress parameters (represented by τ and q_w). The developed function for each size fraction is

$$q_{si}(D_i,\tau) = q_s(\tau) f(D_i,\tau) \quad (2.31)$$

where q_s = total bed load transport per unit width; $f(D_i,\tau)$ = frequency curve for the Rosin distribution and equals

$$f(D_i,\tau) = 100\left(\frac{s}{k}\right)\left(\frac{x}{k}\right)^{s-1} \exp\left[-\left(\frac{x}{k}\right)^{s}\right] \quad (2.32)$$

In this relation 's' is a dimensionless factor that controls the overall spread of distribution and 'k' is the mode of distribution. The values of 's' and 'k' can be derived from the following relations: in terms of unit discharge, q_w

$$s = 10.0\, q_w^{0.42} \tag{2.33}$$

$$k = 62.7 q_w^{2.3} \tag{2.34}$$

Recently, Inpasihardjo (1991) used the excess discharge theory to develop a bed load discharge computation model. In this model he actually combined the grain size distribution approach with the bed load transport concepts (with particle size fraction) introduced by Wilcock and Southard (1988). His bed load transport model is

$$q_{bi} = f_{bli} B(q - q_{ci}) \tag{2.35}$$

for bed load with log-normal (Gaussian) size distribution

$$f_{bli} = \frac{1}{\sigma\sqrt{2\pi}} EXP - \left[\frac{(D_i - D_m)^2}{2\sigma^2}\right] \tag{2.36}$$

for bed load with ideal Rosin size distribution

$$f_{bli} = 100\left[\frac{s}{D_{63}}\right]\left[\frac{D_i}{D_{63}}\right]^{s-1} EXP\left[-\left(\frac{D_i}{D_{63}}\right)^s\right] \tag{2.37}$$

and B is a function of (f_{bmi}, S); f_{bmi} can be obtained similar to f_{bli} but for the bed-material. This model has the attraction that it considers both the particle size fraction of bed-material and bed load, but it has fundamental problems.

2.3.6 Critical Assessment Of Sediment Transport Theories

Since the sediment transport theories have been developed using the threshhold conditions of bed load movement, problems associated with the conditions are incorporated in the structure of the formulae. The velocity theory has relatively less problems (stated in article 2.2.6) however there is scarcity of research work on this theory. On the other hand, stream power is a product of tractive stress and mean flow velocity ($\omega = \tau V_m$), consequently, associated problems with the application of both the methods are multiplying, so do the predicted results based on this theory. It can be said that irrespective of the way in which bed load formulae are developed, the rate of bed load transport is related to the shear stress on the bed or the water flow. Disadvantages associated with the shear stress theory are so many and so significant that certain questions regarding the accuracy and validity of the tractive stress based formulae arise. Another thing to remember while using bed load transport formulae is their empirical or