Modes of Sediment Transport

The sediment load of a river is transported in various ways although these distinctions are to some extent arbitrary and not always very practical in the sense that not all of the components can be separated in practice:
1. Dissolved load
2. Wash load
3. Suspended load
4. Bed load

Dissolved Load
Dissolved load is material that has gone into solution and is part of the fluid moving through the channel. Since it is dissolved, it does not depend on forces in the flow to keep it in the water column. The amount of material in solution depends on supply of a solute and the saturation point for the fluid. For example, in limestone areas, calcium carbonate may be at saturation level in river water and the dissolved load may be close to the total sediment load of the river.

Wash load
Wash load is transported through without exchange with the bed. In rivers, material finer than 0.0625 mm (silt and clay) is often approximated as wash load.

Suspended-sediment load
Suspended-sediment load is the clastic (particulate) material that moves through the channel in the water column. These materials, mainly silt and sand, are kept in suspension by the upward flux of turbulence generated at the bed of the channel.
Suspended-sediment concentration in rivers is measured with an instrument like the DH48 suspended-sediment sampler shown in Figure 4.3. The sampler consists of a cast housing with a nozzle at the front that allows water to enter and fill a sample bottle. Air evacuated from the sample bottle is bled off through a small valve on the side of the housing. The sampler can be lowered through the water column on a cable (as shown in Figure 4.3) or it can be attached to a hand-held rod if the stream is small enough to wade. In either case the sampler is lowered from the water-surface to the bed and up to the surface again at a constant rate so that a depth-integrated suspended sediment sample is collected.
Suspended-sediment concentration is conventionally measured as milligrams per litre (mg/L) which is the same number as gm/m³. So, 1000 mg/L = 1000 gm/m³ = 1 kg/m³.

Suspended-sediment concentration and the grain size of suspended sediments typically appear in the vertical water column distributed as depicted in Figure 4.4.

![Figure 4.3: A cable-mounted U/W suspended-sediment sampler attached to the underside of a heavy load “fish” for collecting samples on a large stone from a boat.

![Figure 4.4: Typical vertical profiles of suspended-sediment concentration (A) & grain size in open-channel flow.](image)

**Relation of sediment concentration to sediment load/discharge**

The basic equation of suspended-sediment discharge is

\[ Q_s = C_o Q \]  

(4.1)

For example, on a River at any section the average annual discharge is 3500 m³/s and the average annual suspended-sediment concentration is 186 mg/L (=186 gm/m³ = 0.186 kg/m³).

To calculate the sediment discharge, we have:

\[ Q_s = (0.186)(3500) = 650 \text{ kg/s} \]

To report the sediment discharge in more practical units of kg/year or tonnes/year we have to complete the conversion and calculation as follows:

\[ Q_s = 650 \text{ kg/s} \]

\[ = (650)(60) \text{ kg/minute} \]

\[ = (650)(60)(60) \text{ kg/hr} \]

\[ = (650)(60)(60)(24) \text{ kg/day} \]

\[ = (650)(60)(60)(24)(365) = 2.0 \times 10^{10} \text{ kg/year} = 2.0 \times 10^7 \text{ metric tonnes/year} \]

That is, the sediment discharge is about 20 million metric tonnes/year.

**Bed Load (Traction Load)**

Bed load is the clastic (particulate) material that moves through the channel **fully supported by the channel bed** itself. These materials, mainly sand and gravel, are kept in motion (rolling and sliding) by the shear stress acting at the boundary. A distinction is often made between the **bed-material load** and the **bed load**.

**Bed-material load** is that part of the sediment load found in appreciable quantities in the bed (generally > 0.062 mm in diameter) and is collected in a bed-load sampler. That is, the bed...
material is the source of this load component and it includes particles that slide and roll along the bed (in bed-load transport) but also those near the bed transported in saltation or suspension. **Bed load,** strictly defined, is just that component of the moving sediment that is supported by the bed (and not by the flow). That is, the term “bed load” refers to a mode of transport and not to a source.

Bed load is extremely difficult to measure directly because the measuring instrument (bed-load sampler) invariably interferes with the flow. A commonly used type of bed-load sampler is shown in Figure 4.12.

![Bed-load sampler](image)

Methods other than direct measurement by bed-load sampler include:

i. Bed-load pits or traps (used to calibrate bed-load equations)

ii. Morphological methods
   a. Bedform surveys
   b. Channel surveys
   c. Sedimentation-zone surveys (delta progradation)

**Bedform surveys**

Where bed-material is moving as bedforms such as dunes, *bedform surveys* can be used to track the downstream movement of sediment (Figure 4.14). This technique relies on high-resolution sonar imaging of the river bed to construct profiles that can be differenced to determine the
volumetric bed-load sediment transport rate. Individual dunes can be tracked in this way or even entire dune fields.

**Channel surveys**

*Channel surveys* can be used to produce sequential morphologic maps of a reach of river that can be differenced (using GIS) to yield amounts of erosion and deposition over time. The principle here is the same as that for bedform surveys but in this case involves the entire three-dimensional channel morphology (Figure 4.15).

![Figure 4.14: Bedform surveys track the downstream translation of features such as prograding dunes on the bed of a river as a basis for determining volumetric bed-load transport rates.](image1)

![Figure 4.15: Channel surveys showing channel alignment at two points in time (2003 & 2004). Morphologic differencing reveals zones of erosion and deposition that can be used to construct a sediment budget for the channel reach.](image2)

**Exner equation for the conservation of bed sediment**

\[
q_s = \text{volume suspended load transport rate per unit width} \ [L^2 T^{-1}]
\]

\[
q = \text{volume bedload transport rate per unit width} \ [L^2 T^{-1}]
\]

\[
\rho_s = \text{sediment density} \ [ML^{-3}]
\]

\[
\eta = \text{bed elevation} \ [L]
\]

\[
\lambda_p = \text{porosity of sediment in bed deposit} \ [1]
\]

(Volume fraction of bed sample that is holes rather than sediment: 0.25 ~ 0.55 for noncohesive material, larger for cohesive material)

\[
g = \text{acceleration of gravity} \ [L/T^2]
\]

\[
t = \text{time} \ [T]
\]

The mass sediment transport rate per unit width is then \(\rho_s q_s\), where \(\rho_s\) is the material density of sediment. Mass conservation within the control volume with a unit width requires that:
\[ \partial / \partial t \text{ (sediment mass in bed)} = \text{mass sediment inflow rate} - \text{mass sediment outflow rate} \]

\[
\frac {\partial} {\partial t} \left[ \rho_s (1 - \lambda_p) \eta \right] \Delta x \cdot 1 = \rho_s \left[ q_{s x} |_{x} - q_{s x} |_{x + \Delta x} \right] \cdot 1
\]

1-D: \[
(1 - \lambda_p) \frac {\partial \eta} {\partial t} = - \frac {\partial q_{s x}} {\partial x}
\]

2-D: \[
(1 - \lambda_p) \frac {\partial \eta} {\partial t} = - \frac {\partial q_{s x}} {\partial x} - \frac {\partial q_{s y}} {\partial y} + D_s - \xi_s
\]

**Exner equation for the conservation of bed sediment for turbidity current**

E\(_s\) = volume rate per unit time per unit bed area that sediment is entrained from the bed into suspension [LT\(^{-1}\)].

D\(_s\) = volume rate per unit time per unit bed area that sediment is deposited from the water column onto the bed [LT\(^{-1}\)].

Time rate of change of sediment mass in control volume = net inflow rate of bedload + deposition rate from suspension – erosion rate into suspension

\[
\frac {\partial} {\partial t} \left[ \rho_s (1 - \lambda_p) \eta \right] \Delta x \cdot 1 = \rho_s \left[ q_{s x} |_{x} - q_{s x} |_{x + \Delta x} \right] \cdot 1 + \rho_s (D_s - \xi_s) \Delta x \cdot 1
\]

1-D: \[
(1 - \lambda_p) \frac {\partial \eta} {\partial t} = - \frac {\partial q_{s x}} {\partial x} + D_s - \xi_s
\]

2-D: \[
(1 - \lambda_p) \frac {\partial \eta} {\partial t} = - \frac {\partial q_{s x}} {\partial x} - \frac {\partial q_{s y}} {\partial y} + D_s - \xi_s
\]