Dynamic Adjustment of River System – Lane's Relationship

The morphology of alluvial river channels is the product of certain governing conditions, amongst which the most important are the quantities of water and sediments introduced into the channel, the calibre of the sediments, and the physiography of the landscape through which the river runs (generally represented by slope).

These conditions were related many years ago by Emory Lane (1955), who presented the qualitative relation:

$$Q_s d \propto QS$$

Where

Q_S is Sediment discharge

Q is water discharge

d is sediment particle diameter

S is the slope of the channel

Rearrangement of the Lane's equation yields the expression of Q_s:

$Q_S \propto Q_W S/d$ ..... (1)

Equation 1 states that sediment transport is directly related to the stream power (represented by QS or Ω) and inversely related to the calibre (largest axis) of the sediment.

This statement usefully emphasizes that the capacity of a stream to transport a sediment load and the competence of the stream to move particular sizes are distinct conditions.

The latter may strongly influence the former, however, depending upon what material is available to the stream.

The interplay of these factors produces distinctive channel morphologies by transporting and sorting (grain size distribution/uniformity) sedimentary material in varying ways.

Rearrangement of the Lane's equation also leads to an expression of sediment load (C_s):

$$C_S = Q_S / Q_W \quad \ldots\ldots\ldots\ldots\ldots \quad (2)$$

Equation 2 states that Lane's relation could be interpreted as sediment load (C_s) being directly related to S and inversely related to d:

$$\text{Since} \quad Q_s d \propto Q_w S \qquad\qquad C_s = f\,(S/d)$$

According to Lane, an increase/decrease in any of these variables will trigger a corresponding change [increase or decrease] in one [or more] of the others, until [a new] equilibrium is established. Lane's principle is applicable wherever any of the four aforementioned variables is subject to change. Thus, morphological adjustments in a river are the net result of changes in water and/or sediment discharge.

One key limitation of Lane's balance is that it is not quantitative. Lane's balance cannot be used to relate the magnitude of inputs to a quantitative estimate of change (output). Additionally, Lane's balance does not have a temporal component and cannot be used to assess the timeframe over which changes to channel equilibrium will occur. Finally, Lane's balance does not address changes in planform or cross section geometry (hydraulic geometry), as the channel can adjust while maintaining its cross-sectional area. But, in spite of these limitations Lane's relation is widely used to understand the morphological adjustments as a result of changes in water and/or sediment discharge.

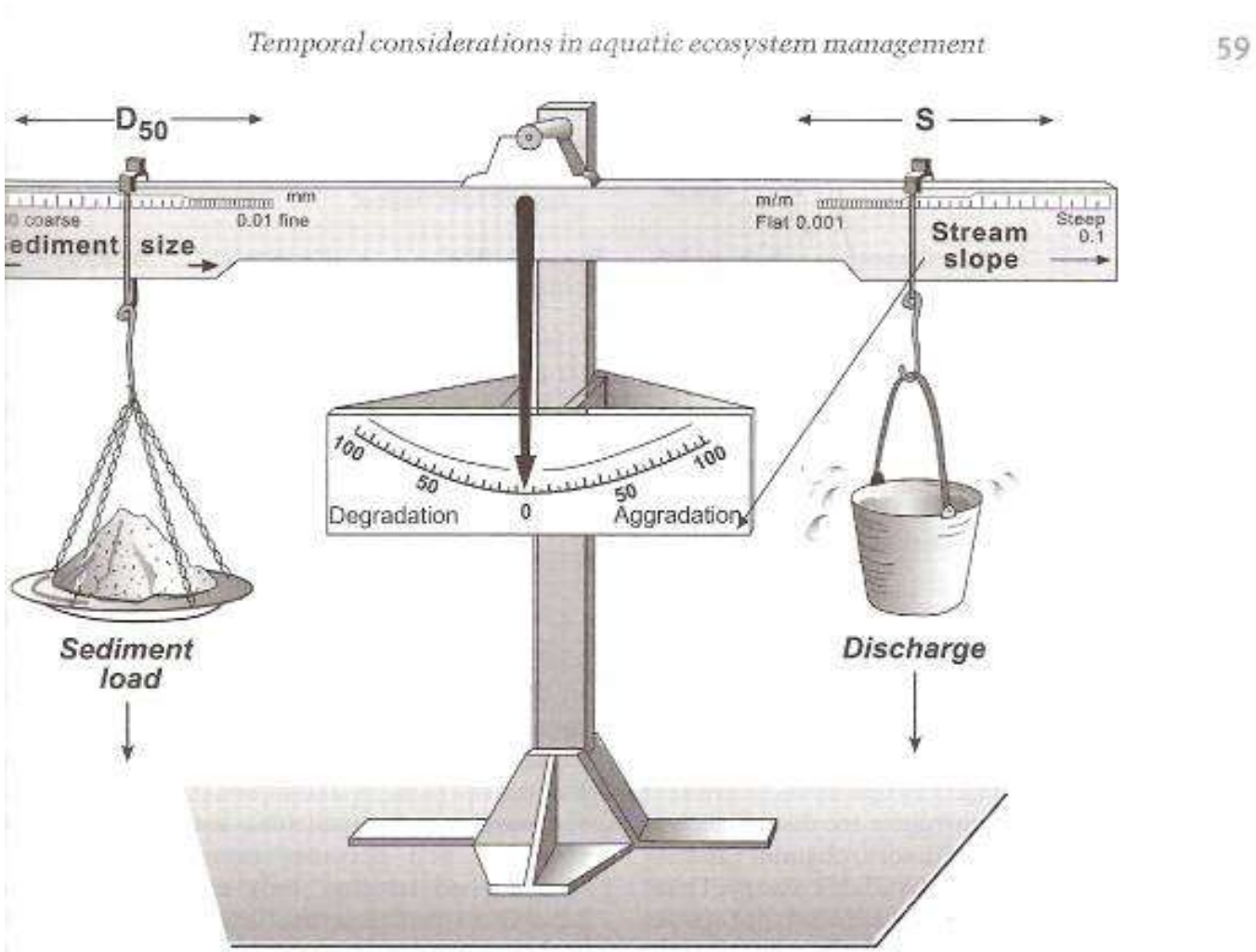
Lane Diagram

Channel equilibrium involves the interplay of four basic factors:

- Sediment discharge ($\mathbf{Q_s}$)
- Sediment particle size ($\mathbf{D_{50}}$)
- Streamflow ($\mathbf{Q_w}$)
- Stream slope ($\mathbf{S}$)

Lane (1955) showed this relationship qualitatively as:

$$Q_s \bullet D_{50} \propto Q_w \bullet S$$



gure 3.2 The flow–sediment balance of river courses
ow–sediment interactions determine the aggradational–degradational balance of river courses. If excess flow occurs er steep slopes, the balance is tilted towards degradation. Alternatively, if excess sediment of a sufficiently coarse ture is made available to the river, the balance is tilted towards aggradation. D_{50} refers to the median bed material ain size (in mm), while s refers to slope (m/m). From Chorley et al. (1984) p. 290. Reproduced with permission from homson Publishing Services, 2004.

Lane's Relation: Rivers, Equilibrium, and Time

Qualitative responses from a state of equilibrium to adjusting sediment load and discharge…

ACTIVITY	RESPONSE	SLOPE
Increase in load	Aggradation	increase
Decrease in load	Degradation	decrease
Increase in discharge	Degradation	decrease
Decrease in discharge	Aggradation	increase

Lane's relation: $Q_s d \propto QS$

Quantitative Analysis of Lane's Relation: The Lane relation of fluvial hydraulics is derived from basic principles of sediment transport. It is expressed as follows:

$Q_s\, d_s \propto Q_w\, S_o$ (qualitative)

The derived quantitative equation is: $Q_s\, (d_s/Y)^{1/3} \propto Q_w\, S_o$ (quantitative)

Unlike the original Lane relation, this new derived relation is dimensionless.

From Darcy-Weisbach equation:

Head loss $h_L = f\, L\, v^2 / gR$

where f is the friction factor, v is the velocity and R is the hydraulic radius.

Or $h_L/L = S_0 = f\, v^2 / gR$

The Froude number is $F = v / (gD)^{1/2}$

For a hydraulically wide channel: $D \cong R \cong y$. Therefore: $S_o = f\, F^2$

A general sediment transport function is: $q_s = \rho_w\, k_1\, v^m$

where k_1 is a function sediment properties and m varies between 3 – 7.

The sediment function is: $q_s = \rho_w\, k_1\, v^3$ (with m = 3 for high Q) and $q = Q/w = vy$

Sediment concentration: $C_s = q_s/(\gamma q)$ where $q = (vy)$ and γ is specific weight ($\rho_w\, g$).

Substituting q_s and q, the sediment concentration can be written as:

$C_s = k_1 v^2/(gy) = k_1 F^2 = k_1 (S_o/f)$ ---- ------ ------- (1)

The relationship between f and Manning's n is: $f = gn^2 / R^{1/3}$

Thus, in general: $f = k_2 n^2 / R^{1/3}$ ---- ---- --- -- (2)

where $k_2 = g = 9.81$

The Strickler's relation between Manning's n and mean particle size d_{50} is:

$n = k_3 d_{50}^{1/6}$ or $n^2 = k_3^2 d_s^{1/3}$ ----- ------ ------ (3)

Putting (3) in (2): $f = k_2 k_3^2 (d_s/R)^{1/3}$ ---- ---- ------- (4)

From (1) and (4): $C_s = q_s/(\gamma q) = Q_s/(\gamma Q_w) = k_1 (S_o/ k_2 k_3^2 (d_s/R)^{1/3})$

$Q_s (d_s/R)^{1/3} = [k_1/(k_2 k_3^2)] \gamma Q_w S_o$

For wide rivers, $R \cong y$.

Thus, the Lane's relation of fluvial hydraulics is expressed as follows:

or $Q_s (d_s/y)^{1/3} \propto \gamma Q_w S_o$ or $Q_s (d_s/y)^{1/3} \propto Q_w S_o$ (considering specific weight γ as a constant)

Assume pre- and post-development cases, with subscripts 1 and 2 for pre- and post-development, respectively. Further define: $Q_s (d_s/y)^{1/3} \propto Q_w S_o$

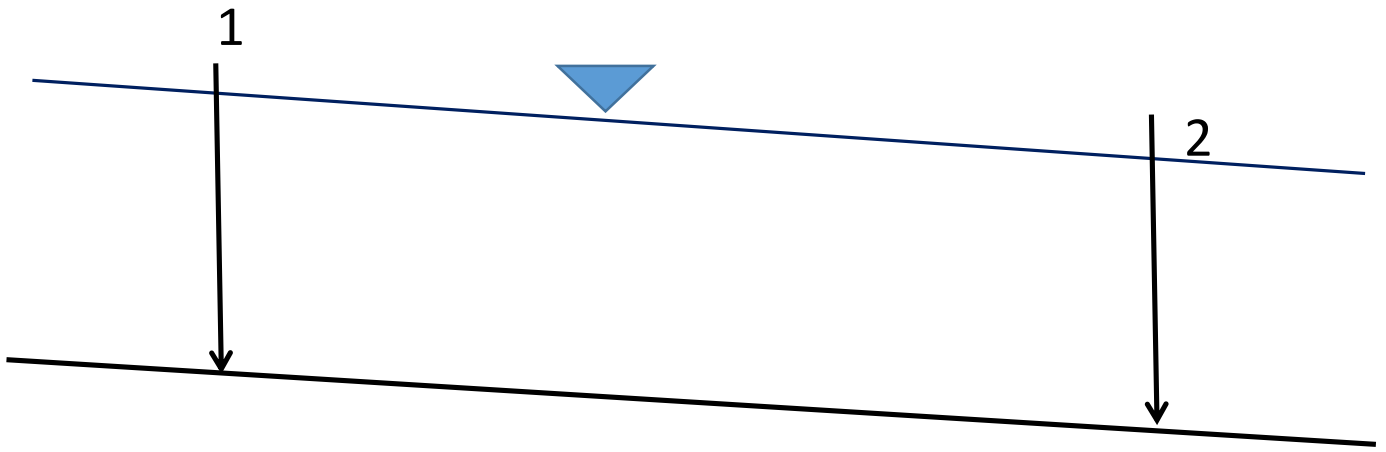
$a = Q_{s2}/Q_{s1}$

$b = d_{s2}/d_{s1}$

$c = Y_2/Y_1$

$d = Q_{w2}/Q_{w1}$

$e = S_{o2}/S_{o1}$



Thus, the modified Lane's relation for pre- and post-development cases becomes:

$[Q_s (d_s/y)^{1/3}]_2 / [Q_s (d_s/y)^{1/3}]_1 = [Q_w S_o]_2 / [Q_w S_o]_1$

Putting values of a, b, c, d and e the modified Lane's relation can be written as:

$$a (b/c)^{1/3} = d e$$

<u>The equation is useful for quantitatively expressing the for pre- and post-developments in a river at equilibrium to a new state of equilibrium.</u>

Example

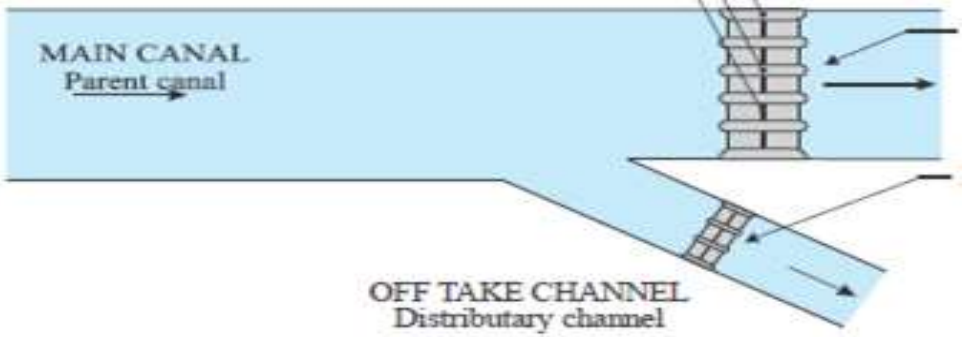
A river reach downstream of a channel diversion intake has d = 0.9 (decrease in Q_w), and a = 0.99 (same Q_s), b = 1 (same d_s), and c = 0.95 (decrease in depth of flow). Calculate and explain the expected changes at the downstream of the diversion.

Solution

As the Q has decreased downstream but the Q_s and d_s have remained the same, the river cannot carry the Q_s. As a result, there would be deposition of sediment (aggradation) and increase of slope (decrease with respect to upstream). The river would then come to equilibrium with the new sediment load and increase in slope. The increase in slope can be calculated from the modified Lane's relation as:

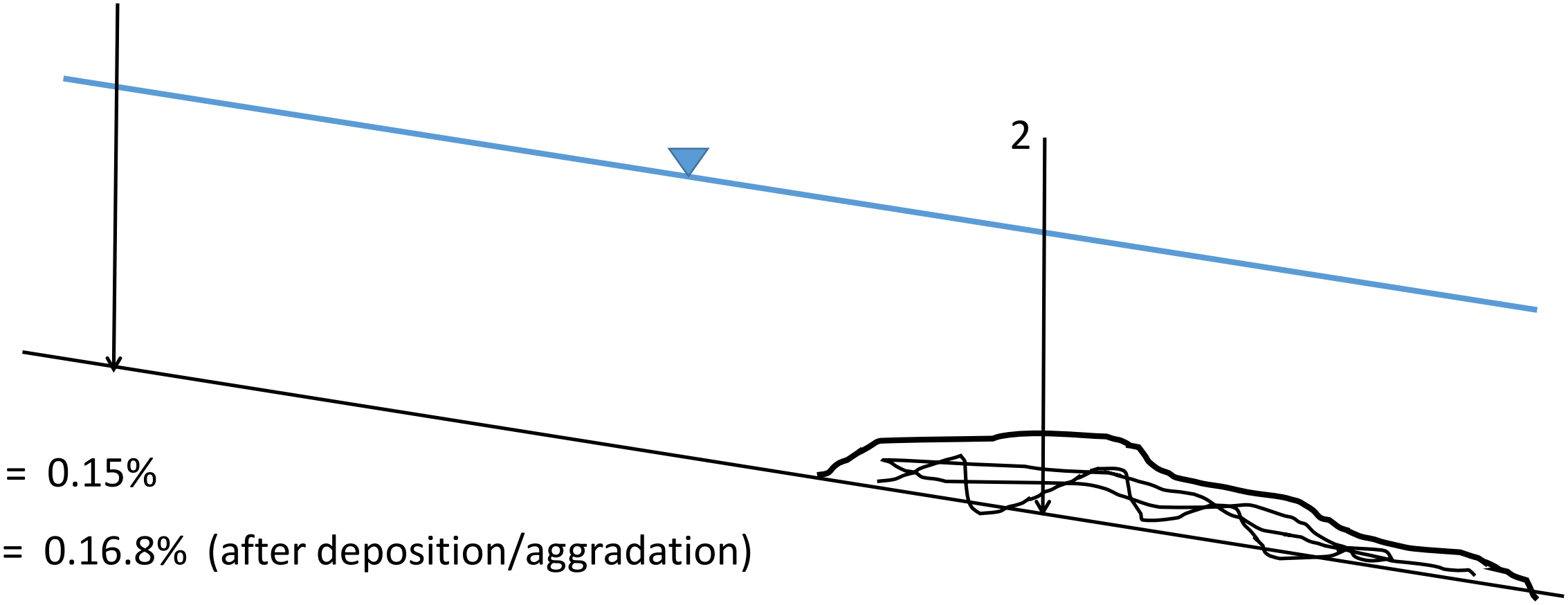
$$a\,(b/c)^{1/3} = d\,e$$

Putting values of a, b, c and d will result in e = 1.12 (aggradation or increase of slope with respect to downstream). As the river would be unable to carry the sediment load the slope will increase by 12% with respect to downstream and the increase would allow the river to carry the new load to a new equilibrium.



$$a\,(b/c)^{1/3} = d\,e$$

$a = 0.99$ $b = 1$ $c = 0.95$ $d = 0.9$



$S_1 = 0.15\%$

$S_2 = 0.16.8\%$ (after deposition/aggradation)

Increase of slope with respect to downstream but decrease with respect to upstream.

Aggradation and Degradation

Increase in Q during the flood increases the stream power (QSe or Ω) and results in erosion of the river bed. The process continues till down stream slope is considerably reduced so that a new equilibrium is achieved between the increased Q and the increased sediment load Q_S (with decrease in energy slope; Se).

Increase in sediment load due to erosion in a catchment, land slide, etc. results in rise in Q_s. Since Q and d_{50} remain the same, it invariably leads to deposition of sediments and increase in energy slope (Se), till the stream power (QSe or Ω) is sufficient to carry the increased Q_s and the relation given by the Lane's equation is satisfied (a new equilibrium is established).

In all diversion structures (for example a dam/barrage), comparatively clear water is withdrawn from upstream (for irrigation, hydropower, water supply etc.) resulting in decrease in Q downstream. As a result stream power (QSe or Ω) gets reduced and hence the sediment carrying capacity (Qs) is reduced, d_{50} remaining the same. Obviously, sediments will be deposited downstream of such diversion points and there will be aggradation and rise in slope till such time as equation is satisfied and a new equilibrium is achieved.

All these morphological changes are examples of aggradation and degradation.

Aggradation and Degradation

In alluvial channels, changes in bed elevations have been observed during flood. There are streams where the bed level has been found to be lowered (degraded) during rising floods (increased stream power, Ω) and aggraded (that is, raised) during the receding flood (decreased).

It is obvious that the variation of the river bed during floods is dependent on the difference between sediment supply into the reach and the sediment transporting capacity of the reach.

If the amount of sediment coming to a reach is less than the amount of sediment going out, the excess sediment is required to meet the capacity of the stream will come from erosion of the bed and there will be lowering of the bed. If the banks are erodible then the sediment will also come from the banks and the channel will widen.

On the other hand, if the amount of sediment coming in is greater than the capacity, then the sediment load must be deposited and the bed level will rise.

The former process is called degradation and the latter is called aggradation.

Aggradation occurs most commonly upstream of a reservoir (dam or barrage) and degradation occurs downstream of a dam or barrage.

Aggradation/degradation in the vicinity of hydraulic structures is principally due to the loss in balance between sediment supply and transport rates. Rivers attain a stable regime over thousands of years through adjustment of its slope and section according to the volume of water and sediment carried over time.

The major cause of change in stream characteristics can be attributed to human activities.

Regardless of degree of channel stability, human activities may produce dramatic changes in the stream characteristics locally and throughout the entire waterway.

Stream improvement works by man made river structures (for use of river water) often result in great departure from the equilibrium than that existing prior to these works.

Dredging or sand mining from the river bed also destabilizes the equilibrium.

The challenge to the engineer is to understand the hydrologic, hydraulic and geomorphologic balances within a given waterway and the catchment and to design project within the frame work of these balances.

Degradation

Channel degradation refers to the general lowering of the bed elevation that is due to erosion. The phenomenon of degradation occurs when the sediment load being transported by a river is less than sediment transporting capacity of the river and the excess sediment needed to satisfy the capacity of the river will be scoured from erodible riverbed.

Degradation results in channel incision and milder slopes, often this phenomenon is observed downstream of a dam constructed on a river.

Dams constructed on rivers alter the equilibrium of flow of water and sediment in alluvial channels. Reservoirs upstream of a dam tend to decrease the magnitude of flood flows by moderating them as a flood flows through, and conversely, they increase low flows by releasing the stored flood water at that time.

The clear water release from the dam also causes the reach below the dam to degrade in the form of a wedge starting below the dam. The magnitude and extent of the degradation below the dams depends on the reservoir size and operation and on the size and availability of the alluvium below the dam.

A phenomenon related to streambed degradation is ***armouring***, where the coarsening of the bed material size results during degradation as finer particles get washed away. When the applied bed shear stress cannot mobilize the coarse bed particles, an ***armour layer*** forms on the bed surface.

The armour layer becomes coarser and thicker as the bed degrades until it is sufficiently thick to prevent any further degradation.

Aggradation

When the sediment transporting capacity of a river at a point becomes less than the sediment load being carried, as a result of reduction the velocity due to an increase in cross section or reduction in slope of the river, the excess sediment get deposited on the river bed. As a result the riverbed rises, the phenomenon being termed as ***aggradation***.

Often this phenomenon is noticed on the upstream of a dam, where the velocity of water in the reservoir is reduced as a result of increase in flow depth.

Aggradation also occurs in a channel when there is a decrease of bed slope for example as the river emerges from the hills and enters relatively flat land.

AGGRADATION AND DEGRADATION

Change in channel bed level (aggradation or degradation) can occur in response to:

- increase or decrease in upstream sediment supply;
- change in hydrologic regime (water diversion or climate change);
- change in river slope (e.g. channel straightening, dredging, etc.);
- increased or decreased sediment supply from tributaries/distributaries;
- sudden inputs of sediment from debris flows or landslides/mudslide;
- faulting due to earthquakes or other tectonic effects such as tilting along the reach, and;
- changing base level at the downstream end of the reach of interest.

Factors that affect long-term bed elevation changes are dams and reservoirs (up- or downstream of the bridge), changes in watershed land use (urbanization, deforestation, etc.), channelization, cutoffs of meander bends (natural or man-made), changes in the downstream channel base level (control), gravel mining from the streambed, diversion of water into or out of the stream, bridge location with respect to stream planform, etc.

RESPONSE OF A RIVER TO SUDDEN VERTICAL FAULTING CAUSED BY AN EARTHQUAKE



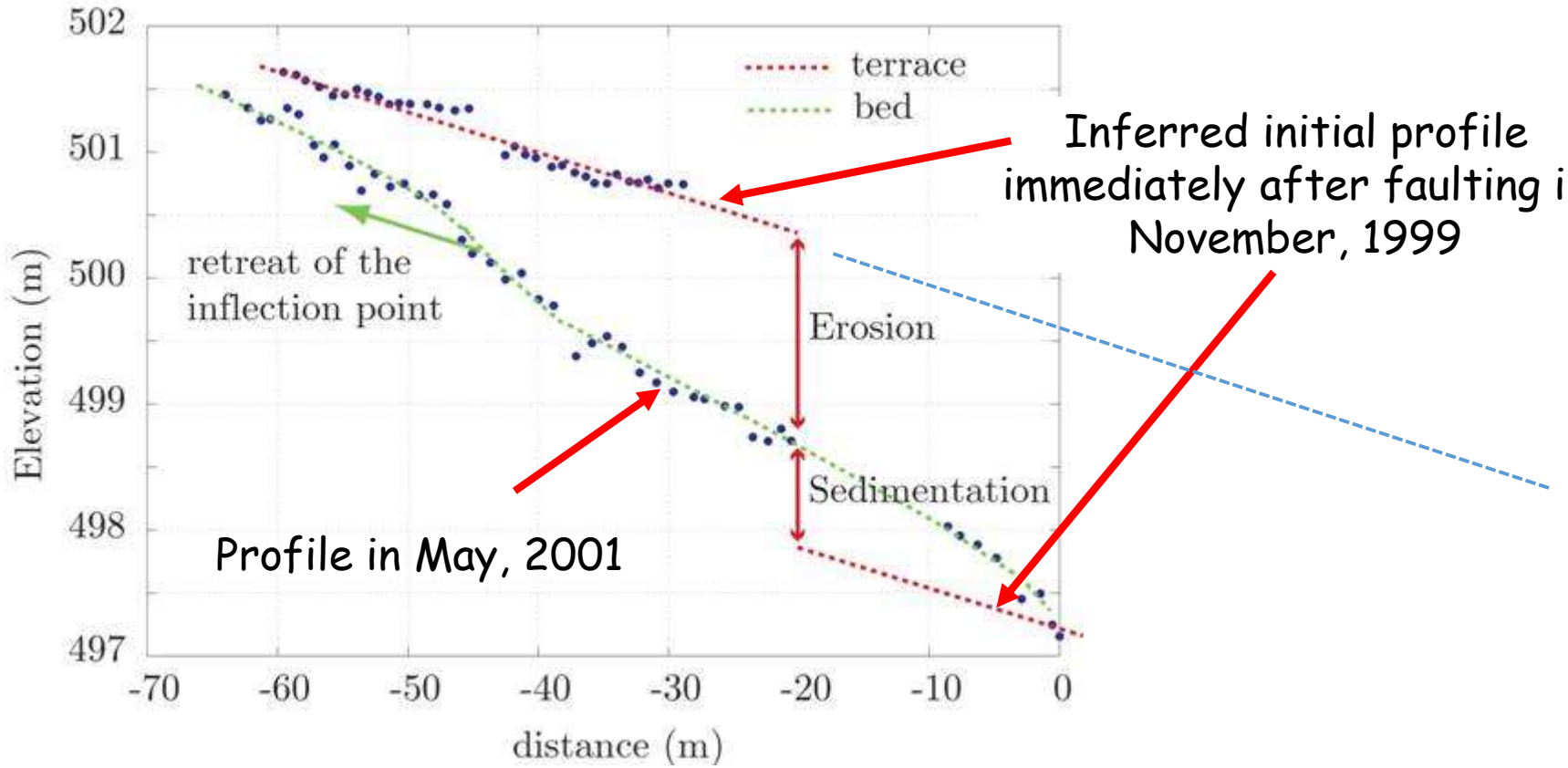
View in November, 1999, shortly after the earthquake caused a sharp 3 m elevation drop at a fault.



View in May, 2000 after aggradation and degradation have smoothed out the elevation drop.

The above images of the Deresuyu River, Turkey, are courtesy of Patrick Lawrence and François Métivier (Lawrence, 2003)

RESPONSE OF A RIVER TO SUDDEN VERTICAL FAULTING CAUSED BY AN EARTHQUAKE



Upstream degradation (bed level lowering) and downstream aggradation (bed level increase) are realized as the river responds to the knickpoint created by the earthquake (Lawrence, 2003)

Differences between aggradation and degradation

Although there are similarities between aggradation and degradation, there are also important differences. These differences include the following.

1. Aggradation refers to an increase in the base level of a river (increase in S), whereas degradation refers to a decrease in the base level (decrease in S).

2. Aggradation is more likely to happen in sediment-loaded rivers, whereas degradation is more likely to happen in sediment-deficit rivers.

3. Aggradation is associated with the deposition of sediment, whereas degradation is associated with the erosion of sediment.

4. Aggradation happens as a river is running out of kinetic energy/stream power, whereas degradation happens as a river picks up more kinetic energy/stream power.

<u>One similarity in both aggradation and degradation is that both processes continue over a long period of time and distance (unquantified) to reach a new equilibrium</u>.

Aggradation vs Degradation

Factor	Aggradation	Degradation
Effect on base level	Increases the base level	Decreases the base level
Sedimentary environment	Happens in sediment-choked rivers	Happens more often in sediment-starved rivers
Associated processes	Associated with deposition	Associated with erosion
River energy	Associated with decreasing kinetic energy	Associated with increasing kinetic energy

Aggradation and Degradation upstream and downstream of dam/barrage

Downstream of the hydraulic structures, there is erosion of stream bed and degradation occurs due to release of comparatively clear water (due to sediment deposition upstream) as well as higher turbulence level. It is also established that clear water causes more erosion compared to silt laden water due to decrease in drag (silts provide damping of turbulence).

It is well known that higher turbulence level causes greater erosion, other parameters remaining the same.

Channel aggradation may also occur in a river reach if due to geological reasons (say, increase of erosion of the catchment) the sediment load being conveyed to the river increases than that can be carried by the river in equilibrium. As a result the river bed rises and forces the channel to carve out its path in a braided fashion.

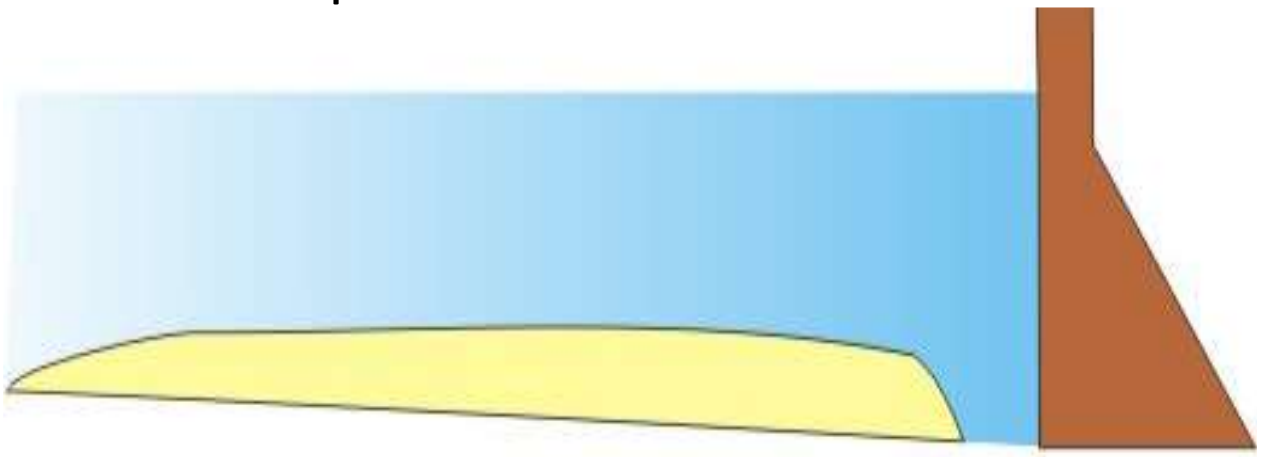
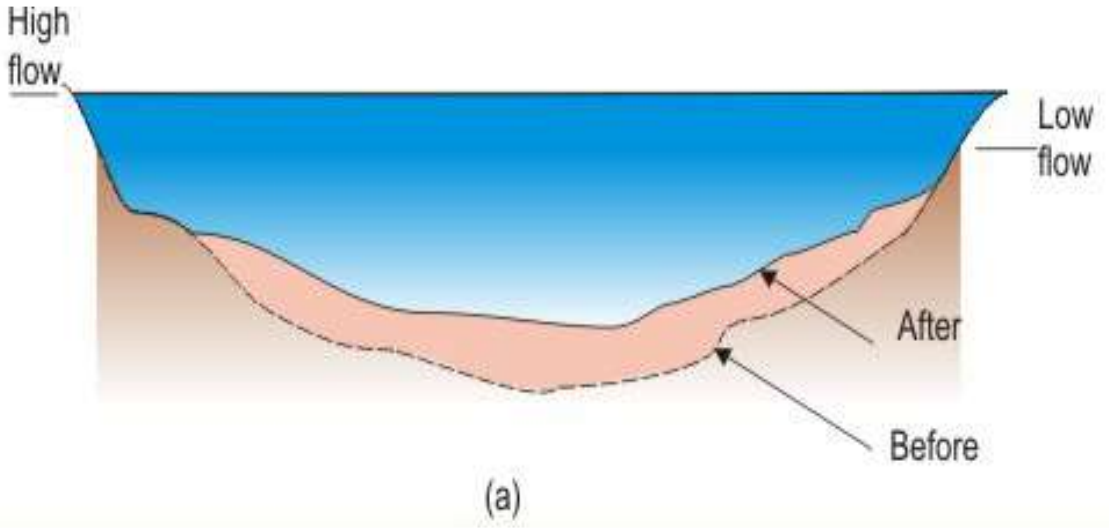
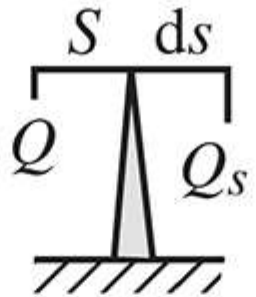


Figure 6. Longitudinal river profile showing sediment deposition on riverbed in the reservoir behind a dam

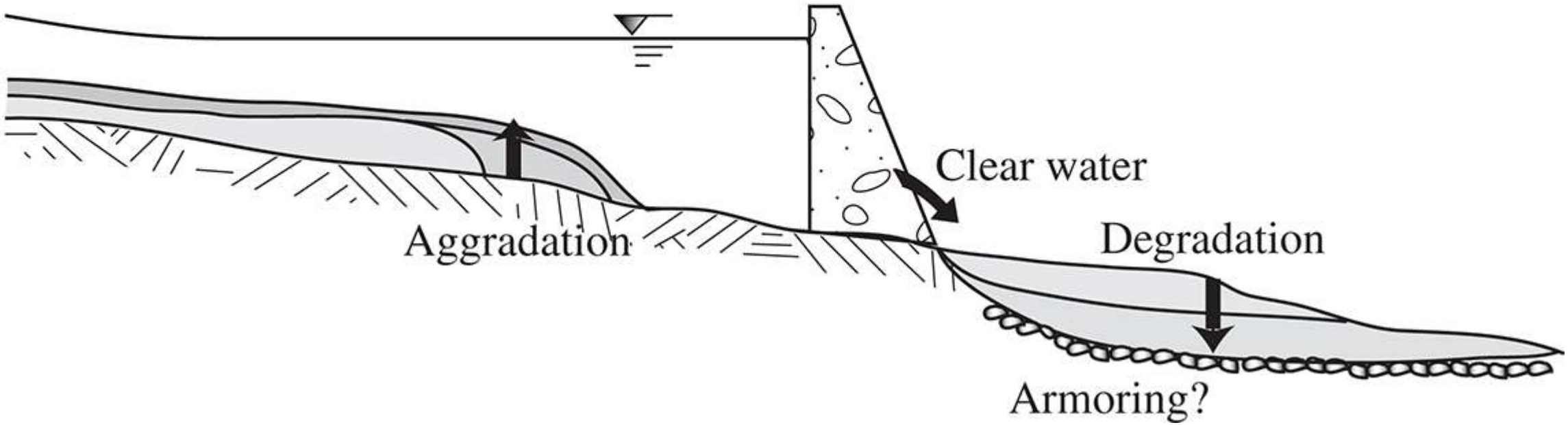


Aggradation after diversion of water

Aggradation and Degradation at a dam site



Cause	S^-, same Q, ds	$Q_s{}^-$, same Q, or Q^-
Effect	Q_s^-	S^- and possibly ds^+



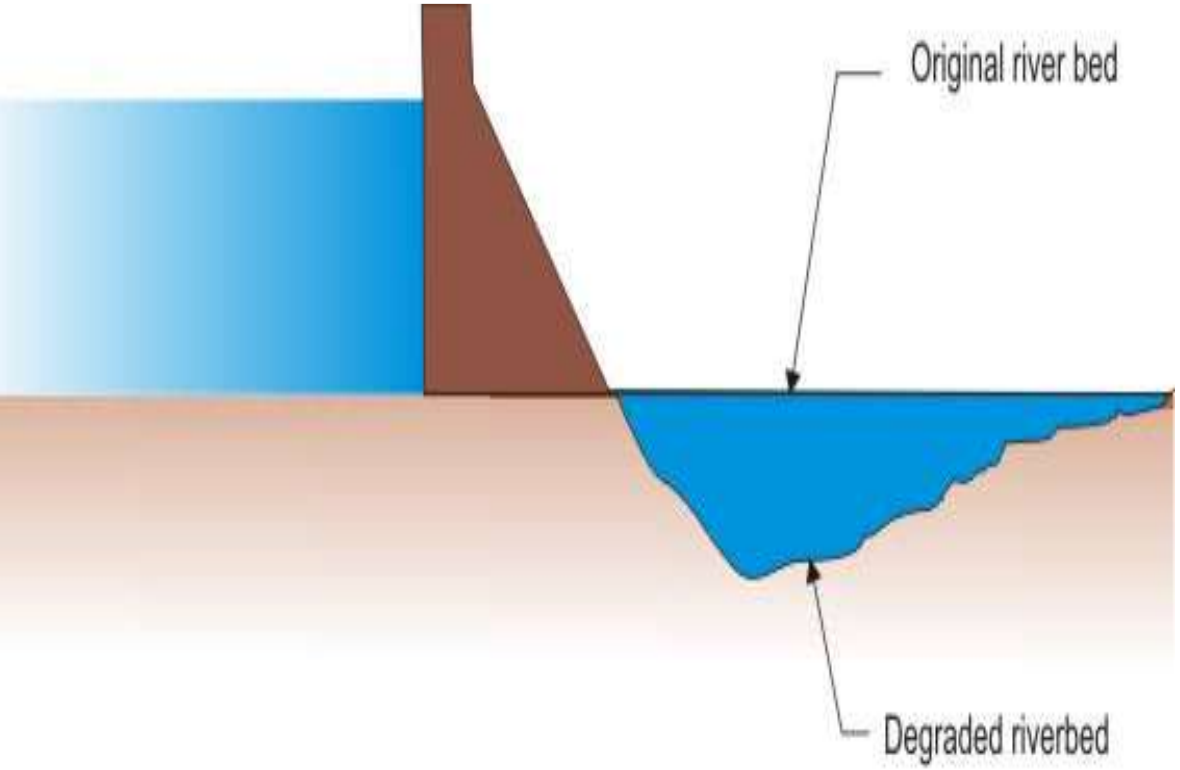


Figure 5. Longitudinal river profile showing river bed degradation along length of river below a dam

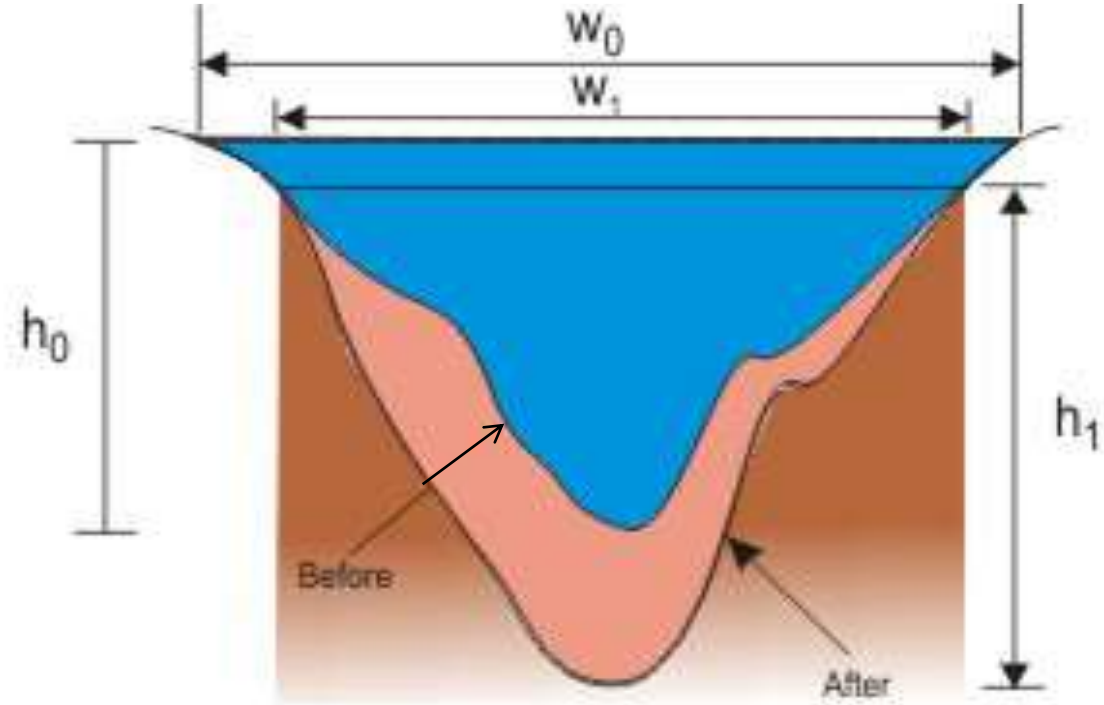


Figure 4. River cross section for bed degradation. Original river width w_o and river depth h_o befor degradation ; After degradation width changed to w_1 and depth to h_1

Assessment of Aggradation and Degradation

B is the width of a channel transporting sediment at a weigh rate of Q_t at a location ***x*** in the channel. The volume rate of sediment transport through the section is Q_t / γ_s where γ_s is the specific weight of the sediment particles, Z is the elevation of the bed above a datum and λ is the porosity of the bed.

$$\frac{\partial Z}{\partial t} + \frac{1}{B\gamma_s(1-\lambda)}\frac{\partial Q_T}{\partial x} = 0$$

This equation is the continuity equation of sediment and states that the bed is lowered if the transport increases along the length and vice versa.

It can be seen that when the flow is steady, the bed level cannot change with time and $\delta Z/\delta t = 0$ and:

$$\frac{1}{B\gamma_s(1-\lambda)}\frac{\partial Q_T}{\partial x} = 0$$

and $Q_T = q_t B$= constant

Hence: $q_{t1}B_1 = q_{t2}B_2 = q_{t3}B_3$ etc.

For channel where B is constant:

$$\delta Z/\delta t + [1/\gamma_s\,(1-\lambda)]\;\delta q_t/\delta x = 0$$

δQ_T changes to δq_t (without B in the equation) and the equation can be used to predict aggradation and degradation.

Case Study

Hossain, T. (1997). Aggradation and Degradation of Khowai River, M.Sc Thesis, BUET
http://lib.buet.ac.bd:8080/xmlui/handle/123456789/371?show=full

Top Width-Elevation Relationship

Top width-elevation relationship for the same cross sections were developed and plotted. This gives a picture of the change in top width between 1988 and 1994 of a specific channel section.

The decrease in top width means the channel has been constricted by deposition of sediment on the edges and the increase in top width results from side wise erosion.

From the above analysis it has become clear that the width of Khowai River has reduced due to siltation on the banks over the period 1988 and 1994. The average reduction in width for this 23.44 km reach has been estimated as 18.2 m (3 m/year).

Thalweg Profile (1965-1988-1994)

In fact thalweg profile does not give a clear idea about the average bed level positions, but it definitely has impacts on the average bed level elevations.

Efforts were made to assess the vertical channel changes (i.e aggradation/ and degradation) by comparing the longitudinal thalweg profile published in 1969 with the 1988 and 1994 BWDB data.

It is observed from the present study that the Khowai River bed is being aggraded at the rate of 67 mm per year up to 6.6 km downstream of Habiganj from Shaistaganj since 1988. The rest of the downstream reach suffered degradation at the rate of 83 mm per year.

However the study revealed that the cross sectional area above bankfull stage has reduced indicating deposition of sediment on the berms and flood plain on both sides of the river.
The overall cross section of the 23.44 km reach below Shaistaganj is being reduced at the rate of 14.84 m^2/year on an average since 1988.

HEC Model Study

Input data: Discharge, water level, suspended load, sediment size, cross section, and future hydrologic data.

The one dimensional morphologic model HEC-6 predicted that there would be continued deposition of sediment indicating continued average aggradation of the bed level by 0.84 m in 1993, 1.47 min 1998 and 2.41 m in the year 2003 along the study reach (87 km) of the river with respect to the year 1988.

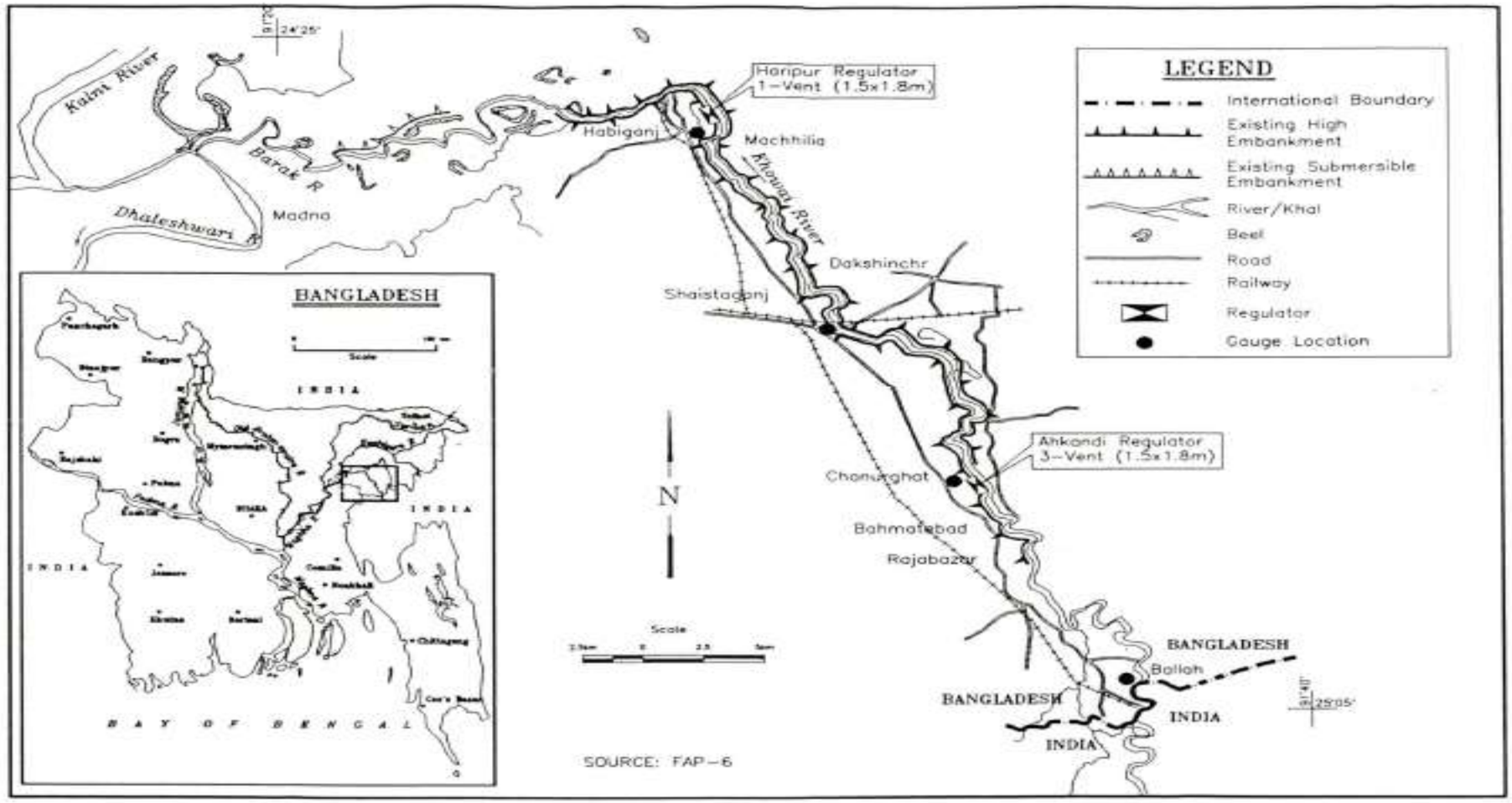


Figure 1.1: Khowai River System

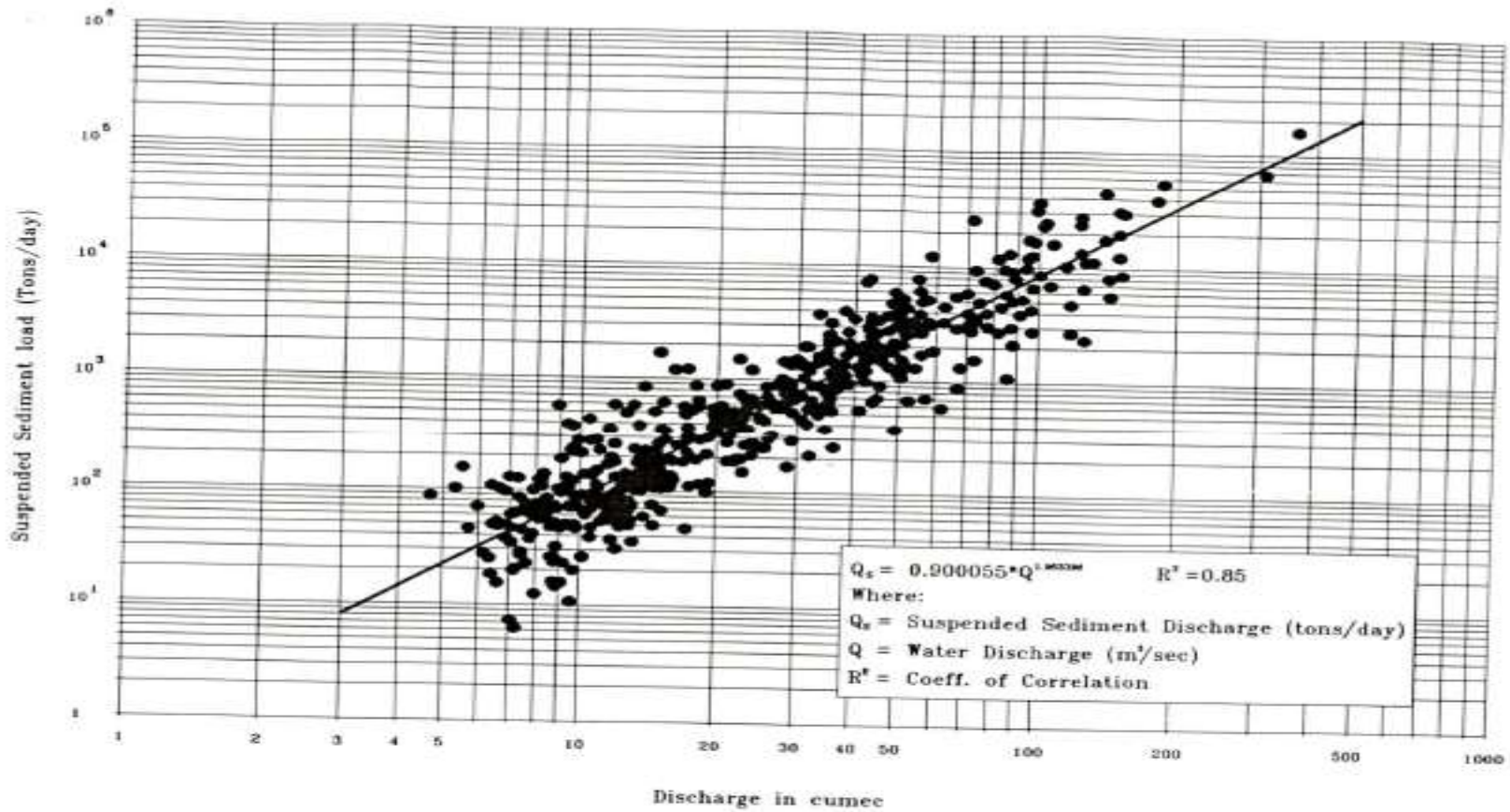


Figure 4.29: Suspended Sediment Rating Curve (1964–93)
Khowai River at Shaistaganj

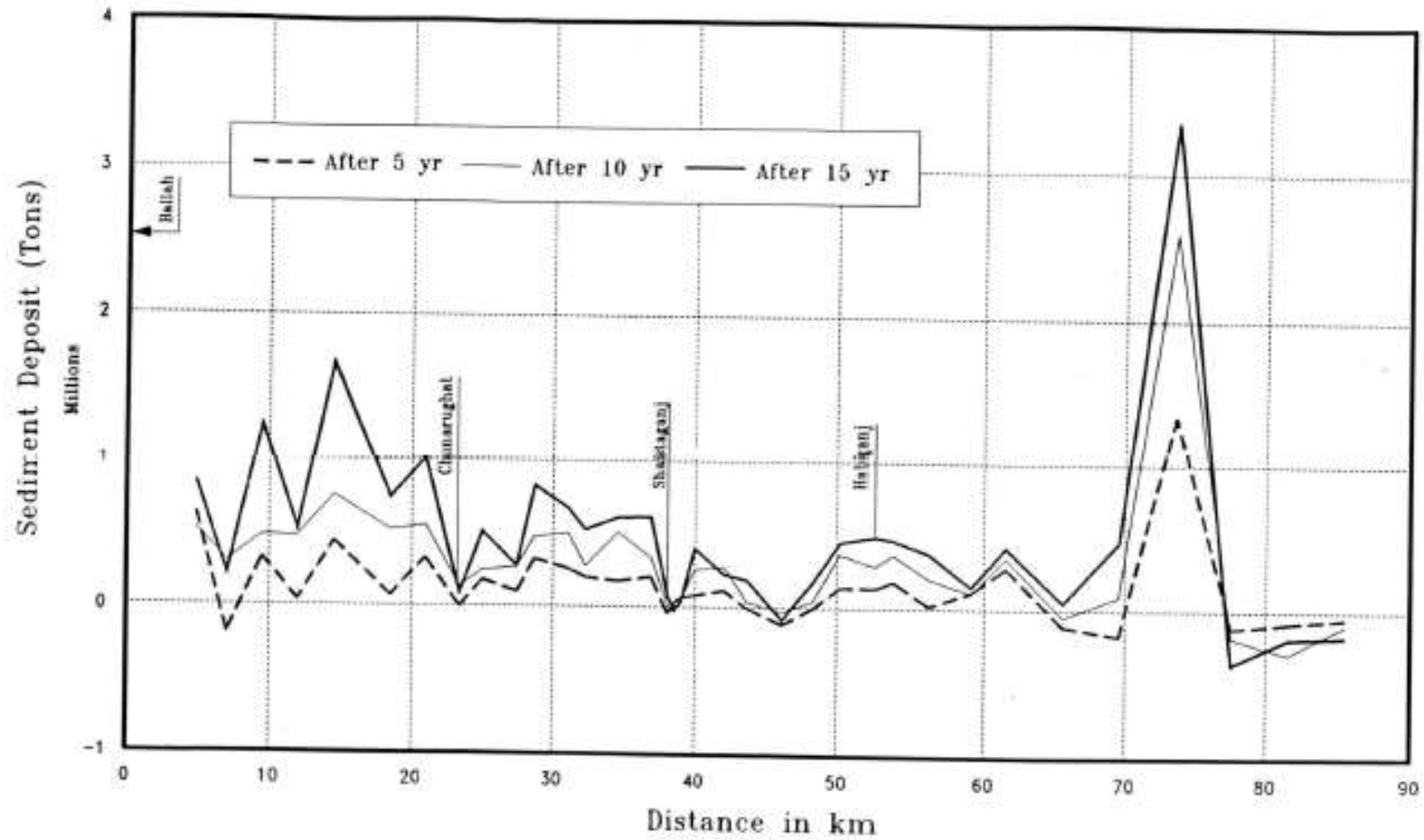


Figure 4.31: Sediment Diposition in Khowai River

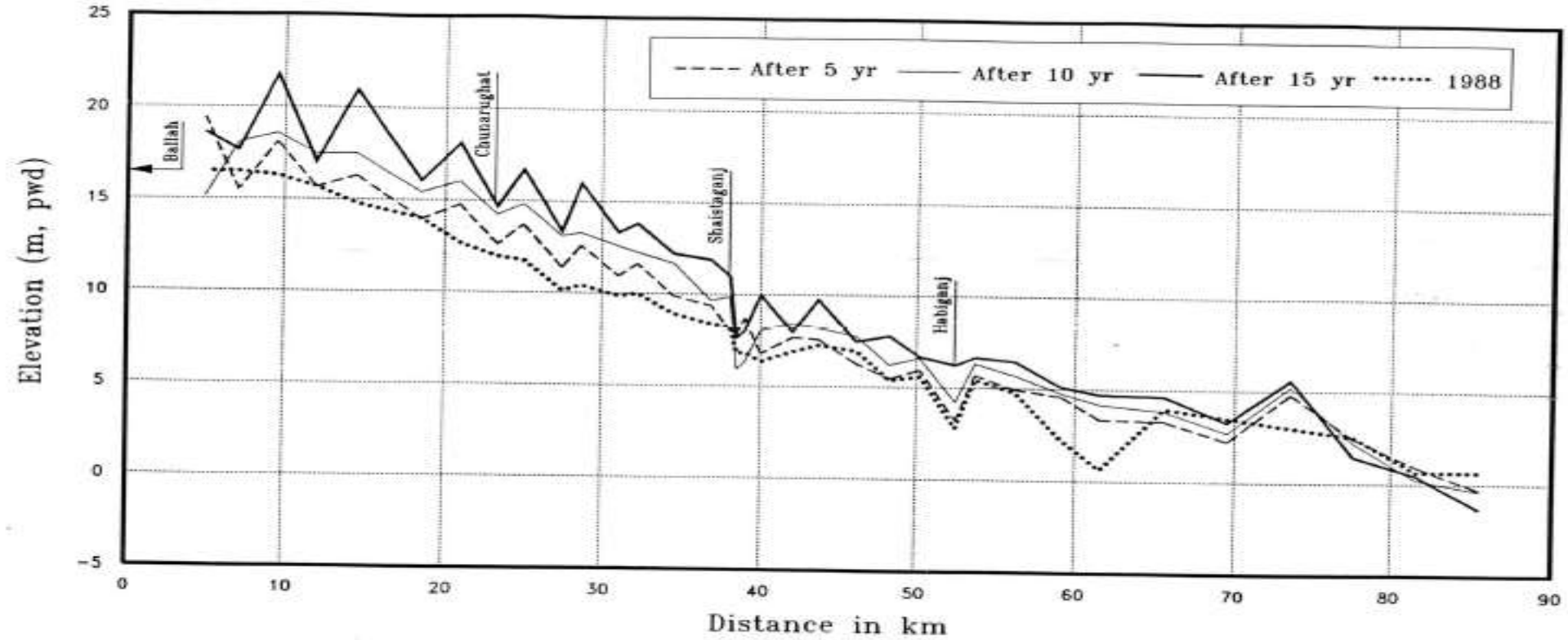


Figure 4.34: Thalweg Profiles of Khowai River