Sediment transport by streams:

- suspended load – carried in suspension
- bedload – dragged or tumbled along stream bottom – typically ~ 10% × suspended load
- dissolved load – solids in solution

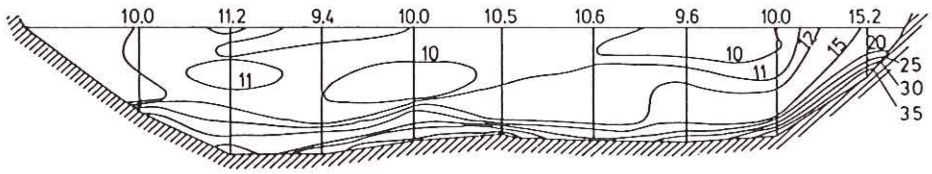


Fig. 4.47. Distribution of suspended load in $g\,m^{-3}$ in Danube at Engelhardtszell on 15. 4. 1957. (From data of Donaukraftwerke Jochenstein AG)

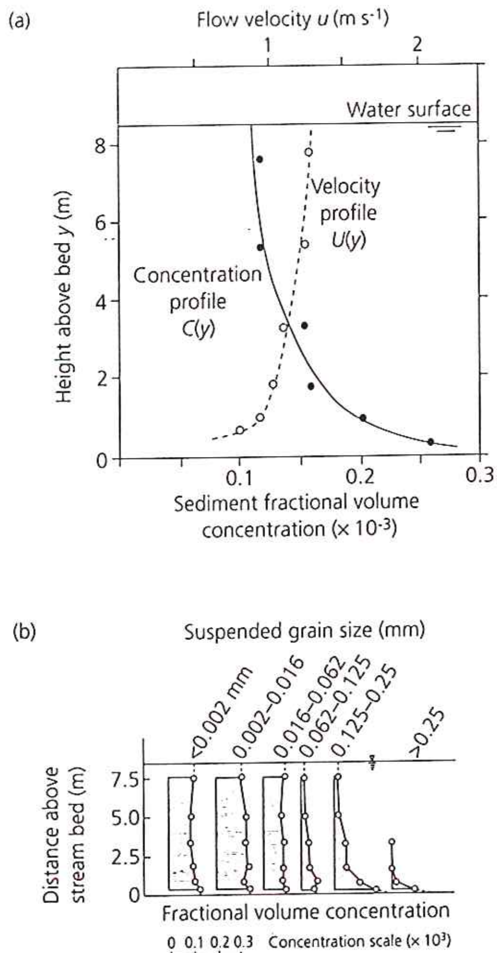


Fig. 5.12 (a) Meaured velocity and suspended sediment concentration profiles in the Mississippi River at St Louis, Missouri, on 24 April 1956. (b) Sediment concentration profiles for a range of grain size intervals. After Colby (1963) [27].

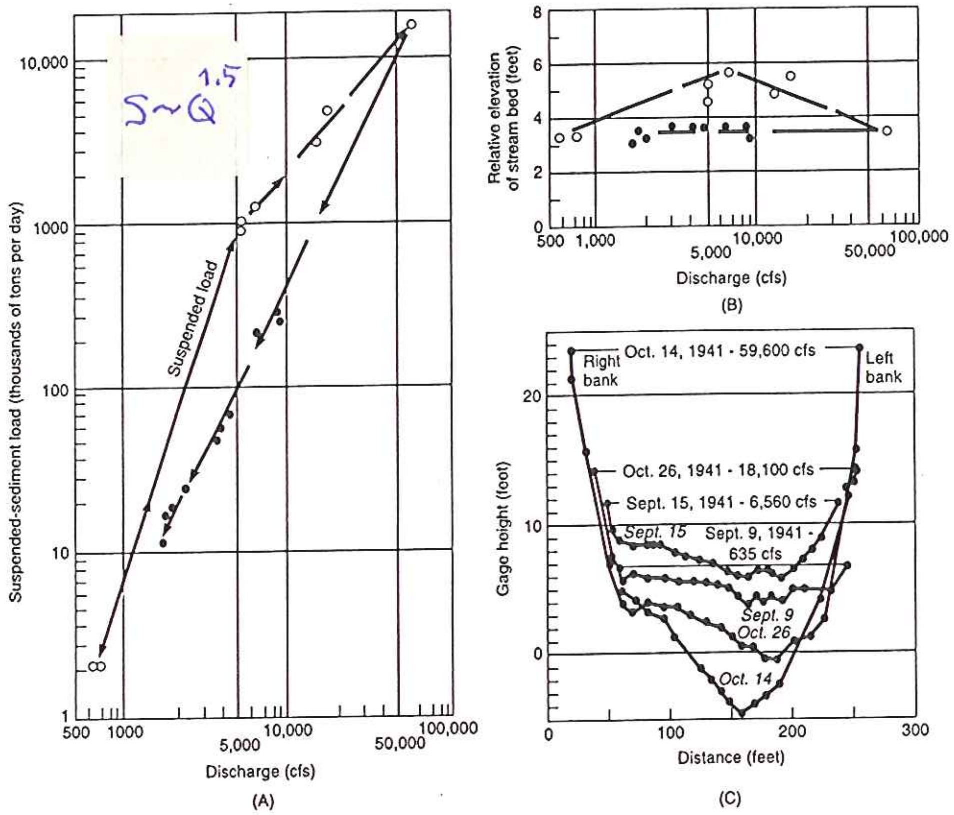
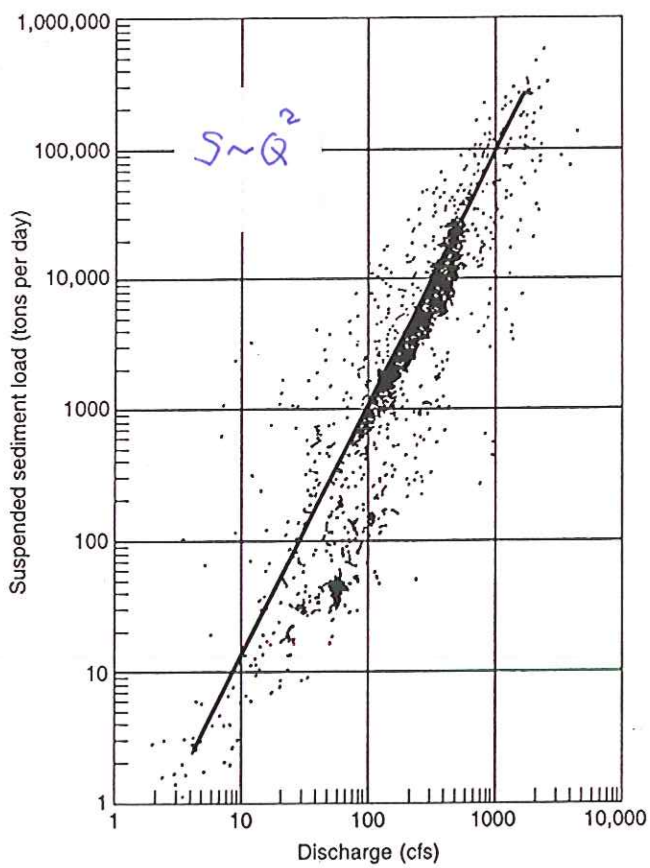


FIGURE 6.14

Changes in (A) suspended load, (B) streambed elevation, and (C) water-surface elevation with discharge during the September–December 1941 flood of the San Juan River near Bluff, Utah.

(Leopold and Maddock 1953)



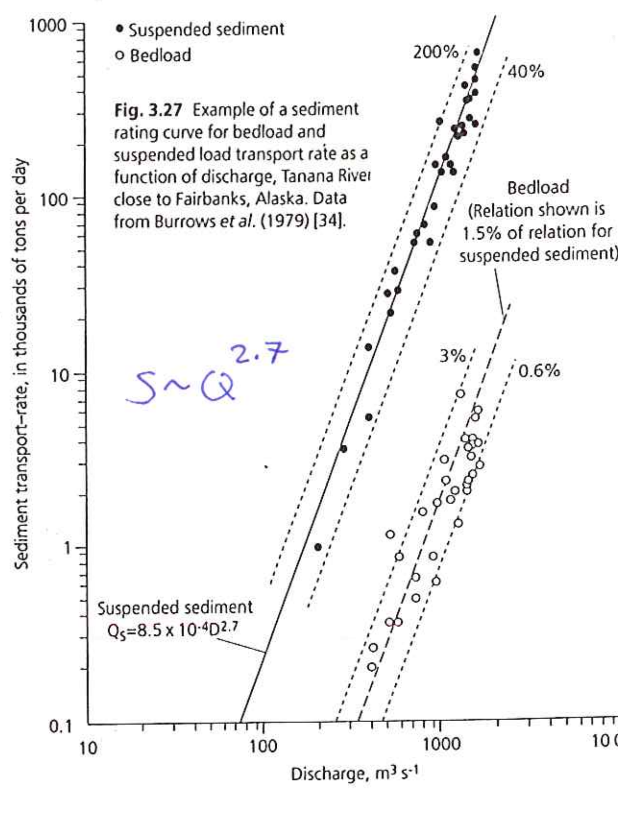
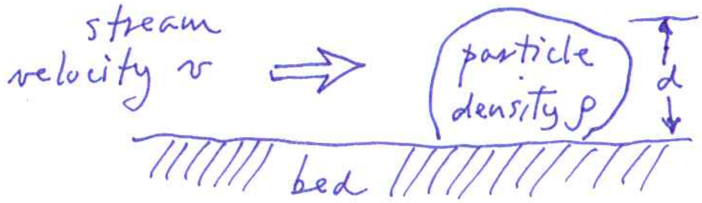


Fig. 3.27 Example of a sediment rating curve for bedload and suspended load transport rate as a function of discharge, Tanana River close to Fairbanks, Alaska. Data from Burrows *et al.* (1979) [34].

Drag force exerted on a single particle resting on streambed:



$$F_{drag} = C_{drag} \cdot \frac{\pi}{4} d^2 \cdot \frac{1}{2} \rho_w v^2$$

cross-sectional area presented to streamflow

density of water

To move the particle along bottom, must exceed the frictional resistance to sliding:

$$F_{resist} = \mu \underbrace{(\rho - \rho_w) \underbrace{\frac{\pi}{6} d^3}_{\text{volume}}}_{\text{buoyant mass}} g$$

coefficient of friction

Equating $F_{drag} = F_{resist}$, we find the critical scouring velocity in turbulent flow:

$$v = \sqrt{\frac{4 g \mu (\rho - \rho_w)}{3 C_{drag} \rho_w} d}$$

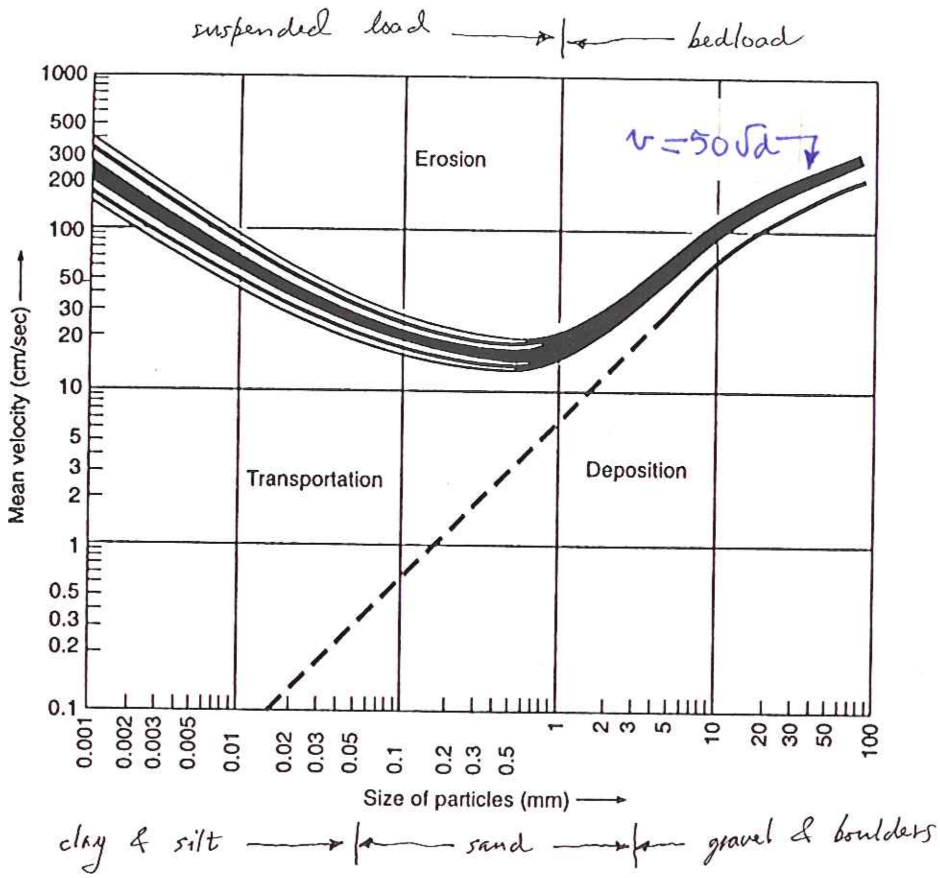
Setting $\mu \approx C_{drag} \approx 1$ and

$\rho = 2700\ kg/m^3$

$\rho_w = 1000\ kg/m^3$

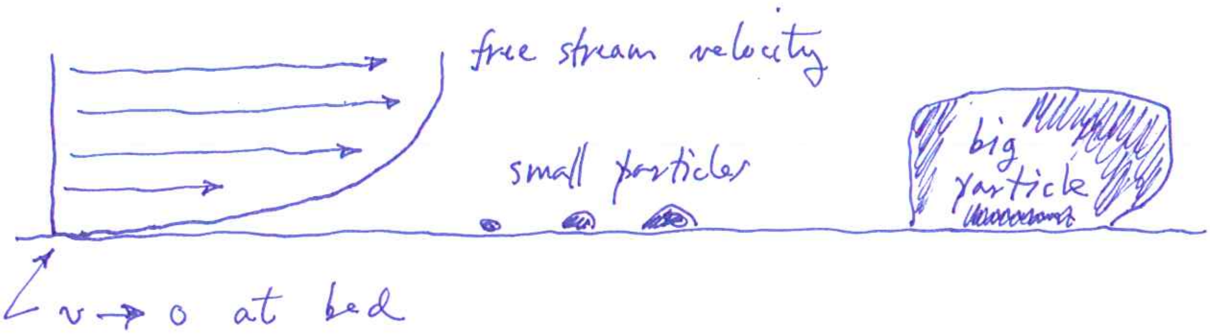
$g = 9.8\ m/s^2$

$$\boxed{v\,(cm/s) \approx 50 \sqrt{d\,(cm)}}$$



The increasing resistance to erosion as d decreases — fine sand, clay & silt — is due to two neglected factors

- increased cohesion
- boundary layer effects



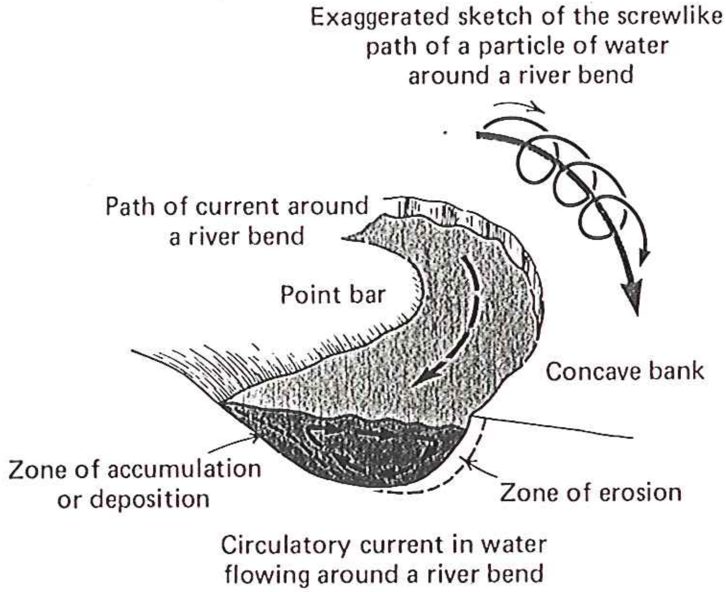


Figure 24
Effect of a curved channel on water flow. (U.S.G.S.)

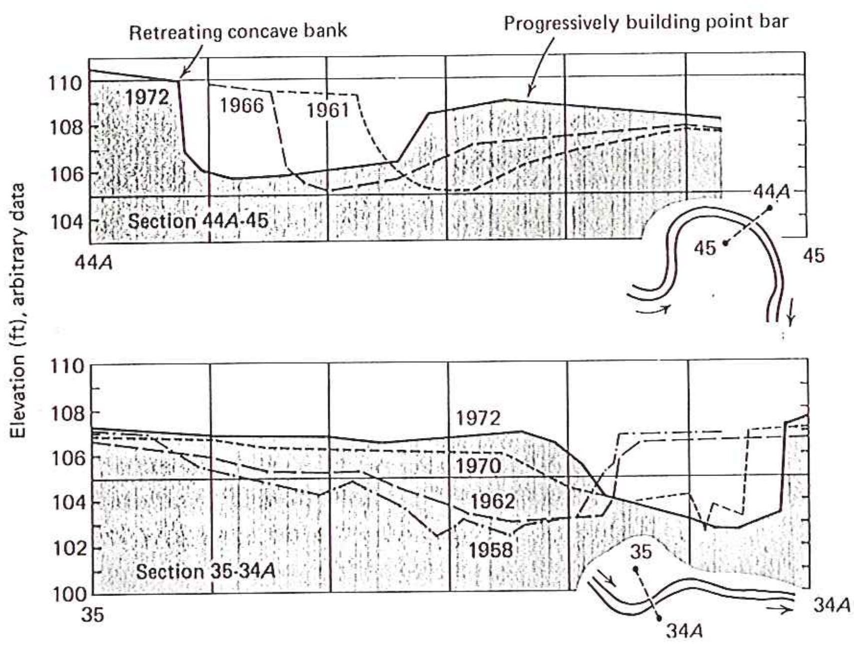
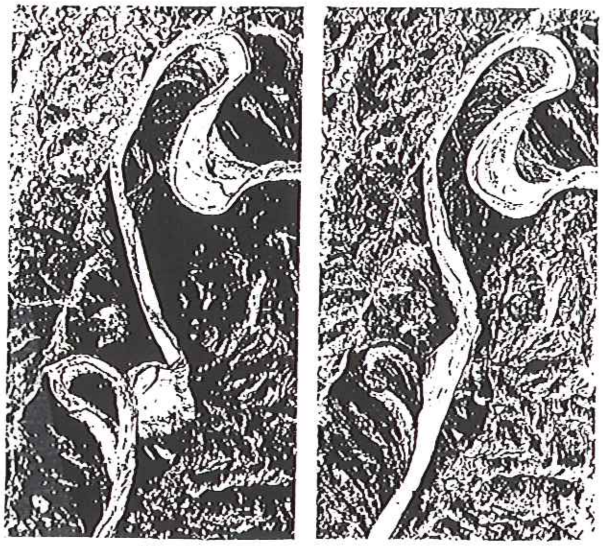


Figure 28
Data obtained from successive resurveys of Watts Branch near Rockville, Maryland, show lateral migration of a river channel by the building of a point bar into the stream and the concurrent erosion of the opposite bank. The continuation of such point bar building results in the development of a flood plain. Diagrams in lower right indicate position of the cross section relative to channel bends. (From Leopold, *Bull. Geol. Soc. America*, June 1973.)



(a) (b)

(c)

Figure 10-4. Flood plain and channel of the Little Missouri River near Watford City, North Dakota. For orientation and scale, see Figure 10-5. (*a*) 1939 vertical aerial photograph; (*b*) 1949 vertical aerial photograph; (*c*) 1958 vertical aerial photograph of the northernmost meander. (Photos: U.S. Dept. Agriculture, from Everitt, 1968.)

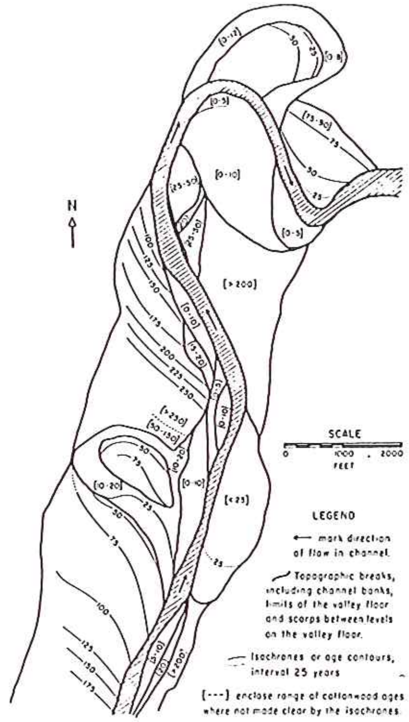


Figure 10-5. Age map of the flood plain of the Little Missouri River near Watford City, North Dakota, based on ages of cottonwood trees. (Everitt, 1968.)

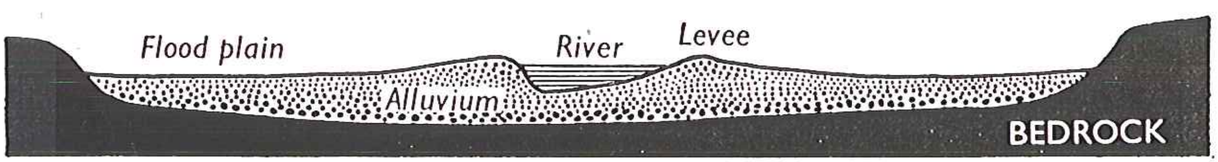


FIG. 389 Schematic section across the flood plain of a stream bordered by natural levees. Vertical scale greatly exaggerated

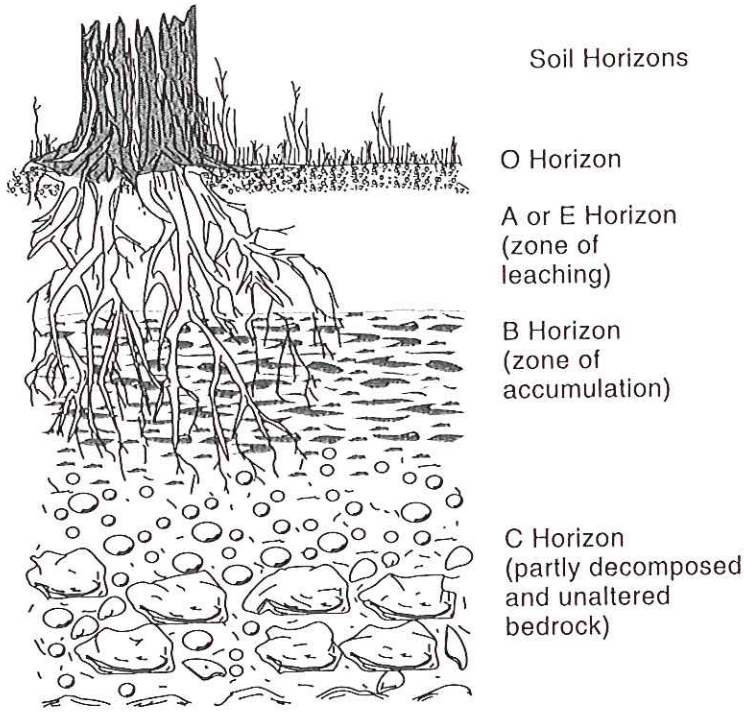


Figure 4.6. Soil horizons formed in a temperate humid climate (James I. Drever, *The Geochemistry of Natural Waters,* 2e, © 1992, p. 145. Reprinted by permission of Prentice Hall, Englewood Cliffs, New Jersey.)

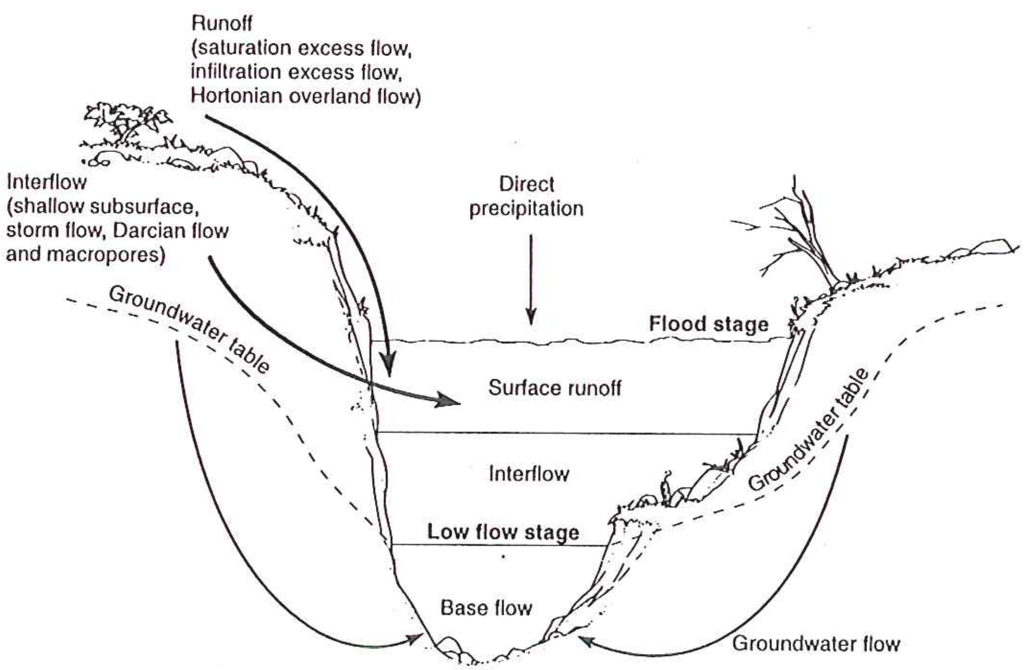


FIGURE 5.7

Schematic of stream channel showing major kinds of water contributions. Arrival of water from any given precipitation event is progressively delayed from runoff to interflow to groundwater flow.

(Based on Kochel 1992)

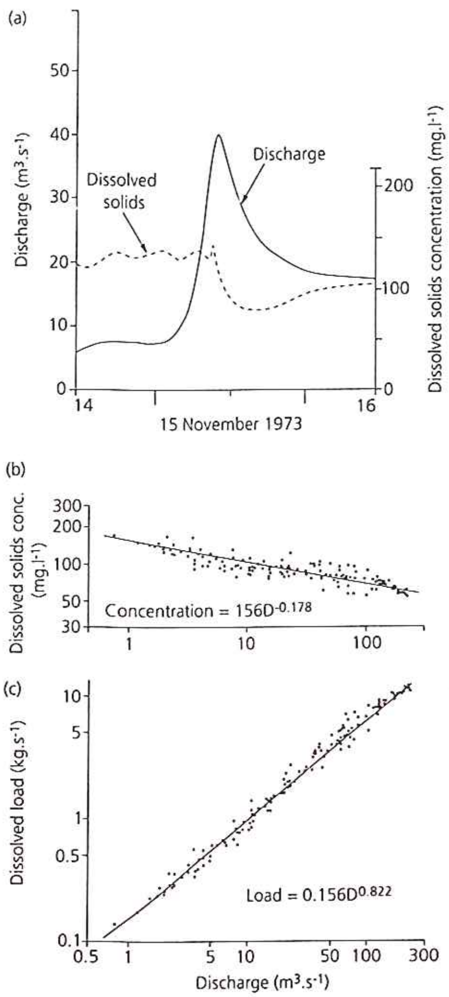


Fig. 3.28 Solute load response to a flood event in a small English river (River Exe at Thorverton). Drop in dissolved solids concentration during peak flood discharges (a) results in the inverse relation between solute concentration and discharge shown in (b), despite the fact that the total dissolved load has a positive relation in the rating curve shown in (c). After Walling (1984) [35].

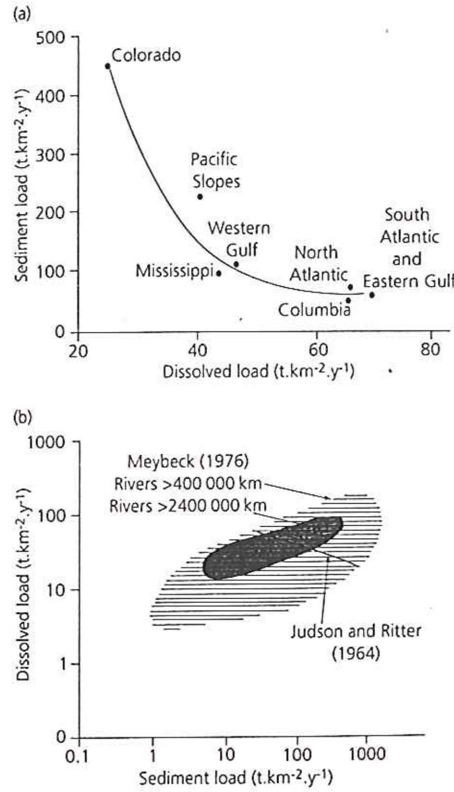


Fig. 3.25 Relationships between the dissolved and suspended sediment components of the total river load in US rivers (a) after Judson & Ritter (1964) [32] and (b) based on world-wide data (after Meybeck (1976) [30]).

Rough rule of thumb:
total load $\approx \frac{2}{3}$ suspended $+ \frac{1}{3}$ dissolved

TABLE 5.11 Sources of Major Elements in World River Water (in Percent of Actual Concentrations)

Element	Atmos. Cyclic Salt	Weathering: Carbonates	Weathering: Silicates	Weathering: Evaporites[a]	Pollution[b]
Ca^{++}	0.1	65	18	8	9
HCO_3^-	<<1	61[c]	37[c]	0	2
Na^+	8	0	22	42	28
Cl^-	13	0	0	57	30
SO_4^{--}	2[d]	0	0	22[d]	54
Mg^{++}	2	36	54	<<1	8
K^+	1	0	87	5	7
H_4SiO_4	<<1	0	99+	0	0

road salt

fertilizer production + coal mining

[a] Also includes NaCl from shales and thermal springs.

[b] Values taken from Meybeck (1979) except sulfate, which is based on calculation given in the text.

[c] For carbonates, 34% from calcite and dolomite and 27% from soil CO_2; for silicates, all 37% from soil CO_2; thus, total HCO_3^- from soil (atmospheric) CO_2 = 64% (See also Table 5.13).

[d] Other sources of river SO_4^{--}; natural biogenic emissions to atmosphere delivered to land in rain, 3%; volcanism, 8%; pyrite weathering, 11%.

TABLE 5.5 Concentrations of Major Elements in Continental Rocks and Soils and in River Dissolved and Particulate Matter

	Continents		Rivers				Element Weight Ratio	
Element	Surficial Rock Concentration (mg/g)	Soil Concentration (mg/g)	Particulate Concentration (mg/g)	Dissolved Concentration (mg/l)	Particulate Load (10^6 tons/yr)	Dissolved Load (10^6 tons/yr)	River Particulate/ Rock	Particulate/ (Particulate + Dissolved)
Al	69.3	71.0	94.0	0.05	1457	2	1.35	0.999
Ca	45.0	35.0	21.5	13.40	333	501	0.48	0.40
Fe	35.9	40.0	48.0	0.04	744	1.5	1.33	0.998
K	24.4	14.0	20.0	1.30	310	49	0.82	0.86
Mg	16.4	5.0	11.8	3.35	183	125	0.72	0.59
Na	14.2	5.0	7.1	5.15	110	193	0.50	0.36
Si	275.0	330.0	285.0	4.85	4418	181	1.04	0.96
P	0.61	0.8	1.15	0.025	18	1.0	1.89	0.96

Note: Elements with no gaseous phase only. Particulate and dissolved loads based, respectively, on the total loads, 15.5×10^9 tons solids/yr and 37,400 km^3 water/yr.
Sources: After Martin and Meybeck 1979; Martin and Whitfield 1981; Meybeck 1979, 1982.

major elements: Ca & Na mostly in dissolved load

Roughly speaking, only about 1/2 of the dissolved load is derived from natural weathering and chemical erosion of continental rocks.
Other 1/2 from various sources:

- ions in rainwater
- solution of atmospheric CO_2 in pore spaces
- pollution

TABLE 5.13 Sources of Rock Weathering-Derived HCO_3^- in World Average River Water

Weathering Source	Percent of Total HCO_3^- from Soil CO_2	Percent of Total HCO_3^- from Carbonate Minerals
Calcite + Dolomite	27	34
Ca-silicates	13	—
Mg-silicates	15	—
Na-silicates	6	—
K-silicates	3	—
Total	64	34

Note: For method of calculation, see text. (An additional 2% of total HCO_3^- is added by pollution; see Table 5.11.)

TABLE 5.1 Major Rivers that Flow to the Sea, Listed in Order of Discharge

River	Location	Annual Discharge: Water (km³/yr)	Annual Discharge: Dissolved Solids (Tg/yr)	Annual Discharge: Suspended Solids (Tg/yr)	Dissolved/ Suspended Ratio	Drainage Area (10^6 km²)
1. Amazon	S. America	6300	275	1200	0.23	6.15
2. Zaire (Congo)	Africa	1250	41	43	0.95	3.82
3. Orinoco	S. America	1100	32	150	0.21	0.99
4. Yangtze (Chiang)	Asia (China)	900	247	478	0.53	1.94
5. Brahmaputra	Asia	603	61	540	0.11	0.58
6. Mississippi	N. America	580	125	210 (400)	0.60	3.27
7. Yenisei	Asia (Russia)	560	68	13	5.2	2.58
8. Lena	Asia (Russia)	525	49	18	2.7	2.49
9. Mekong	Asia (Vietnam)	470	57	160	0.36	0.79
10. Ganges	Asia	450	75	520	0.14	0.975
11. St. Lawrence	N. America	447	45	4	11.3	1.03
12. Parana	S. America	429	16	79	0.20	2.6
13. Irrawaddy	Asia (Burma)	428	92	265	0.35	0.43
15. Mackenzie	N. America	306	64	42	1.5	1.81
17. Columbia	N. America	251	35	10 (15)	3.5	0.67
20. Indus	Asia (India)	238	79	59 (250)	1.3	0.975
Red (Hungho)	Asia (Vietnam)	123	?	130	?	0.12
Huanghe (Yellow)	Asia (China)	59	22	1100	0.02	0.77

Note: Tributaries are excluded. Tg = 10^6 tons = 10^{12} g.

Sources: Water and suspended solids from Milliman and Meade (1983) and Milliman and Syvitski (1992). Dissolved solids calculated from Table 5.7 and Pinet and Souriau (1988) (for the Irrawaddy). Suspended load values in parentheses indicate pre-dam values.

total load = $\frac{2}{3}$ suspended + $\frac{1}{3}$ dissolved

Erosion rates of major river basins of world

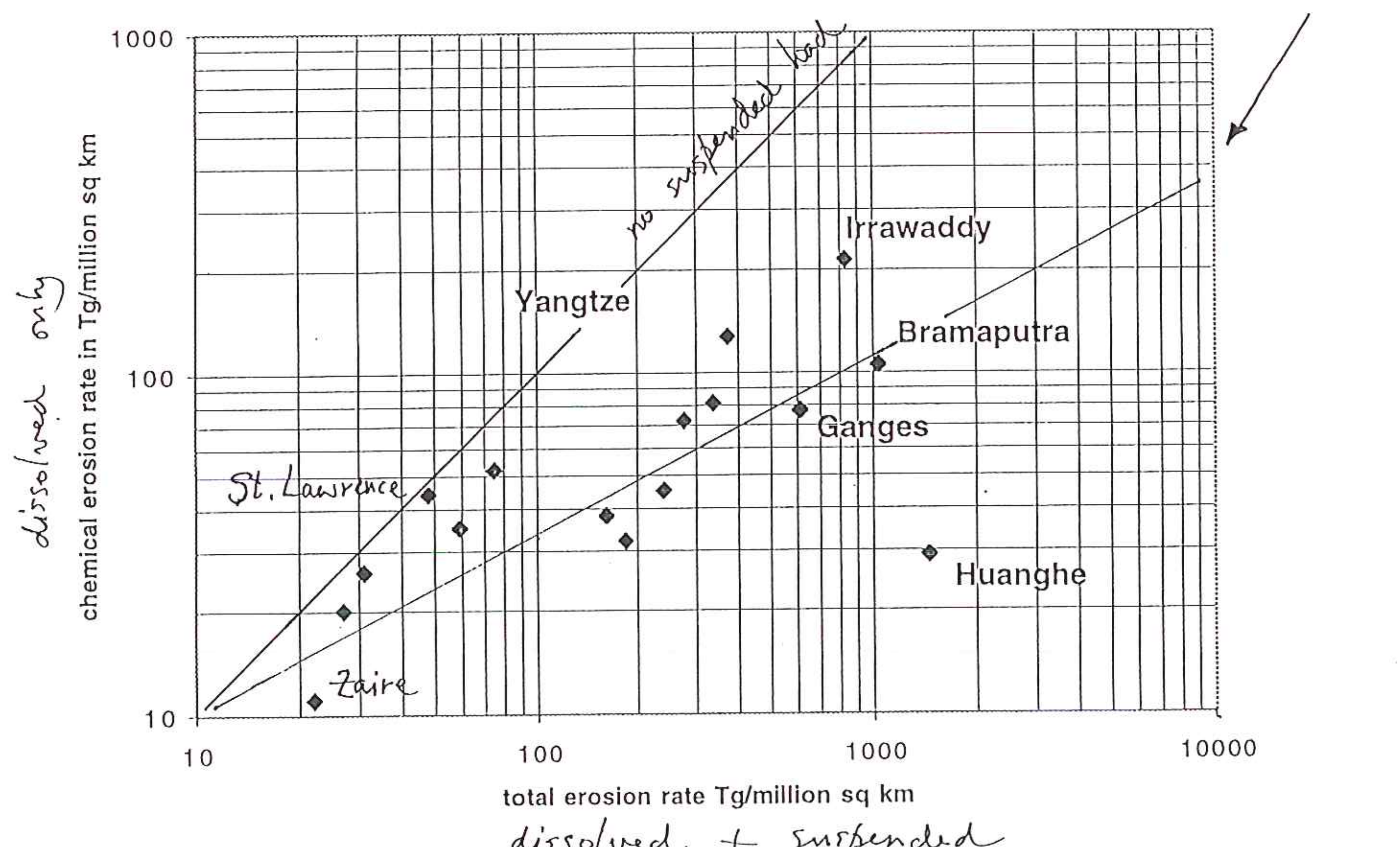


TABLE 5.2 Suspended Sediment Carried by Rivers to the Ocean (in Metric Tons)

Continent	Drainage Area Contributing Sediment to Ocean (10^6 km^2)	Sediment Discharge (10^6 tons/yr)	Sediment Yield (tons/km^2/yr)	Mean Continental Elevation (km)
North America	15.4	1020	66	0.72
Central America[a]	2.1	442	210	—
South America	17.9	1788	97	0.59
Europe	4.61	230	50	0.34
Eurasian Arctic	11.17	84	8	~0.2
Asia	16.88	6349	380	0.96
Africa	15.34	530	35	0.75
Australia	2.2	62	28	0.34
Pacific & Indian Ocean Islands[b]	3.0	9000[c]	3000[c]	~1.0
World total	88.6	20,000[d]	226[d]	

[a] Includes Mexico.

[b] Japan, Indonesia, Taiwan, Phillipines, New Guinea, and New Zealand (Oceania).

[c] From Milliman and Syvitski (1992).

[d] From Milliman and Syvitski (1992). Data reflect greater sediment discharge from South America, the Alps-Caucusus Mountains, and northwest Africa, in addition to Oceania.

Sources: After Milliman and Meade (1983) and Milliman and Syvitski (1992), elevations from Fairbridge (1968).

Total sediment discharge by all worlds' rivers:

$$2 \cdot 10^{10} \frac{\text{tons}}{\text{yr}} \text{ suspended load } \left(1 + \frac{1}{4} + \frac{1}{10}\right)$$

dissolved load from continental rocks

bedload

Sediment yield:

$$226 \frac{\text{tons}}{\text{km}^2\,\text{yr}} \text{ suspended } \left(1 + \frac{1}{4} + \frac{1}{10}\right) = 300 \frac{\text{tons}}{\text{km}^2\,\text{yr}}$$

Corresponding erosion or denudation rate:

$$300 \cdot 10^3 \frac{\text{kg}}{\text{km}^2\,\text{yr}} \times \frac{1}{2700} \frac{\text{m}^3}{\text{kg}} \times 10^{-6} \frac{\text{km}^2}{\text{m}^2} \times 10^3 \frac{\text{mm}}{\text{m}} \approx 0.1 \frac{\text{mm}}{\text{yr}}$$

typical source rock density

$$\boxed{\text{World-wide average erosion rate} \quad \langle \dot{e} \rangle \approx 0.1 \text{ mm/yr} = 0.1 \text{ km/Myr}}$$