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The relationship between suspended and bed load transport in river channels

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Abstract According to the existing literature, the clastic load of the rivers of the world is about four times larger than the dissolved load. Similarly, the suspended load is several times greater than the bed load transport. Values commonly fall within the bounds 85–99% suspended load to 1–15% bed load. The precise proportion depends on the transport power of the river, the hydrological regime, the geological structure of the catchment and human activity. However, the availability of new methods of measurement makes it possible to verify existing data concerning both forms of clastic load. This contribution aims to explore further the relationship between suspended load and bed load transport, to highlight the great divergence evident in the proportions of the total load accounted for by the two load components, and to explain the source of this divergence. The study is based on available literature documenting fluvial transport and incorporates the results of measurements undertaken in the lower Vistula River in Poland.

Key words bed load; dissolved load; fluvial transport, sediment budget; suspended load; Vistula River

INTRODUCTION

According to the literature there are three kinds of fluvial transport by rivers: (a) dissolved load or solute load, (b) wash load or suspended load, L_s, and (c) bed load, L_b. The latter two are referred to as the clastic load, L_c, or solid load. It has been estimated that about 15×10^9 t of clastic load and about 3.5×10^9 t of dissolved load are discharged to the oceans every year. This means, that the clastic load of the world's rivers is about four times greater than the dissolved load. Although the above proportions are generally accepted and there is broad agreement in the scientific research carried out by different authors, the precise relationship (i.e. the relative proportions of the total clastic load in %) between suspended load and bed load is still uncertain.

It is generally accepted that the suspended load of a river will be several times greater than the bed load flux. The proportions are generally within the bounds 85–99% (L_s) to 1–15% (L_b). The bed load contribution can be very small for major rivers, such as the River Amazon or the Huanghe (China). The precise proportions will depend on the transport power of the river, the hydrological regime, the geological structure of the catchment and human activity (agriculture, industry, building construction, river regulation, etc.). The availability of more accurate methods for measuring clastic loads in recent years (particularly bed load) has caused some revision of existing assessments of the relative importance of the two components of the clastic load.

It can be assumed that suspended load commonly dominates clastic load transport. However, new methods of measurement make it possible to re-assess earlier data concerning the relative importance of both forms of clastic load. The aim of this contribution is to discuss the relationship between suspended load and bed load transport, to highlight the great divergence of values for the relative contributions of the two load components, and to explain the source of this divergence. No attempt has, however, been made to assess the reliability of the measurement techniques, the correctness of the calculations and the representativeness of the data provided by the various sources used.

The work is based on the available literature documenting both suspended sediment and bed load transport. The extensive, but fragmented, literature focusing on either suspended load or bed load was not used, unless it was possible to obtain data on both load components for the same (comparable) time period from different sources. Data have been obtained for many rivers of the world, including the Amazon and the rivers of China and Russia. In addition, the work incorporates the results of measurement carried out in the lower reaches of the Vistula, between its confluence with the right-bank Narew tributary and its confluence with the Wda tributary (Babiński, 1992, 1994, 1999). This 300-km long river reach was regulated in the 19th century and at the turn of the 1960s a water reservoir (the Wloclawek Reservoir) was constructed there. As a result, the river reach can be divided into four sub-sections: (a) upstream from Wloclawek, unregulated, “wild”, with a braided-anastomosing channel; (b) the Wloclawek Reservoir, (c) the section downstream from the dam characterized by intensive erosion; and (d) the regulated lower section, with a pattern of alternate bars and pools (Fig. 1). Using this subdivision it was possible to examine sediment transport by the Vistula in relation to different channel types.

SUSPENDED LOAD TRANSPORT (L_s)

The suspended sediment load of a river is composed primarily of clay and silt particles. According to Knighton (1998, p.118), this equates to the <0.062-mm fraction. The magnitude of the suspended sediment load of a river will reflect the denudation processes operating in the upstream catchment, and more particularly:

(a) the source of the mobilised material: e.g. whether it originates from surface erosion, mass movements, gully erosion or channel bank erosion; and
(b) the rate of sediment supply, which will in turn reflect the amount of rainfall, the erodibility of the soil, the topography of the catchment and the density of the vegetation cover.

Both the sources of the fine sediment transported in suspension and the processes resulting in sediment mobilization are becoming increasingly influenced by human activities, such as agriculture, industry, coal mining and building construction. Recently, urban areas have become important as a sediment source, through inputs of sewage and sewage effluent to rivers. Suspended sediment transport is generally quantified by means of:

- measurements of suspended sediment concentration (i.e. collecting water samples with samplers and determining the sediment concentration either gravimetrically or by using optical methods);
- direct measurements of the amount of material supplied to the river by channel erosion and related sources; and
- the amount of sediment deposited in lakes, retention reservoirs, deltas, estuaries and coastal areas.

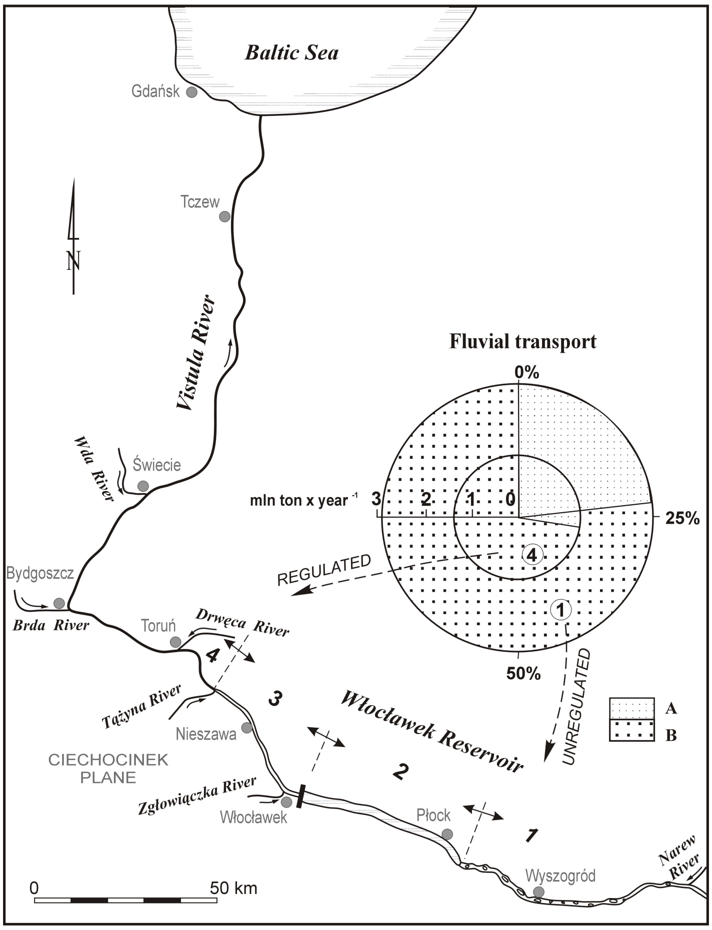

Fig. 1 The relationship between suspended load (A) and bed load (B) transport for the lower Vistula River in the unregulated (upstream from the Wloclawek Reservoir) section and the regulated (downstream from dam) section.

The basic measurement for calculating the suspended load is the sediment concentration or turbidity expressed in terms of the weight density of the suspension in mg l^{-1} or kg m^{-3} of water. Concentrations range from a few mg l^{-1} up to 1800 kg m^{-3} in the Huanghe (Yellow) River in China. Spatial variations depend mainly on the geological character of the river basin and concentrations frequently increase downstream (e.g. concentrations in the Dvina River increase more than 1.5 times). However, in some cases they reduce, and a decrease of 16–17% has been reported for the Huanghe (Yellow) River (see Chalov *et al.*, 2000). Temporal variation of water turbidity reflects the changing supply, with increased inputs during storm events or periods of snowmelt, resulting in increased concentration. The relationship between concentration and discharge is frequently characterized by hysteresis, with higher concentrations on the rising stage than on the falling stage, or *vice versa*.

BED LOAD TRANSPORT (L_b)

Bed load is transported along the river bed by rolling, sliding or saltation; although where turbulence is strong particles may move momentarily into suspension. This diversity of transport mechanisms makes bed load transport difficult to quantify. The associated measuring equipment is frequently complicated to use. Many methods have been employed for measuring bed load. Amongst the most frequently used approaches are:

- "catchers" or traps permanently installed across the entire cross-section of small rivers or deployed temporarily at various locations on the river bed (Anon, 1954);
- direct measurements of particle movement using tracers or markers, including painted stones, fluorescent sand, magnetic material, radioactive material, magnetic detectors, etc. (Ergenzinger, 1982);
- acoustic and magnetic devices;
- direct measurements of the intensity of sand transport (Młynarczyk, 1996);
- monitoring of bedforms, such as ripples and dunes (Babiński, 1992; Alekseyevsky & Chalov, 1997); and
- sedimentation in lakes and deltas.

The amount of bed load transported depends primarily on natural factors, such as the geology, morphology and morphometry of the river bed, and on human activity. However, values reported are often significantly influenced by subjective factors, depending on the method employed and the analysis undertaken. For example, even when using the same type of "catcher" at a given point of measurement, the results obtained could range between 5 and 725% (Born, 1958). Measurement errors can be several times greater than the value under consideration. Consequently, there are many uncertainties associated with available bed load data.

THE RELATIONSHIP BETWEEN SUSPENDED LOAD AND BED LOAD TRANSPORT (L_s:L_b)

As mentioned above, the relative magnitude of the bed load and suspended load transported by a river can vary significantly, depending on the transporting power (hydrology) of the river and the geological character of the river basin from which the material comes (Fig. 2). These factors are increasingly modified by human activity.

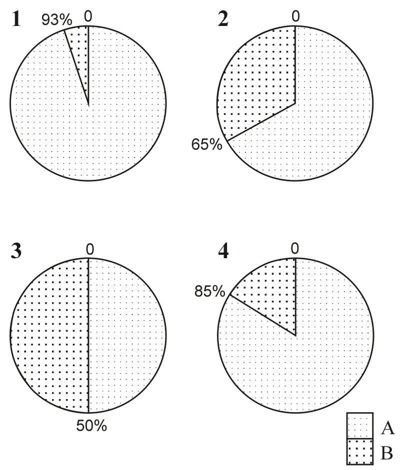

Fig. 2 The relationship between bed load transport (L_b) and suspended load transport (L_s) 1. large rivers (Amazon, Huanghe, Yangtze); 2. forest/steppe zone; 3. temperate/periglacial zone; 4. average in "old" literature.

Table 1 The relationship between bed load, L_b, and suspended load, L_s, (clastic L_c) transport for rivers in Russia and China; based on Alekseyevsky & Mykhynov (1991) and Chalov *et al.* (2000).

River	Station	Watershed area (km^2)	Discharge Q ($m^3 s^{-1}$)	L_s (Mt $year^{-1}$)	L_b (Mt $year^{-1}$)	L_b:L_s (L_c) (%)
Bielaja	Ufa	100 000	744	2.5	0.35	14
Moloma	Shchetininki	10 500	92.4	0.126		51
Dniestr	Dubossary		286	0.202	0.176	87 (47)
Dvina Nord	Abramkovo			13.2	2.03	15
Kama	Tjulkino	81 800	982	0.245	0.24	99 (50)
Dema	Bochkarevo	12 500	32.5	0.104		6
Sheshma	Petropavlov	3 110	11.8	0.072		13
Ob	Novosybirsk	216 000	1750	13.38	1.37	10
Lena	Kiusjur			22.66	17.45	77 (44)
Volga	Astrakchan		7500	8.4	3.16	38
Terek			345	17.6	0.6	3
Amu-daria		400 000	1760	135	2.2	1.6
Yangtze	Wuhan			425.0	25.2	6
Huang-he	Tsahetan			1736.0	4.48	0.3

The data regarding the magnitude of bed load and suspended load transport in several rivers in Russia and China, reported by Alekseyevsky & Mykhynov (1991) and Chalov *et al.* (2000) (Table 1) show a clear inverse relationship, in that in rivers where the suspended load is high, but the bottom material is fine-grained, bed load represents only a small proportion of the total load. For example, L_b:L_s for the Huanghe is 0.1–0.3%, for the Amudaria 1.6%, and for the Yangtze from 2.4–0.7%. However, for rivers in forested regions (e.g. the Northern Dvina), values increase to 14.4–35%. The highest ratios of suspended load to bed load are associated with rivers of the temperate and periglacial zones, e.g. the Lena, the Dniestr and the Kama (77–99%).

Milliman & Meade (1983) claim that bed load accounts for only approximately 10% of the clastic flux to the oceans. According to Klimaszewski (1978, p.338), however, the ratio of suspended load to bed load is conditioned by the geology and morphology of the terrain and the climate and can vary within the range 1–70%. However, the suspended load is commonly dominant. This is particularly the case in areas with an equatorial climate, where, for example, the sediment load of the Amazon comprises only about 1% bed load (see Summerfield, 1991, p.380; or Stoddart, 1969, p.54), the remainder of the clastic load being silt (40%) and clay (50%), which is transported in suspension. Bed load contributes a greater proportion of the load in some mountain rivers, but its contribution generally remains less than 10%. Knighton (1998) claims that, overall, bed load accounts for 85% of the clastic load. However, recent research on sand bed dynamics in Russian and Bialorussian rivers has shown that the ratio L_b:L_s may be dominated by bed load transport, or at least equal proportions of bed load and suspended load (Darbutas, 1992).

For the River Odra at Słubice in Poland, Pasławski (1971) has shown that there is a very clear differentiation of the ratio L_b:L_s, depending on flow magnitude, as represented by dry, average and wet years. In all cases, bed load transport was dominant, with values of 51, 57 and 70%, respectively, showing that the bed load contribution to the total clastic load increases with discharge magnitude.

An early investigation of bed load transport in the River Vistula (Poland) undertaken using Born's "catcher" (Anon, 1999) and involving a comparison with the suspended sediment load, showed that bed load contributed only 2–5% of the total sediment load (Jarocki, 1957). Later studies (Babiński, 1992, 1994, 1999), relating to the period after the construction of the Wloclawek Dam (hydrological years 1971–1995), identified a change in this ratio in favour of the bed load, with a distinct division into unregulated and regulated reaches and a clear influence of the Wloclawek Dam (Fig. 1).

During "wet" years the lower Vistula transports more than 5×10^6 t of clastic material though its braided section and over 2×10^6 t through the regulated section (Babiński 2002). However, in the "dry" years the transport is respectively only about a quarter (1.3×10^6 t) or third (0.6×10^6 t) of these values. Considering the average values obtained for the period 1971–1995, the Vistula transported 2.9×10^6 t of clastic material in the reach upstream of the Wloclawek section and 1.3×10^6 t in the Torun section. This means that the shift in river bed character from braided to straight (slight meanders constrained by groynes), reduced the clastic load transport by 50%. The Wloclawek Reservoir exerts an important influence by trapping the entire bed load and reducing the suspended load by 42–43%. Downstream from the reservoir, transport increases again due to channel incision and tributary inputs. In both the braided and the regulated sections, bed load transport was dominant. The ratio of bed load to clastic load (L_b:L_c) in the study period, expressed as a percentage, ranged between 66.1–87.4% in the braided section and 59.8–83.5% in the regulated (straight) section. Averaging the above data provides values for the L_b:L_c ratio of 76.8 for the unregulated section and 72.9 for the regulated section (Fig. 1).

SUMMARY

1. The geology of a river basin and its climate, particularly the amount and intensity of precipitation, will exert a key influence on the magnitude of the clastic load. The vegetation cover also influences sediment transport indirectly. Together these factors control erosion and delivery of sediment to the rivers. In addition, the channel pattern, fluvial processes, the morphology of the bed, discharge magnitude and bed-forming (bar-forming) flows also exert an important influence on sediment transport.
2. Important factors influencing the relative importance of the suspended load and bed load include the characteristics of the eroding surface, slope steepness (mountain rivers are commonly characterized by a high L_b), climate (the suspended load is dominant (85–99%) in rivers of the equatorial zone, whereas bed load is much more important (L_b approx. 50%) in the rivers draining those areas of Central Europe influenced by the last glaciation, with even higher values for the rivers Nida and Odra (Poland) and the lower Vistula up to 87%) (Figs 1 and 2).
3. Discharge magnitude exerts an important influence on the L_b:L_s ratio. During the rising stage of a flood the transporting power of the river will increase and the importance of bed load transport will also commonly increase.
4. Human activity has an increasing impact on clastic load transport, as a result of dam construction and channel regulation.
5. The majority of researchers still refer to the dominance of suspended load over bed load, although the ratio between them is decreasing in favour of bed load.

6. It is suggested that underestimation of bed load transport in favour of the suspended load results from: (a) less precise measurements and errors associated with the methods of calculating bed load transport. These problems are connected with the river bed cross-section. Whereas the suspended load is transported almost uniformly within the cross-section, the bed load is transported only on the river bed; (b) more intensive measurement programmes on rivers where the suspended sediment load is dominant; and (c) errors in interpreting suspended sediment transport in relation to the overall clastic load. The work of Summerfield (1991) provides an example. When discussing chemical and mechanical denudation he refers to only two types of load: the solid load, considered exclusively as a suspended load, and the solute load. Knighton (1998, p.88), quoting "old literature" (data collected in the first half of the 20th century), claims that, in the case of bed load, its 15% share in total river transport is rarely taken into consideration.

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