Sediment Transfer through the Fluvial System (Proceedings of a symposium held in Moscow, August 2004).
IAHS Publ. 288, 2004

The relationship between sediment yield and drainage basin area

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Abstract Hydrological data for small and intermediate sized rivers in the plains and mountains of the temperate belts of Eurasia were analysed. Total suspended sediment yield increases downstream faster than the basin area for rivers with undisturbed or slightly disturbed basins. Rivers with intensively cultivated basins are also characterized by an increase in total suspended sediment yield downstream, but this increase is slower than the increase in basin area and the specific suspended sediment yield therefore decreases downstream. Deposition very often prevails over erosion in the lower reaches of these rivers. Both relationships are not distinctly expressed for river basins with intermediate proportions of cultivated area and for large rivers.

Key words agricultural activity; basin area; downstream trend; human activity river; suspended sediment yield

INTRODUCTION

Suspended sediment yield data are widely used for evaluating the effects of various natural and anthropogenic factors on the intensity of erosion processes. However, sediment yield is also influenced by basin area. Makkaveev (1955) suggested that this dependence is the main reason why accurate estimates of erosion rates cannot be derived from information on specific sediment yield. As a result, researchers frequently use sediment yield data for only a restricted range of basin sizes. However, this reduces the size of the database. Researchers may therefore find it necessary to deal with comparatively large ranges of basin area within which the effects mentioned above cannot be completely excluded.

The question arises as to whether there is a general relationship between total and specific sediment yield and basin area and what this relationship is. An inverse relationship between specific suspended sediment yield and drainage basin area has been generally reported in the literature (Karaushev, 1977; Schumm, 1977). This trend indicates that the total suspended sediment yield increases downstream, but not as fast as the basin area increases. As a result, specific suspended sediment yield decreases as basin area increases. A positive relationship between specific sediment yield and drainage basin area observed for some rivers was usually considered to be a deviation from the general trend (Karaushev, 1977; Owens & Slaymaker, 1992). It is clear that analysis of the above mentioned trends could provide an improved understanding of the characteristic features of erosion and deposition in river basins.

DATA

A database of suspended sediment yield and controlling factors for 4200 hydrologic stations located on rivers all over the world was used. Attention focused on the data from rivers in the plains and low mountain areas of the Eurasian temperate belt, with basin areas up to 250 000 km^2. (This provided data from monitoring stations in 352 river basins). Some of the results of the analysis have been published previously (Dedkov & Mozzherin, 1984, 1992, 1996.)

The river basins were split into three categories according to the area of arable land, viz:

(a) uncultivated basins or basins with limited cultivation (tillage area <30%, forest area >70%);
(b) basins with intermediate amounts of cultivation (tillage and forest 30–70%);
(c) intensively cultivated basins (tillage area >70%, forest area <30%).

Data on basin areas (S, km^2), water discharge (Q, l s^{-1}), total suspended sediment yield (R, t year^{-1}), specific suspended sediment yield (r, t km^{-2} year^{-1}) were used for the analysis.

Some new information was also obtained specifically for the analysis. Firstly, *differential specific suspended sediment yield* (DSSSY), characterizing the basin area between two monitoring stations on the same river, was determined using the following equation:

$$r_d = (R_1 - R_2) / (S_1 - S_2) \text{ t km}^{-2} \text{ year}^{-1} \quad (1)$$

where index 1 and index 2 refer to the two monitoring stations, with 1 downstream from 2 and r_d is DSSSY.

It is clear that DSSSY reacts to changes in suspended sediment yield, and, consequently, changes in the relationship between erosion and accumulation, faster than the specific suspended sediment yield itself (*the integral specific suspended sediment yield*, characterizes erosion on the whole basin area upstream from a given hydrologic station) (Fig. 1). Increasing values of DSSSY indicate that erosion increases, and reducing values show that sedimentation prevails.

In addition, several coefficients, which characterize the increase downstream of the following parameters were also calculated: basin area (S_n / S_m), water discharge (Q_n / Q_m), a total suspended sediment yield (R_n / R_m), specific suspended sediment yield ($r_n - r_m$), where index n is a hydrologic station located downstream from the other hydrologic station (index m).

RESULTS

The results of the analysis demonstrate that the relationship between specific suspended sediment yield and drainage basin area in the forest and forest-steppe zones of the temperate belt of Eurasia is different for basins with a relatively undisturbed landscape and basins which are part-cultivated.

Rivers with uncultivated basins or basins with limited cultivation (category a)

These rivers are characterized by low suspended sediment yields. The specific yield in plain areas seldom exceeds 20–30 t km^{-2} year^{-1}, and in low mountains it increases to 50–70 t km^{-2} year^{-1}. Where there is a dense vegetation cover, surface (sheet and gully) erosion is limited, and the main sediment supply is provided by erosion of river channel and banks.

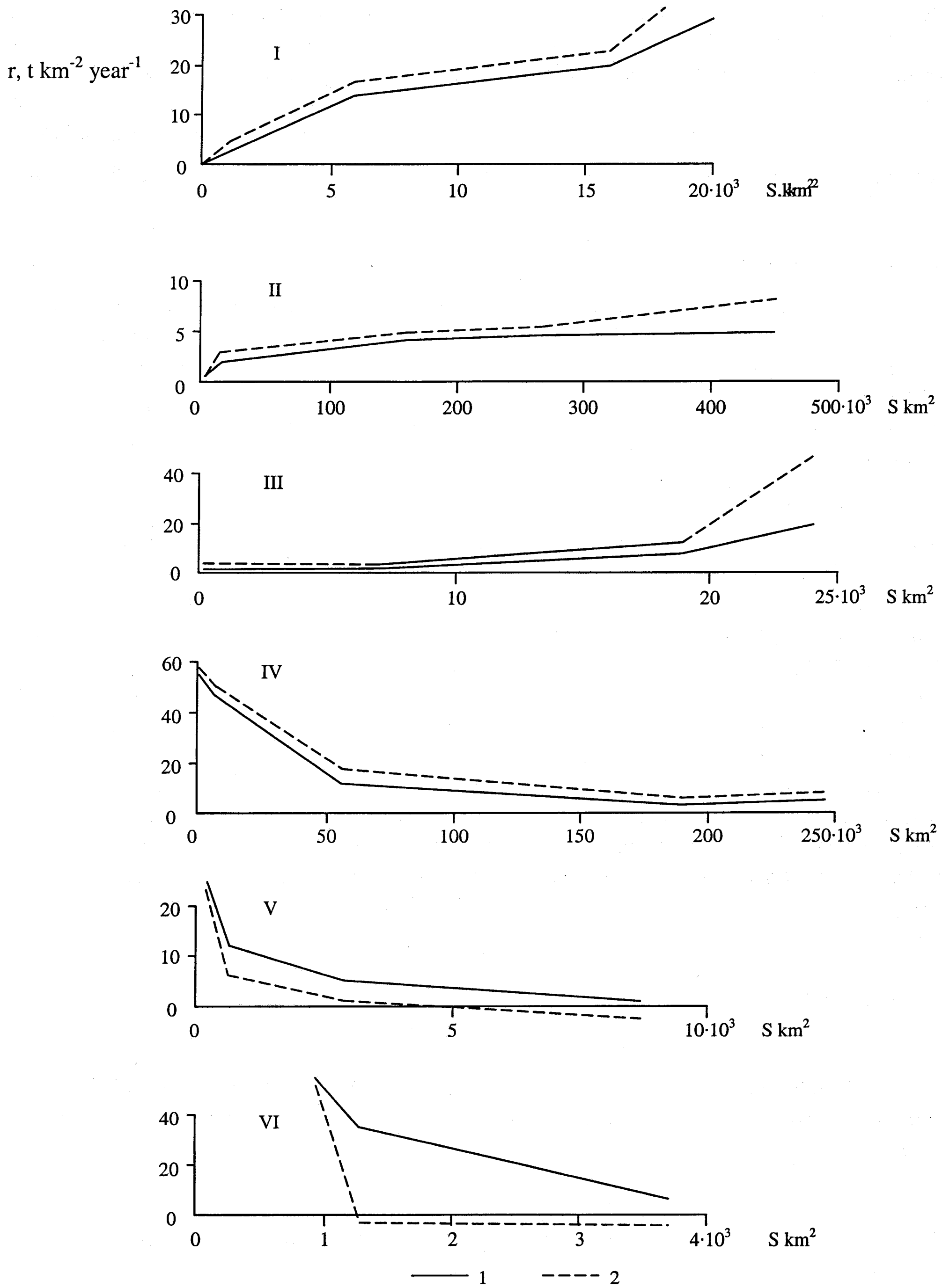

Fig. 1 The relationship between specific suspended sediment yield (*r*) and drainage basin area (*S*, 10^3 km^2) for rivers with basins with a limited cultivation area (I, II, III) and intensively cultivated basins (IV, V, VI). (1), integral specific sediment yield; (2), differential specific sediment yield (DSSY). Rivers: I, Chusovaya; II, Nizhnyaya Tunguska; III, Vym'; IV, Oka; V, Tersa; VI, Kalmius.

Water discharge commonly increases downstream approximately proportionally to the increase in catchment area, though more often the rate of increase in the former is less than the increase in the latter (Q_n / $Q_m \leq S_n$ / S_m). Total sediment yield increases even more rapidly downstream, due to the approximately cubic relationship between sediment discharge and water discharge ($Q_s = Q_w{}^n$, where $n = 2.6$ for lowland rivers and $n = 3$ for mountain rivers) (Makkaveev, 1955). The increase in total sediment yield for a given river always exceeds the increase in basin area (R_n / $R_m > S_n$ / S_m) (Fig. 2). Therefore the values of specific suspended sediment yield (both integral and to an even greater extent, differential) increase regularly downstream (Fig. 1). This positive relationship between specific suspended sediment yield and drainage basin area (Fig. 3(a)) is typical for uncultivated basins or basins with limited cultivation.

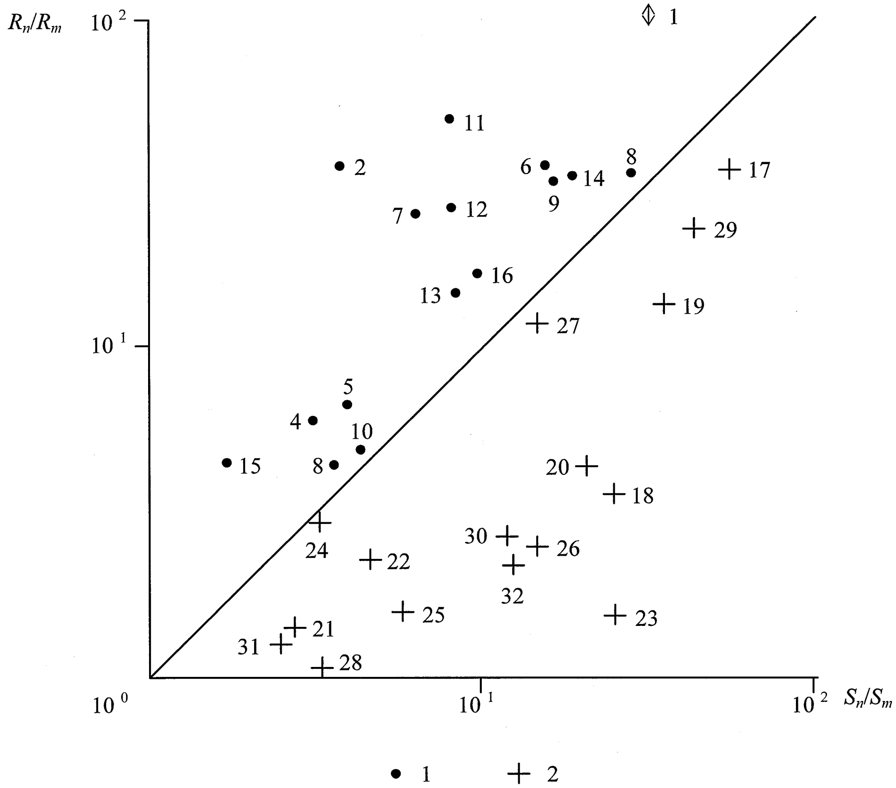

Fig. 2. The relationship between sediment yield increase (R_n / R_m) and basin area increase (S_n / S_m) for sparsely cultivated (1) and intensively cultivated (2) river basins. Rivers: Category a: 1, Chusovaya; 2, Wym'; 3, Soswa; 4, Nizhnyaya Tunguska; 5, Ussuri; 6, Dirysa; 7, Om'; 8, Belaya; 9, Malka; 10, Bureja; 11, Wasygan; 12, Kan; 13, Witim; 14, Aldan; 15, Zeja; 16, Ai; 17, Upper Lena; 18, Indigirka; 19, Kamchatka; 20, Tom'; Category c: 21, Hoper; 22, Ilovlja; 23, Svijaga; 24, Samara; 25, Sal; 26, Eruslan; 27, Tersa; 28, Dema; 29, Kalaus; 30, Sheshma; 31, Tobol; 32, Ishim; 33, Mius; 34, Kalmius; 35, Medvediza; 36, Seversky Donez; 37, Oka; 38, Argun; 39, Osym; 40, Bolshoy Irgiz.

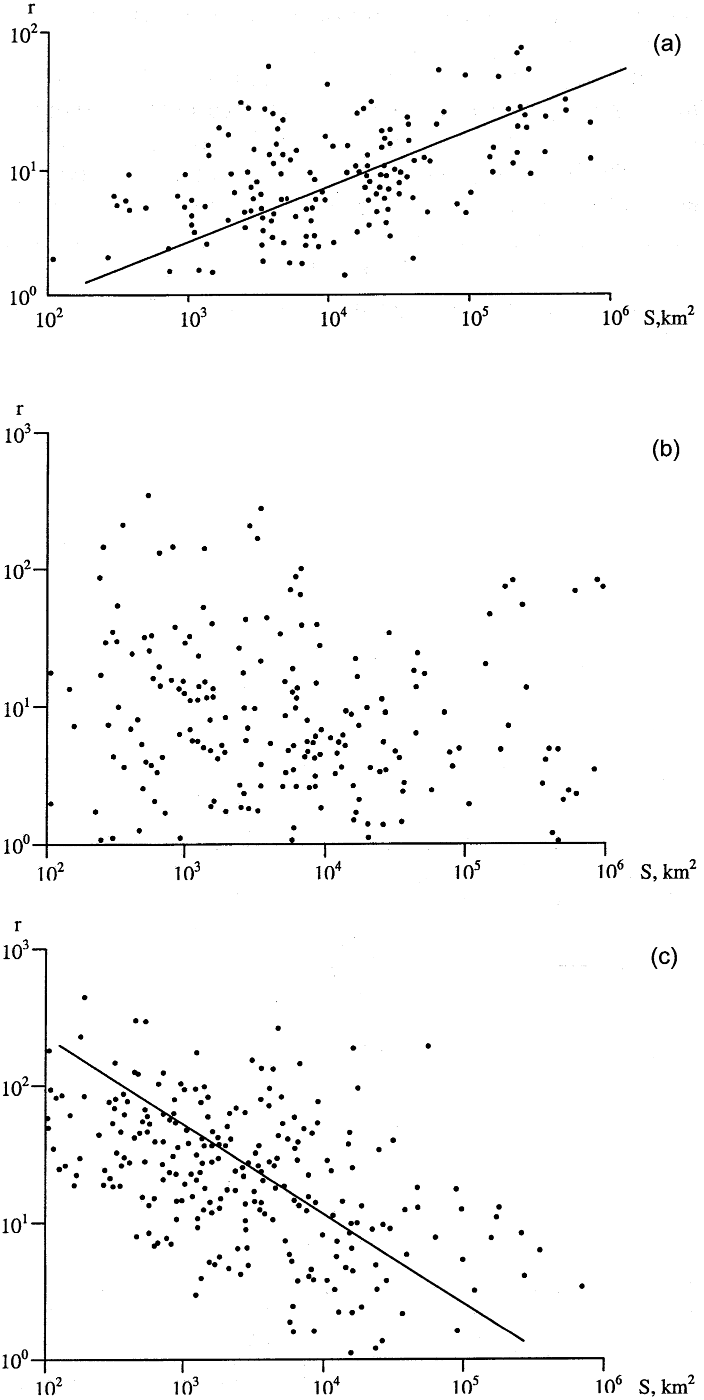

Fig. 3 Relationships between specific suspended sediment yield (*r*, t km^{-2} year^{-1}) and drainage basin area (*S*, km^2). (a) uncultivated or sparsely cultivated basins; (b) intermediate cultivated basins; (c) intensively cultivated basins.

Rivers with basins with intermediate proportions of cultivated land

Figure 3(b) shows the relationship between specific suspended sediment yield (integral) and drainage basin area for small- and medium-sized river basins in category b for the temperate belt of Eurasia. The significant dispersion of points and the low correlation coefficient can be explained by the high variability of the catchments with respect to their area, relief, geological structure, and the area of arable land *vs* forest land.

Because of the dominance of channel erosion in basins of category a, there is a relatively high proportion of bed load sediment, which constitutes about 20% of the suspended sediment load (Mozzherin, 1994).

Rivers with intensively cultivated basins (category c)

Rivers of this group are characterized by the largest specific suspended sediment yields for the plain rivers. The averages values of specific sediment yield are 60–100 t km^{-2} $year^{-1}$, and the maximum is almost an order of magnitude larger (Fig. 3(c)). Such high values of suspended sediment yield reflect intensive surface erosion on arable lands. Surface erosion is a key component of the suspended sediment yield. The proportion of bed load sediment reduces to 5–10% of the suspended sediment load, because sheet erosion primarily supplies the rivers with fine material.

Rivers with intensively cultivated basins are also characterized by an increase in total suspended sediment yield downstream. However, this increase occurs more slowly than the increase in basin area (R_n / R_m < S_n / S_m) (Fig. 2). The rivers are overloaded by sediment derived from the catchment surface and some of this sediment is depositional, causing the increase in sediment yield to slow downstream. Correspondingly, specific suspended sediment yield, both integral and even to a greater extent DSSSY, decrease downstream. Moreover, in the lower reaches of some rivers the total sediment yield reduces due to its deposition. In these regions, the DSSSY has negative values (Fig. 1,V and VI).

A negative relationship between specific sediment yield and drainage basin area is observed on the rivers of category c in periods with intensive snow melting and after high intensity rains, which erode the surface of the catchment. During low water periods, the input of sediment from the catchment surface is close to zero, and a positive relationship between specific sediment yield and drainage basin area exists.

Contemporary sedimentation on flood plains with deposits up to 2–2.5 m thick is widespread in the agricultural belt of Eurasia (Dedkov & Mozzherin, 1984; Owens & Slaymaker, 2000) and is the consequence of intensification of erosion of the catchment surface after slope cultivation. Radiocarbon dating of these sediments on the flood plains confirms that they are synchronous with periods of cultivation.

If arable lands are for some reason abandoned and become covered by forest, then the reverse process takes place. The rivers transport less sediment derived from the catchment surface and erosion of the river bed and banks increases, markedly promoting the formation of a new lower level flood plain. A similar phenomenon was described by Polish researchers in the upper reaches of the Visloka River (the right-hand tributary of the Vistula River) where between 1938 and 1990 the forest area increased from 30% to 67% on abandoned lands and, correspondingly, the area of arable land reduced (Lach & Wyzga, 2000).

It should be noted that almost for a quarter (23%) of the river basins of category c an inverse relationship between specific sediment yield and drainage basin area is not found, or is only faintly expressed. This can be explained by the existence of various hydrotechnical structures, and sharp changes in hydrological, geological and other conditions. However, the predominance of the negative relationship between specific sediment yield and drainage basin area is typical for cultivated regions of the temperate belt of Eurasia (Fig. 3(c)).

CONCLUSION

The negative relationship between specific sediment yield and drainage basin area which was, until recently, considered by many researchers to be a general global relationship for the temperate belt (without arid regions), is only characteristic of intensively cultivated basins. It was shown that this relationship was most clearly defined for temperate belt specific sediment yields. A positive relationship between specific sediment yield and drainage basin area is observed for uncultivated basins or basins with limited cultivation, which are characterized by the lowest suspended sediment yields.

The conclusions presented are gradually gaining recognition. For example, Walling & Webb (1996) wrote that the questioning of the traditional view, provided by Dedkov & Mozzherin, shows that the inverse relationship between specific sediment yield and basin area is to a large extent a reflection of human impact on the fluvial system, rather than a basic precept (Walling & Webb, 1996). They also point out that "the basic precept" probably results from the dominance of studies undertaken in the USA, which is characterized by strong anthropogenic impact. It can be suggested that in Russia also, the conclusion about the universal character of inverse relationships was also primarily based on studies undertaken in cultivated regions.

In this connection the study of erosion and sediment yield, carried out by Renwick (1996) is of interest. He showed that specific sediment yields increase, and the inverse dependence on basin area becomes more strongly expressed, the more intensively the region is cultivated. Thus, for the USA as well, changes in specific sediment yield downstream show different trends, depending on the relative areas of arable lands and forest land within the river basin.

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