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Suspended sediment yield from continents into the World Ocean: spatial and temporal changeability

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Abstract Attempts have been made to determine the suspended sediment yield from rivers of the various continents and islands into the World Ocean. Its differentiation into natural and anthropogenic components, and analysis of its contemporary trend variability were undertaken. The total global suspended sediment yield into the World Ocean equals 15.5×10^9 t year^{-1}. The main suppliers are continental Asia and the islands of the west and southwest parts of the Pacific (their contribution to the total global suspended sediment yield into the World Ocean is 73.4%). The least sediment is supplied by Australia (1.1%). Recent human activity has increased suspended sediment yield into the World Ocean by 2.6 times. The largest anthropogenic increase of suspended sediment yield found is on the islands of the west and southwest parts of the Pacific (by 3.7 times) and in Europe (by 3.4 times); the least intensification characterizes South America (by 1.2 times). The analysis of long-term time series of suspended sediment yield shows that during the second half of the 20th century a rising trend of erosion intensity and suspended sediment yield prevailed in South and Central America, East Africa, West Europe, South and South-East Asia and Australia. A reduction of suspended sediment yield took place in East Europe, northwest and east-central parts of Asia and west part of North America. The main factor determining these global scale changes is diverse human activity.

Key words anthropogenic factor; changeability; continent; erosion; river basin; suspended sediment yield; trend; World Ocean

INTRODUCTION

In the last three decades of the 20th century a database on suspended sediment yield (SSY) and its controlling factors, which contains information for 4140 river basins of the Earth, was created by geomorphologists of Kazan State University (Russia). The data analysis allowed determination of the basic regularities of spatial development of erosion processes and suspended sediment yield (Dedkov & Mozzherin, 1984; Dedkov & Mozzherin, 2000; Dedkov, 2004). The next tasks of our investigations were attempts to determine the SSY from continents into the World Ocean and to sub-divide the SSY into natural and anthropogenic components, and also to research trends of erosion intensity and SSY changes on the Earth during the second half of the 20th century.

DATA AND STUDY METHOD

The works of almost 30 researchers, published during the second half of the 20th century, arrived at very different estimates of the sediment mass carried by rivers into the

World Ocean (Dedkov & Mozzherin, 2000). Especially large differences in estimates—from 5.2×10^9 t year^{-1} (Corbel, 1964) to 51.1×10^9 t year^{-1} (Fournier, 1960)—are characteristic for works of the period 1950–1960 based on comparatively small numbers of observations. In the last two decades the range of estimates narrowed considerably.

The area of the Earth having a water flow into the World Ocean (area of external water flow) is 97.6×10^6 km^2 (65.5% of total area of dry land of the Earth). The other 51.4×10^6 km^2 (34.5%) is deprived of water flow into the World Ocean (area of internal water flow). From the total area of dry land with water flow into the World Ocean, only 52.6×10^6 km^2 (53.9%) are provided with direct data on SSY. These data are for 330 rivers from our database with hydrological stations at river mouths or near to them. The total SSY into the World Ocean from all 330 rivers is approx. $10\,248.7 \times 10^6$ t year^{-1}, or 195 t km^{-2} year^{-1}. It is noteworthy that this specific SSY is near to that obtained for 4140 hydrological stations of the Earth including the area of internal water flow (202 t km^{-2} year^{-1}, including 70 t km^{-2} year^{-1} for the plains and 374 t km^{-2} year^{-1} for mountain regions).

For the vast area of external water flow for which no direct data on SSY are available (45.0×10^6 km^2, or 46.1% of all regions with water flow into the World Ocean), SSY was determined by data extrapolation from neighbouring river basins with hydrological stations, with corrections for relief, lithology, runoff, vegetation cover and land use intensity. The values of such corrections depended on earlier established dependences of SSY on the various natural and anthropogenic factors (Dedkov & Mozzherin, 1984; Lvovitch *et al.*, 1991 and others). The estimated SSY from areas where no data are available is 5219.9×10^6 t year^{-1}, or 116 t km^{-2} year^{-1}. Consequently, the SSY from such areas is considerably (by 1.7 times) less than that from areas with direct SSY data. This may be explained by the fact that hydrological stations are located mainly in territories with large anthropogenic influences on SSY (Dedkov, 2004).

Total global SSY has two components: natural and anthropogenic. The natural component is formed by erosion in natural conditions not influenced by human activity. The anthropogenic component reflects greater erosion intensity and increase of SSY under the influence of human activity, mainly agricultural.

To estimate the influence of the anthropogenic factors on SSY, all (4140) river basins of the dry land of the Earth in our database were divided into three principal categories of land use intensity. Unmastered or poorly mastered (cultivated area less than 30%) river basins were classed as Category I, the SSY of which is conventionally accepted as a natural (i.e. pre-agricultural) component. River basins with an intermediate degree of mastering (cultivated area from 30% to 70%) were classed as Category II, and with strong mastering as Category III (cultivated area more than 70%). For the whole Earth the increases of SSY from the river basins of one category to another are shown in Table 1. The indices of reduction of specific SSY from Categories II and III to Category I (i.e. to almost the natural level) are adopted as the coefficients of anthropogenic transformation (CAT); $CAT_{(II/I)}$ and $CAT_{(III/I)}$, respectively. With the aid of these coefficients all basins of Categories II and III were compared with basins of Category I, i.e. with almost natural (pre-agricultural) levels of erosion intensity and SSY.

The research of trends in erosion intensity and SSY changes involved more than 1500 long-term time series of SSY observations (Gusarov, 2000, 2001, 2002a,b, 2003). Most of the data are from the territory of the Former Soviet Union (mainly data of Bobrovitskaya, 1994) as well as from the territory of the USA (48 series) and Central

Table 1 Specific suspended sediment yield (t km^{-2} $year^{-1}$) and coefficients of anthropogenic transformation (times) in river basins with different categories of land use intensity (whole Earth).

Relief	River basin area	Categories of land use intensity I	II	III	$CAT_{(II/I)}$	$CAT_{(III/I)}$
Plains	Small basins <5000 km^2	10	36	130	3.6	13.0
	large basins >5000 km^2	16	33	130	2.1	8.1
Mountains	All basins	240	592	660	2.5	2.8

and West Europe; the lesser part the data is from South America, Africa and South, East and South-East Asia. The following sources of information have been used: materials of regime observations by the Hydro-Meteorological Service of the Former Soviet Union; the electronic databases of the Canadian National Water Research Institute (http://www.cciw.ca) and the Geological Survey of the USA (http://www.usgs.gov); numerous works on the subject, published in Russia and elsewhere.

RESULTS

The following main results were obtained:

1. The total global suspended sediment yield from dry land into the World Ocean is estimated at approx. 15 469 × 10^6 t $year^{-1}$. Similar results were obtained by Alekseev & Lisitcina (1974), 15.7 × 10^9 t $year^{-1}$; Milliman (1991), 16.0 × 10^9 t $year^{-1}$; Lvovitch *et al.* (1991), 14.9 × 10^9 t $year^{-1}$; Walling & Webb (1996), 15.0 × 10^9 t $year^{-1}$ and others.
2. The natural component of SSY from dry land into the World Ocean is 5978 × 10^6 t $year^{-1}$. The difference between the total global SSY into the World Ocean and its natural component is the value of the anthropogenic component, 9491 × 10^6 t $year^{-1}$. Consequently, the anthropogenic component of SSY into the World Ocean exceeds the natural component by approx. 1.6 times, and the total global SSY into the ocean as a result of human activity increased by approx. 2.6 times. A number of other researchers, using other methods, came to the conclusion that anthropogenic factors doubled the total global SSY (Milliman, 1991; Walling & Webb, 1996 and others). From our data we conclude that on the plains of the Earth the total SSY increased by 6.0 times, whereas in the mountains it increased by 1.6 times.
3. Separate regions of the Earth supply different amounts of suspended sediments to the World Ocean. Table 2 shows that continental Asia is the principal supplier of suspended sediment, producing more than half (59%) of the total global SSY. There is a large distinction in SSY between the north part of Asia (basin of the Arctic Ocean) and the southeast part (basins of Indian and Pacific Oceans). The area of external water flow of the southeast part of Asia exceeds that in the north part by 1.4 times, but its rivers transport 95.6 times more suspended sediment into the World Ocean (7742 × 10^6 t $year^{-1}$ and 81 × 10^6 t $year^{-1}$, respectively). The specific SSY in the river basins of the southeast part exceed those in the north part by 110 times (about 990 t km^{-2} $year^{-1}$ and 9 t km^{-2} $year^{-1}$, respectively). Rivers with record masses of suspended sediments for the whole dry land of the Earth

Table 2 Modern suspended sediment yield (SSY) into the World Ocean.

Regions of the Earth	Total SSY into the World Ocean ($\times 10^6$ t year^{-1}/ %)	Natural component, ($\times 10^6$ t year^{-1}/ %)	AI (times)	Specific SSY (t km^{-2} year^{-1}) total / natural
Europe	579.6 / 3.8*	171.6/ 29.6**	3.4	69 / 20
Asia	9 132.7 / 59.0	3 525.2/ 38.6	2.6	337 / 130
Africa	1 043.1 / 6.7	314.0/ 30.1	3.3	57 / 17
North America	1 080.0 / 7.0	322.9/ 29.9	3.3	50 / 15
South America	1 238.4 / 8.0	993.7/ 80.2	1.2	72 / 58
Australia	164.6 / 1.1	54.8/ 33.3	3.0	44 / 15
Pacific islands	2 230.2 / 14.4	595.5/ 26.7	3.7	1 770 / 458
Whole Earth	15 468.5 / 100.0	5 977.7/ 38.6	2.6	158 / 61

AI – anthropogenic increase of SSY
* Portion of total global SSY into the World Ocean
** Portion of total SSY into the World Ocean from this region

drain into the Pacific and Indian Oceans: the Yellow River, 2800 t km^{-2} year^{-1} and the Ganges with the Brakhmaputra, 2700 t km^{-2} year^{-1}. Each of the large rivers of Siberia, the Ob, Enisei and Lena, annually transport less than 1×10^7 t of sediment into the Arctic Ocean. Such distinctions in SSY between the two parts of Asia are predictable. Favorable conditions for intense erosion, both natural (high relief, heavy atmospheric precipitation and large runoff, widespread easily eroded rocks) and anthropogenic (intensive and long established agricultural use of plains, the densest rural population on the Earth) combine in the southeast part of continent. In the north part of Asia the very small SSY into the World Ocean is related to the vast areas of low relief and comparatively poor agricultural usage of the natural landscapes of the tundra and taiga zones.

Second place in SSY into the World Ocean is taken by the islands of the west and southwest parts of the Pacific. In spite of the comparatively small area of this territory its rivers transport more suspended sediments into the World Ocean than any continent, except for Asia, and show the greatest specific SSY, 1770 t km^{-2} year^{-1} (Table 2). In Taiwan the specific SSY is 14 200 t km^{-2} year^{-1}, in New Guinea is 1200 t km^{-2} year^{-1} and in New Zealand is approx. 800 t km^{-2} year^{-1}. Such large SSY in the island part of the Pacific is related to the heavy rains, high relief, small areas of river basins and considerable agricultural transformation of natural landscapes.

South America shows the third highest SSY, due only to considerable aforestation, the greatest among all continents, and weakest agricultural usage. However, the location of the main part of the continent in the humid tropics and the mountain system of the Andes causes heavy atmospheric precipitation and greatest runoff among all continents (Table 3). On the plains of the Earth in natural conditions the largest SSY is characteristic of the humid tropics and the equatorial zone (Dedkov & Mozzherin, 1984).

North America and Africa are almost equal in the area of external water flow, but have different environmental conditions, yet identical masses of suspended sediments are transported to the World Ocean (about 1×10^9 t year^{-1}). The specific SSY in the mouths of large rivers of both continents periodically exceeds 100 t km^{-2} year^{-1}, with mean values of 50–60 t km^{-2} year^{-1}. In North America the rivers

Table 3 The main factors of suspended sediment yield on the areas of external water flow.

Regions of the Earth	Main factors				
	Area of external water flow ($\times 10^6$ km² / %)	Mean absolute height (m)	Mean specific runoff (L s^{-1} km^{-2})	Mean aforestation (%)	Mean degree (category) of land use intensity
Europe	8.4 / 8.6*	300	12.2	30	2.5
Asia	27.1 / 27.8	950	21.5	17	1.7
Africa	18.3 / 18.8	650	7.3	34	1.9
North America	21.6 / 22.1	720	11.5	36	2.3
South America	17.2 / 17.6	580	21.6	47	1.7
Australia	3.7 / 3.8	215	6.3	14	1.5
Pacific islands	1.3 / 1.3	400	~30.0	30	2.0
Whole Earth	97.6 /100.0	690	17.8	28	1.9

* Portion of total global area of external water flow.

Table 4 Areas ($\times 10^6$ km^2) with different trends of erosion intensity and suspended sediment yield changes in hemispheres of the Earth during the second half of the 20th century.

Trends	Hemispheres of the Earth	
	Northern	Southern
Rising	34.02 (34.7)	24.94 (72.0)
Descending	26.83 (27.4)	1.69 (4.9)
Relatively permanent	21.30 (21.8)	5.42 (15.6)
No data	15.79 (16.1)	2.60 (7.5)
Total area	97.97 (100.0)	34.65 (100.0)

In parentheses, %

serve as basic suppliers of sediment into the World Ocean from the strongly agriculturally developed plains of the USA. In Africa, the low mountains and plateaux of tropical and equatorial climatic zones are characteristically not so strongly mastered, but are more humid and with large runoff.

In Australia the area of external water flow is the smallest among all continents. Consequently, the smallest specific SSY and the smallest portion of total global sediment yield into the World Ocean is from Australia.

4. During the second half of the 20th century the dry land of the Earth was dominated by areas with mainly rising trends of erosion intensity and SSY changes (Fig. 1, Table 4). The ratio of areas with different erosion intensity and SSY changes trends in various regions and within different climatic zones of the Earth was uneven during this period. The majority of the areas dominated by mainly rising trends of erosion intensity are located in the equatorial, subequatorial and tropical zones. A lower number of such areas is located in climatic zones of the mid-latitudes and high-latitudes. More considerable is the decrease of erosion intensity and SSY (descending trend) in river basins of the arctic, subarctic and temperate climatic zones of the Northern Hemisphere (Table 5, Table 6).
5. Changing anthropogenic factors (i.e. reforestation and deforestation, cultivation and grazing, etc.) and hydro-climatic conditions are the main reasons for trend variations in erosion intensity and SSY changes on the Earth during the second half of the 20th century. The ratio of areas in which specific factors predominate is different on the continents (Table 7) and within climatic zones (Fig. 2).

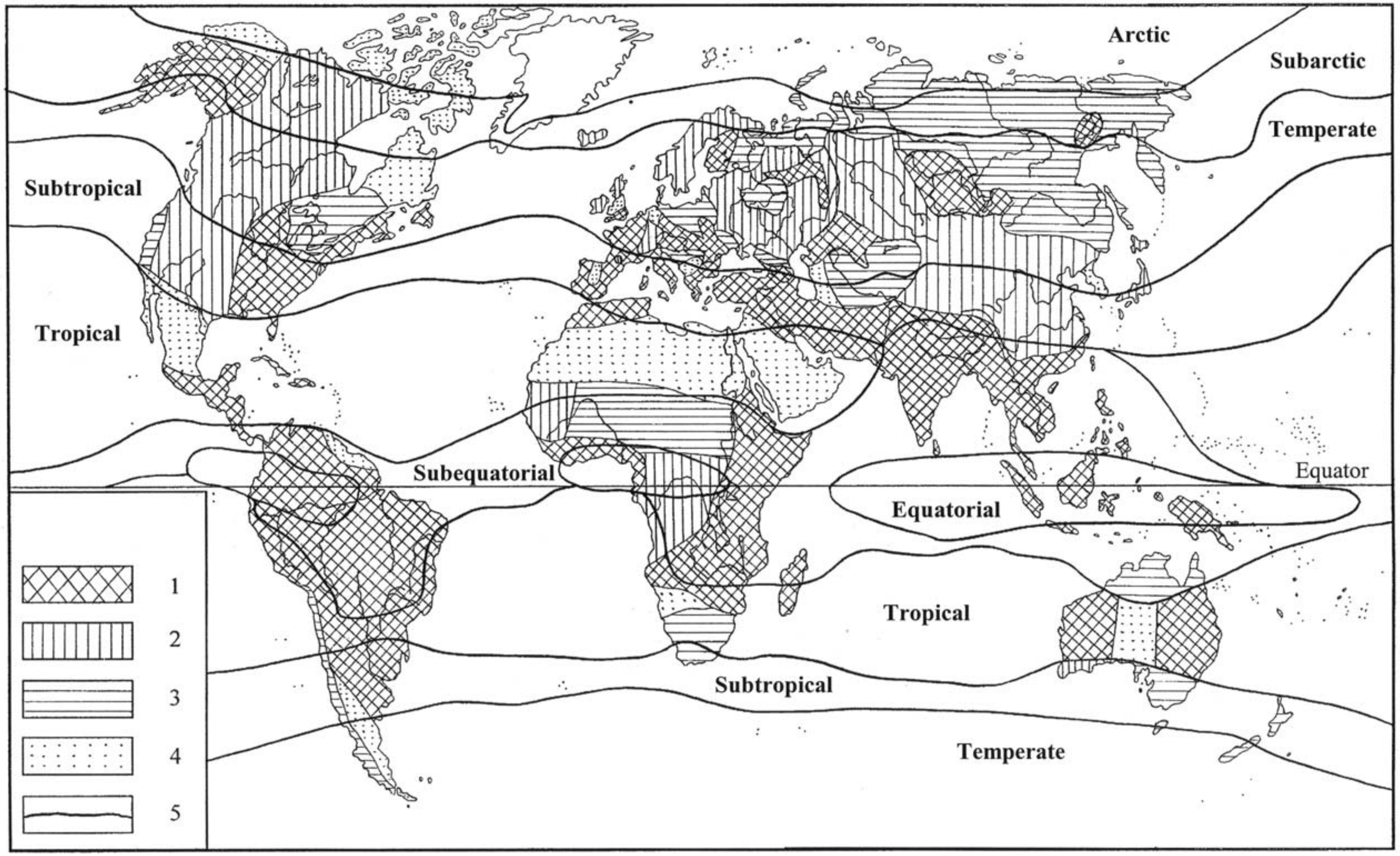

Fig. 1 Map of trends of erosion intensity and suspended sediment yield changes on the Earth during the second half of the 20th century. Trends: 1, rising; 2, descending; 3, relatively permanent; 4, no data; 5, border of climatic zones. Climatic zones: Ar, arctic; SA, subarctic; Te, temperate; ST, subtropical, Tr, tropical; SE, subequatorial, Eq, equatorial.

Table 5 Areas with different trends of erosion intensity and suspended sediment yield changes in various regions of the Earth during the second half of the 20th century.

Trends	Regions of the Earth					
	Africa	Australia and Oceania	South America	North America	Europe	Asia
Rising	11.40 / 37.7	4.59 / 52.6	15.96 / 89.4	5.89 / 26.7	3.45 / 34.2	17.67 / 40.5
Descending	4.25 / 14.1	0.24 / 2.8	–	9.36 / 42.4	4.12 / 40.8	10.55 / 24.2
Relatively permanent	7.26 / 24.0	2.77 / 31.7	0.56 / 3.1	2.06 / 9.3	2.08 / 20.6	12.02 / 27.6
No data	7.32 / 24.2	1.13 / 12.9	1.33 / 7.5	4.79 / 21.6	0.44 / 4.4	3.38 / 7.7
Total area	30.23 / 100.0	8.73 / 100.0	17.85 / 100.0	22.10 / 100.0	10.09 / 100.0	43.62 / 100.0

Numerator, $\times 10^6$ km^2; denominator, % of total area.

Table 6 Areas ($\times 10^6$ km^2) with different trends of erosion intensity and suspended sediment yield changes in climatic zones of the Earth during the second half of the 20th century.

Climatic zones	Trends			No data	Total area
	Rising	Descending	Relatively permanent		
Arctic	– (0.0)	1.98 (53.4)	1.73 (46.6)	1.54	5.25
Subarctic	1.20 (16.4)	2.54 (34.6)	3.59 (49.0)	0.80	8.13
Temperate (N)	7.28 (24.0)	14.03 (46.2)	9.06 (29.8)	1.53	31.90
Subtropical (N)	8.63 (50.3)	6.87 (40.0)	1.76 (9.7)	2.72	19.98
Tropical (N)	2.90 (70.7)	0.61 (14.9)	0.59 (14.4)	8.60	12.70
Subequatorial (N)	11.78 (67.9)	1.05 (6.1)	4.51 (26.0)	0.59	17.93
Equatorial (N + S)	6.10 (74.7)	1.90 (23.2)	0.17 (2.1)	–	8.17
Subequatorial (S)	11.50 (79.7)	0.83 (5.8)	2.10 (14.5)	–	14.43
Tropical (S)	7.94 (82.6)	0.19 (2.0)	1.48 (15.4)	1.74	11.35
Subtropical (S)	1.63 (48.1)	0.24 (7.1)	1.52 (44.8)	0.41	3.80
Temperate (S)	– (0.0)	– (0.0)	0.32 (100.0)	0.45	0.77

In parentheses, %; hemispheres: N, northern; S, southern.

Table 7 Areas with predominant factors of trends of erosion intensity and suspended sediment yield changes in various regions of the Earth during the second half of the 20th century.

Factor	Regions of the Earth					
	Africa	Australia and Oceania	South America	North America	Europe	Asia
A	11.40 / 49.8	–	16.52 / 100.0	1.15 / 6.6	3.85 / 39.9	17.94 / 37.1
H	4.25 / 18.5	7.33 / 96.4	–	1.48 / 8.6	2.79 /28.9	14.01 / 34.8
A-H	7.26 / 31.7	0.27 / 3.6	–	14.68 / 84.8	3.01 / 31.2	11.29 / 28.1
No data	7.32 / –	1.13 / –	1.33 / –	4.79 / –	0.44 / –	3.38 / –
Total area	30.23 / 100.0	8.73 / 100.0	17.85 / 100.0	22.10 / 100.0	10.09 / 100.0	43.62 / 100.0

Factors: A, anthropogenic; H, hydro-climatic; A–H, relative anthropogenic–hydro-climatic; numerator – $\times 10^6$ km^2; denominator – %.

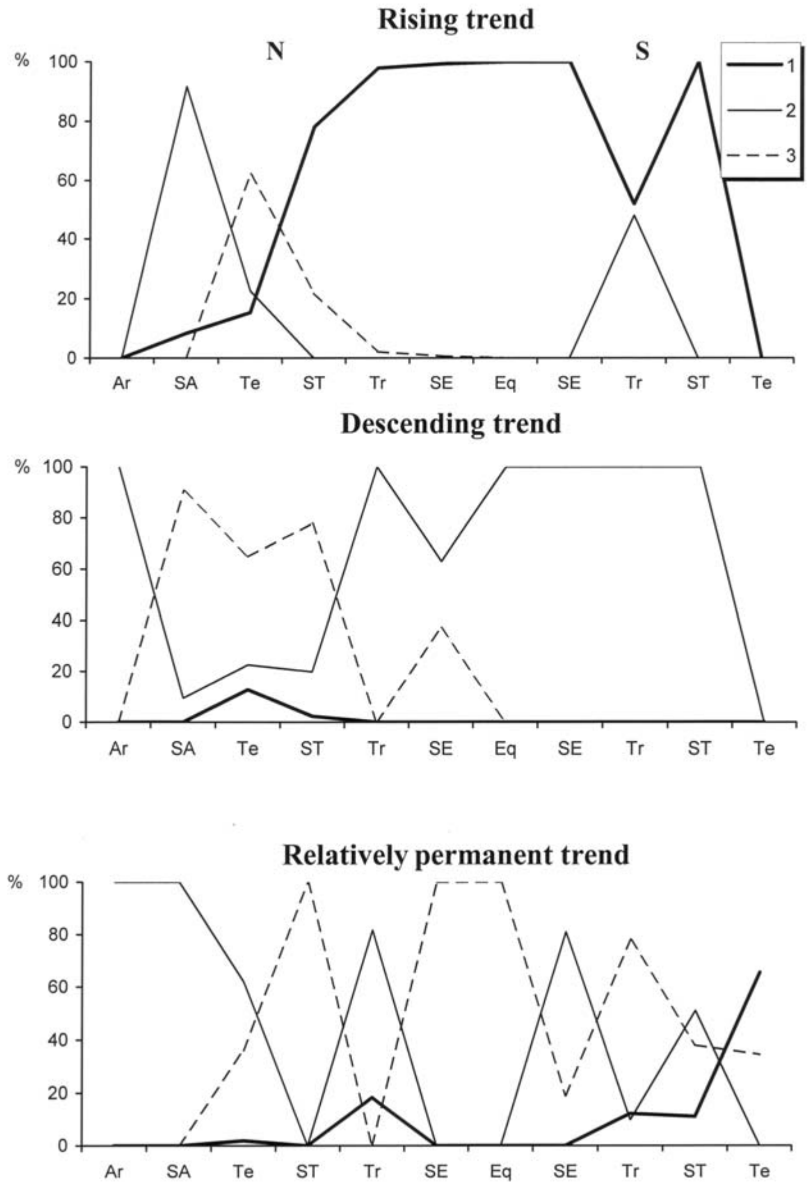

Fig. 2 Factor structure of areas with different trends of erosion intensity and suspended sediment yield changes on the Earth during the second half of the 20th century. *Factors*: 1, anthropogenic; 2, hydro-climatic; 3, relative anthropogenic–hydro-climatic. *Climatic zones*: Ar, arctic; SA, subarctic; Te, temperate; ST, subtropical; Tr, tropical; SE, subequatorial; Eq, equatorial.

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