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Long-term variations in mean erosion and sediment yield from the rivers of the former Soviet Union

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Abstract Annual sediment yield data from the rivers of the former Soviet Union (FSU) are analysed. Assessments of variations in water erosion from slopes, sediment concentration and sediment yield are made on the basis of a hydromorphological method developed previously by the author. Trends in water discharge, sediment yield and sediment concentrations in rivers have been analysed. These trends are shown in new maps of sediment concentrations in rivers of the FSU. The map scales are: 1:2 500 000; 1:10 000 000 and 1:25 000 000. Changes in climate characteristics and anthropogenic effects give rise to a non-stationarity in the observation series for suspended sediment yield.

INTRODUCTION

A schematic map of regions with major temporal trends in sediment yield (expressed as a percentage of the total number of observation series showing significant trends) makes it possible to identify vast areas of the former Soviet Union (FSU) with non-stationary sediment yield regimes (Bobrovitskaya, 1994). This emphasizes the need to produce a more detailed map showing the areal distribution of various trends in sediment yield and a new map of sediment concentrations in rivers.

The first map of sediment concentrations in the rivers of the USSR was prepared in 1939 by G. V. Lopatin for the European USSR (Lopatin, 1939). In 1949 G. I. Shamov published the first map of sediment concentrations in the rivers of the entire USSR (Shamov, 1949). That map has since been improved several times (Lopatin, 1952). Many authors prepared a set of regional maps published in *Surface Water Resources*; and in 1972 these maps were generalized by K. N. Lisitsyna. The scale of that map was 1:10 000 000.

Numerous studies have attempted to establish the relationship between sediment concentration and various physiographic and anthropogenic factors (e.g. Poliakov, 1946; Glushkov, 1961; Lisitsyna & Aleksandrova, 1972; Bobrovitskaya, 1972; Shamov, 1954; Makkaveev, 1955; 1984). None of these studies considered non-stationarity of the observation series. An attempt is made in this paper to prepare a new map of sediment concentrations with particular reference to the trends in sediment yield variations.

DATA SOURCES

A large amount of network observation data, including water discharge, sediment concentrations and sediment yield from slopes and from small, intermediate and large rivers have been used by the author. Data from 2800 stations for sediment yield measurements and from 3000 stations for water discharge measurements have been assembled. The duration of the observation series on sediment concentrations varies between one and 52 years; the durations of the water discharge series are 100 years and longer. The author has created a database of annual sediment yields and the factors which influence this yield, and a special archive of air photographs has been produced for the assessment of erosion from slopes.

ASSESSMENT OF TRENDS IN SEDIMENT YIELD AND SEDIMENT CONCENTRATIONS

The method applied involves hydrological, morphological and statistical analyses of the observation series on sediment yield or sediment concentrations in rivers and analysis of the factors associated with anthropogenic impact (Bobrovitskaya, 1994).

The Kolyma River at Ust-Srednekamsk may be considered as a case study. The basin area is 99 400 km^2. Water discharge and sediment yield measurements were initiated in 1941 and are still continuing without gaps. Analysis of the long-term record of water discharge variations shows that runoff in the Kolyma River is subject to variations when a number of dry years and wet years follow in succession (Fig. 1(a)). Since 1965, a gradual increase in sediment concentrations and sediment yield has been observed, although the years with high and low values of sediment concentration and yield and water discharge in general coincide. Evidence of higher sediment concentrations and higher sediment yield is also observed in their cumulative curves, although the cumulative water discharge curve shows no change (Fig. 1(b)).

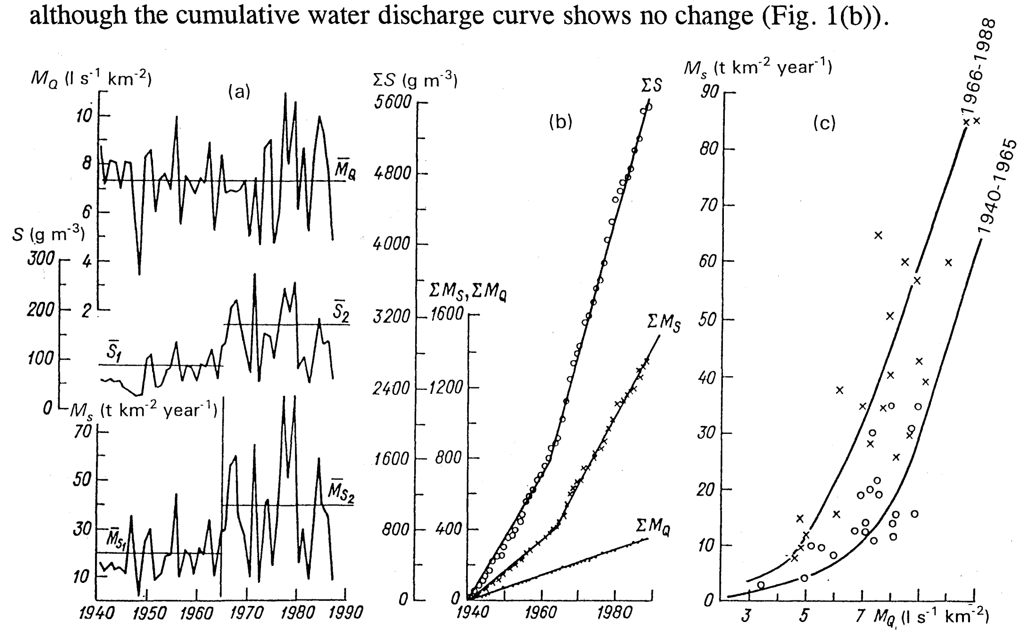

Fig. 1 The Kolyma River at Ust-Srednekansk: (a) chronological graph of variations in annual water discharge (M_Q, sediment yield (M_s) and sediment concentration (S); (b) integral curves of annual water discharge (M_Q), sediment yield (M_s) and sediment concentration (S); (c) Dependence of specific sediment yield (M_s) upon specific water discharge (M_Q).

The relationship between annual sediment yield and annual water discharge can be subdivided into two periods, the first curve for the period 1941-1965, and the second curve for the period 1966-1988 (Fig. 1(c)). A comparison of mean sediment concentrations for those periods shows that sediment concentrations and sediment yield during the second period increased by 104%. A more detailed assessment of the stationarity of the sediment yield and sediment concentration series showed significant differences both for average values and for variances. Among the anthropogenic factors affecting the sediment yield of the Kolyma River, gold mining is important because the surface soils are removed over large areas thus producing conditions for intensive erosion.

This scheme of analysis has been applied to the data from all stations in Russian and adjacent countries. Field surveys and aerial observations by the author, airborne and satellite imagery, data from the soil resources survey and other information have also been used in the analysis.

METHODOLOGY FOR A COMPILATION OF SEDIMENT CONCENTRATION MAPS

In the case of irreversible changes in the conditions affecting sediment concentrations in river basins, it is recommended that the value of sediment concentration obtained for a relatively uniform period should be used. The conditions leading to irreversible changes in sediment yield, however, are not well-established in hydrology. For example, even in the case of reservoir construction, the reservoir may eventually silt up and sediment transport through the reservoir will be resumed. Thus after a long period of time the sediment yield may be similar to the natural level. Irreversible changes may probably only be observed in the case of small river channels filled by soils eroded from basin slopes and in the case of complete blocking of these channels.

During the preparation of a new map of sediment concentrations it was decided to map mean annual values of sediment concentration in intermediate-sized rivers for a long-term period; it was also decided to indicate trends by a conventional sign. Station distribution in terms of the basin area was as follows: rivers with drainage areas less than 100 km^2, 11%; with drainage areas from 100 to 500 km^2, 21%; and 500-100 000 km^2, 61%. About 7% of the stations were on large rivers.

Analysis of the mean square root errors of sediment yield values as a function of the duration of the series shows that in 82% of cases this is less than 30% if the observation series is 10 years or longer. This is quite sufficient with the existing accuracy of sediment yield measurements. Therefore, in the compilation of new maps of sediment concentration at the scales of 1:2 500 000 and 1:10 000 000, data from stations with observation series of 10 years and longer were used. Shorter series were used as supplementary data.

Sixteen sheets of the map (scale 1:2 500 000) present information on the hydrological stations where sediment concentrations and sediment yield have been observed. The number of the stations, the mean annual sediment concentration in the river and the percentage sediment yield change presented as a fraction numerator (with a plus or a minus sign depending on the trend) based on a comparison of the period of anthropogenic impact (if discovered) with the previous period when the impact was not observed,

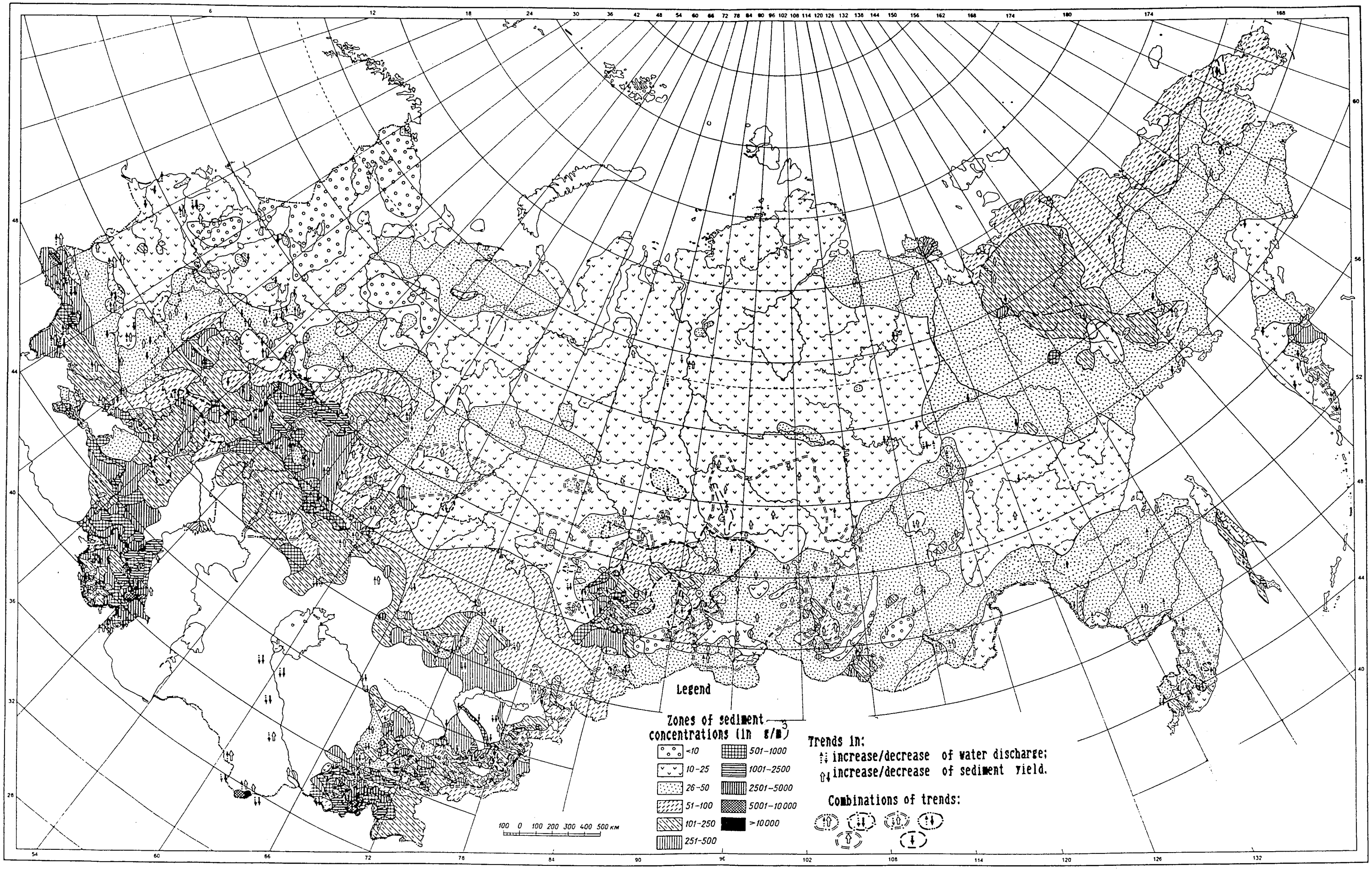

Fig. 2 Mean annual sediment concentration of rivers in Russia and the CIS.

and with the percentage water discharge change for the same period shown as the denominator, are shown.

The following symbols are also used: arrows show increase or decrease in sediment yield and different colours are used for the 11 zones of sediment concentrations, as well as for the anthropogenic factors greatly affecting sediment yield and sediment concentrations. Large zones with consistent uni-directional changes in sediment concentration and yield are identified on the map. If increases in sediment concentration and yield alternate with decreases in some areas, arrows are used at each station to indicate increase or decrease of these values, respectively. In the case of mineral deposit mining, only those areas which may cause changes in sediment concentration, sediment yield and water discharge are shown. This mainly involves gold mining and excavation of precious metals, oil, gas and diamonds. On the basis of the 1:2 500 000 scale map, a map of scale 1:10 000 000 scale has been prepared. A variant of this map (reduced several times) is shown in Fig. 2. Only sediment concentrations and trends in water and suspended sediment discharges are shown on this map, because it is very small.

SPATIAL VARIATION OF ZONES OF SEDIMENT CONCENTRATIONS IN THE RIVERS OF RUSSIA AND IN THE RIVERS OF ADJACENT COUNTRIES

Mean sediment concentrations for the rivers of Russia cover a wide range, from less than 10 g m^{-3} up to more than 10 000 g m^{-3}. In general, sediment concentrations within the range 25-100 g m^{-3} are most often observed in the rivers of Russia.

The zone of sediment concentrations < 10 g m^{-3} is located on the Kola Peninsula and in Karelia in the tundra and forest tundra; in the upper reaches of the Mezen, Pinega and part of the northern Dvina rivers and in the upper reaches of the Abakan River in the forest zone; and within the drainage area of Lake Teletskoje. In the basins of small marshland rivers with numerous lakes, the sediment concentration ($S_{small\ riv}$) tends to decrease to 1 g m^{-3}. In the areas where mineral deposits are excavated, (e.g. nickel ores) sediment concentrations tend to increase up to 38 g m^{-3} ($K_{min} = S_{small\ riv}/S_{zone} = 0.4$; $K_{max} = S_{small\ riv}/S_{zone} = 7.8$).

The zone of sediment concentrations within the range 10-25 g m^{-3} covers most of the east European plain, and the west Siberian and Yan-Indigirka lowlands in the tundra and forest zones; the upper reaches of the Kolyma River, the Indigirka River basin and tributaries of the middle and lower Ob River reaches; and northern and western areas of Kamchatka. In the basins of small rivers with swamps and lakes the concentration of sediments tends to decrease to 1 g m^{-3}, whereas in the zones with oil and gas deposits or gold mining and at sites of new settlement construction the sediment concentration can increase to 270 g m^{-3} ($K_{min} = S_{small\ riv}/S_{zone} = 0.1$ and $K_{max} = S_{small\ riv}/S_{zone} = 15.4$). Several large rivers flow across this zone and sediment concentrations in these rivers (e.g. in the Irtysh River) can reach 160 g m^{-3}.

The zone with sediment concentrations within the range 26-50 g m^{-3} is found on the Smolensk-Moscow and mid-Russian uplands and the Klin-Dmitrov ridge in the forest and forest-steppe zones; on the lower right bank area of the northern Dvina basin and in the mid and lower Pechora River basin in the tundra and forest zones; in the upper reaches of the Yrtysh River in the Urals; in the rivers of Shoria, Bijsk griva and part of the Kuznetsk Alatau; in the upper reaches of the Yenisei and Lena rivers, and in the trans-Baikal region; and in parts of the rivers of the Far East, Kamchatka and Sakhalin. In marshy forested basins of small rivers the sediment concentration tends to decrease to 4 g m^{-3} (K_{min} = 0.10). At gold mining sites, however, it increases up to 692 g m^{-3} (K_{max} = 18.2). The concentration of sediment in the rivers flowing across this zone is higher than in the zone and a value of 93 g m^{-3} is found in the Pechora River (K_{max} = 2.4).

Higher sediment concentrations (51-100 g m^{-3}) are found in the southern mid-Russian upland, in the Privolzhskaya upland, in Chukotka and in intermediate-sized tundra rivers discharging to the east Siberian Sea.

The zone of sediment concentrations within the range 100-200 g m^{-3} occurs in the lower Don River, in the southeastern part of the Volga basin and on the steppes of the Altai region. Intensive erosion of lowlands and gullies in small basins results in sediment concentrations up to 1500 g m^{-3} (K_{min} = 1.0; K_{max} = 10). In the Yana River basin (at Verkhoyansk), in some areas of the Privolzhskaya upland of the forest-steppe zone, in the southern Urals, in the Stavropol region, in some parts of the Altai region and in the Kuban basin the sediment concentration ranges from 251 to 500 g m^{-3}.

Higher sediment concentrations (501-1000 g m^{-3}) are observed in the northwestern Privolzhskaya upland, in some parts of the Altai region (in the Alej and Kuchuk rivers, and on the left shore of the Novosibirsk reservoir), in some areas of the Kuban basin and in most of the rivers discharging to the Caspian Sea. The existence of these high sediment concentrations can be accounted for both by geomorphological factors and by the intensive agricultural practices on basin slopes.

The highest sediment concentrations in Russian rivers are observed in the northern Caucasus, these are 1001-2500 g m^{-3}, 2501-5000 g m^{-3}, 5001-10 000 g m^{-3} and even higher.

Low sediment concentrations (10-25 g m^{-3}) are observed in the rivers of Estonia, Lithuania, Latvia, Belarus and northern Ukraine. This is explained by the flat topography, by the swamp and forest terrain, and by coarse soils. In some cases, however, when the slopes of small river basins are ploughed intensively, the sediment concentrations can increase up to 50-100 g m^{-3}. In the forest-steppe zone of the Ukraine, sediment concentrations are in the range 26-50 g m^{-3}, although they tend to be higher in the lower Dnieper reaches (up to 100-250 g m^{-3}). In the Carpathian mountains, the concentration of sediment is not high and values lie in the range 50-500 g m^{-3}. In the rivers of the Volyno-Podolsk upland, the sediment concentration ranges from 250 to 500 g m^{-3}.

The physiography of the Caucasus is quite variable. Sediment conditions are therefore also variable. In the rivers of Georgia, sediment concentrations vary within the range 80-1450 g m^{-3}, in Armenia they are within the range 19-760 g m^{-3}, and in Azerbaijan they vary from 54 to 9190 g m^{-3}.

On the flat steppes of Kazakhstan, the sediment concentrations fall within the range 100-250 g m^{-3} and tend to increase up to 250-500 g m^{-3} in the case of hummocky topography. In the Nura River basin the sediment concentration decreases to 25-50 g m^{-3}. The maximum concentration of sediment is observed in the Kargala River basin (semi-desert zone).

Over most of the Kirgizia territory, the sediment concentrations range between 100 and 250 g m^{-3}. The lowest values (10-25 g m^{-3}) are observed in the southeastern part of

Lake Issyk-Kul, and the highest values were found in the Toktogulskoje reservoir (more than 1000 g m^{-3}).

In Uzbekistan, the lowest sediment concentrations are observed in the Chardarinskoje reservoir basin (10-13 g m^{-3}). On the plain and piedmont areas these concentrations range between 25 and 250 g m^{-3}. In the Karatau region, they vary within 250 and 500 g m^{-3}, and in the mountain areas the sediment concentrations increase up to 5200 g m^{-3}.

The maximum sediment concentrations in the adjacent countries are observed in Turkmenia, i.e. 54 000 g m^{-3} in the Kushke River, and 76 000 g m^{-3} in the Murgab River.

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