Modelling Soil Erosion, Sediment Transport and Closely Related Hydrological Processes (Proceedings of a symposium held at Vienna, July 1998). IAHS Publ. no. 249, 1998.

Application of formulae of transporting flow capacity for the computation of suspended sediment in the Lena River

NELLY N. BOBROVITSKAYA & CLAUDIA M. ZUBKOVA

State Hydrological Institute, 23 Second Line, 199053 St Petersburg, Russia

Abstract Different theoretical and empirical formulae of the transporting capacity of flow are analysed. A possible use of some of these formulae is studied for computation of suspended sediment yield in the Lena River, which is one of the largest rivers in the world. Its basin is located within the Siberian platform, and the Baikal and Verkhoyansk-Kolyma mountain folded areas. It embraces the zones of Arctic wilderness tundra, forest-tundra and taiga. According to the nature of flow, the Lena River is subdivided into three parts: upper part (1690 km long)—from the head up to the confluence with the Vitim River; middle part (1400 km long) from the Vitim River confluence up to the Aldan River confluence; and the lower part (1310 km)—from the Aldan River confluence up to Stolb Island. Water discharges have been measured here since 1925 and sediment yield has been measured since 1936–1940 in the framework of the Roshydromet system. The analysis made by the authors shows that average annual sediment concentration for a long-term period along the river length varies only slightly, i.e. from 31 to 39 g m^{-3}. The suspended sediment yield is shown to be as follows: at the end of the first part it equals 44 kg s^{-1}; in the middle part it is 220–240 kg s^{-1} and in the mouth it equals 630 kg s^{-1}. Sediment yield from the basins of small rivers and from bank erosion cause the increase of sediment yield down the Lena River. Sediment concentration on the swamped basins varies from 2 to 10 g m^{-3} under natural conditions; 50–60 g m^{-3} on hilly terrain; to 80–100 g m^{-3} or more in gold mining areas. The low sediment concentration in the Lena River and in its tributaries is explained by the permafrost areas, and by forested and swamp areas. When the top cover is disturbed, gullies develop quite intensively, causing soil scour and a greater sediment concentration in the rivers. A simple empirical formula has been proposed to compute sediment concentration. The parameters of this formula depend on the phases of the hydrological river regime.

INTRODUCTION

Up till now methods of computing average annual values of sediment yield have been mostly developed (e.g. Lisitsyna & Aleksandrova, 1972; Bobrovitskaya, 1972). Methods of assessing sediment yield for short time intervals, in particular, instantaneous or daily values have been developed but to a lesser degree. This is explained by the greater variability of river sediment concentration and yield for time periods shorter than a year. Therefore, for computation a large amount of initial information which is generally missed is required. It is especially difficult to obtain information about river sediment yield in the northern regions of Russia. The authors have analysed long-term variations in sediment yield of the Lena River and made an attempt to compute daily water sediment concentrations using formulae for flow transporting capacity with hydrology phases taken into account.

DATA SOURCES

The Roshydromet observation data from 61 gauges on water discharge and suspended sediment have been used in the paper. Gauges with observations on suspended sediment for 20 or more years are shown in Fig. 1.

ANALYSIS OF SUSPENDED SEDIMENT YIELD FORMATION IN THE LENA RIVER BASIN

The territory observed belongs mostly to three of the largest tectonic structures of east Siberia: Siberian platform, Baikal and Upper-Kolyma folded mountain regions. The Siberian platform comprises tablelands, stratum plateaus and plains. The Baikal and Verkhoyansk-Kolyma regions are characterized by mountains developed from considerably metamorphosed Palaeozoic rocks and predominantly Mesozoic folding, respectively. Within the Upper Kolyma region, lowlands are widespread.

The climate of the Lena basin is extremely continental. During the winter period the air temperature drops to between –50 and –60°C, and in summer it rises to 20–30°C. The temperature difference between the coldest and warmest months reaches 45–65°C, which corresponds to the world maximum. Annual precipitation varies from 200–250 mm on the Laptev Sea coast to 1000 mm in the mountains in the southern part of the Lena basin.

In the central Yakutia lowland 250–300 mm rainfall occurs, mostly during the warm period each year. Winter precipitation is about 20% of the annual value. Snow cover is preserved for 7–8 months.

Soil cover formation takes place in the conditions of a very complicated relief, extreme continental climate, and shallow permafrost. In the mountain tundra belt, soil cover is represented by a thin layer of mountainous-tundra, peat-hydromorphic, and gley peat-hydromorphic soils, and in the forest belt by mountainous-taiga peat soils. On mountain peaks rock soils are typical. Tundra soils are thin, significantly moist and slightly humified. Taiga soils are characterized by a different content of podzolic soils, low moisture, higher salinity and are comparatively highly fertile. Alluvial soils cover the flood terraces of the Rivers Lena, Viluy, Indigirka, Vitim, and Kalara.

Within the Lena basin four geobotanic zones are identified: the Arctic rock wilderness zone covering the islands of De Long and Anzhu as well as upper parts of mountain areas; the tundra zone covering the Islands of Bolshoy Lyakhovsky, Maly Lyakhovsky, Stolbovoy, and a narrow coastal stripe of north Yakutia; the zone of forest-tundra representing a narrow transitional stripe from the tundra zone to the taiga zone; the taiga zone which covers 75% of the Lena basin.

River runoff in the study area is mainly formed during the warm period each year (75–95%). River floods start in the southern part of the basin in late April–early May, and in the northern part in late May–early June. The flood duration on most of the rivers is 35–40 days. About 20–30% of spring flood is formed due to liquid precipitation. In mountainous regions melting ice contributes to the flood.

The greater part of annual sediment yield (80–100%) is formed during the spring–summer (spring) period. During the winter period water sediment concentration and yield are close to zero.

Fig. 1 Hydrological stations in the Lena River basin with observation periods for sediment concentration of over 20 years.

Permafrost greatly affects the development of fluvial processes. Frozen soils and subsoils are washed out with great difficulty, however, under water and rising temperatures banks are intensively washed out, especially during the drifting of ice.

The layer of summer soil and subsoil melting is highly variable and varies from 0.5 to 5 m deep. Subsurface ice and water over ice are widespread. Permafrost impedes the development of gullies. But any disturbance in the vegetation and soil cover results in the fast development of gullies, particularly during the storm rainfall. Where permafrost is close to the surface there is a rapid saturation by water of an active layer. Further moisture inflow turns then washes away the melted (diluted) upper soil layer. This factor is the main cause of increasing river water sediment concentration during the flood and high-water periods. Soil washing out results in degradation of the ploughed areas. In the southern part of the Lena basin, washed out soils amount to 20% of ploughed fields. However, sediment income to rivers is insignificant, as on the plain areas which have gentle slopes there are many lake hollows where sediments accumulate. Swamps and lakes cover up to 10% of the area.

Thus, the main factors that promote the formation of low sediment concentrations in the Lena basin are permafrost, forested and swamp areas, lakes and only a small amount of agricultural cultivation.

LONG-TERM VARIATIONS IN RIVER SUSPENDED SEDIMENT YIELD AND CONCENTRATION

To study long-term sediment yield in the Lena basin, the observation records at 16

Table 1 Statistical parameters of observed average annual runoff in the Lena River basin.

Code	River—station	Area (km^2)	Period	N	Runoff ($l\ s^{-1}\ km^{-2}$)	Water discharge ($m^3\ s^{-1}$)	C_v	C_s
03005	Lena—Gruznovka	41 700	1922–1975	54	4.60	192	0.27	0.66
03021	Lena—Zmeinovo	140 000	1936–1975	40	8.08	1130	0.15	-0.31
03036	Lena—Solyanka	770 000	1933–1996	64	8.76	6740	0.16	0.37
03042	Lena—Tabaga	897 000	1927–1994	68	8.76	7860	0.16	0.23
03821	Lena—Kjusjur	2 430 000	1935–1987	53	6.78	16 480	0.11	0.15
03065	Tutura—Grechova	7100	1936–1975	40	5.01	35.6	0.26	0.39
03087	Kirenga—Shorokhovo	46 500	1927–1975	49	14.0	651	0.14	-0.22
03106	Vitim—Bodaibo	186 000	1925–1975	51	8.17	1520	0.22	0.11
03202	Namana—Myakinda	16 600	1945–1987	43	1.80	29.9	0.44	0.76
03210	Buotana—Brolog	12 200	1935–1987	53	3.32	40.5	0.33	0.36
03219	Aldan—Tommot	49 500	1926–1987	61	10.4	515	0.19	0.02
03225	Aldan—Okhotskiy Perevoz	514 000	1927–1996	64	8.25	4240	0.18	0.08
03229	Aldan—GMS Verkhoyanskiy Perevoz	696 000	1942–1987	46	7.73	5380	0.15	0.08
03246	Timpton—Nagornyi	613	1926–1987	56	15.5	9.5	0.26	0.47
03321	Viluy—Suntar	202 000	1927–1987	60	3.71	749	0.27	0.37
03329	Viluy—Khatyryk-Khomo	452 000	1935–1987	52	3.16	1430	0.27	0.68

N = number of years;

C_v and C_s are coefficients of variation and skewness respectively.

stations for over 20 years were used (Fig. 1). Unfortunately, in spite of the fact that observations of sediment concentration were started in 1936–1940, the observation series for most rivers have many gaps. Statistical parameters of the series of runoff and sediment yields are given in Tables 1 and 2.

The average water discharges in the rivers of the Lena basin varies from 29.9 to 16 480 $m^3 s^{-1}$. Average long-term sediment concentration changes along the river length is insignificant as sediment yield rises almost proportionally to increasing water discharge. Sediment yield from the basins of small rivers and bank erosion cause the increase of sediment yield down the Lena River. Sediment concentration on the swamped basins varies from 2 to 10 g m^{-3} under natural conditions; it equals 50–60 g m^{-3} on hilly terrain; but it may vary from 80 to 100 g m^{-3} and more in gold mining areas.

An analysis of the sediment concentration map shows that in the Lena basin three zones of sediment concentration are formed: <10 g m^{-3}, 25–50 g m^{-3}, and 50–100 g m^{-3} (Bobrovitskaya, 1996). A low sediment concentration in the Lena River and in its tributaries is explained by the permafrost areas in its basin, and by forested and swamped areas, too. When the top cover is disturbed, gullies develop quite intensively, causing soil scour and greater sediment concentration in rivers.

The characteristic feature of long-term variations in water discharge in the Lena basin is a prolonged period of rise since 1938 to 1982 (Fig. 2). In this period one can

Table 2 Statistical parameters of observed average annual suspended sediment yield in the Lena River basin.

River—station	Area (km^2)	Period	N	Sediment concentration (g m^{-3})	Suspended sediment discharge (kg s^{-1})	Suspended sediment yield (t km^{-2} $year^{-1}$)	C_v	C_s
Lena—Gruznovka	41 700	1940–1975	28	38	7.3	5.52	0.52	1.21
Lena—Zmeinovo	140 000	1941–1975	23	39	44	9.91	0.58	0.87
Lena—Solyanka	770 000	1956–1987	20	33	220	9.01	0.58	1.37
Lena—Tabaga	897 000	1942–1987	30	31	240	8.44	0.57	0.84
Lena—Kjusjur	2 430 000	1960–1987	20	38	630	8.18	0.44	0.90
Tutura—Grechova	7100	1950–1975	25	26	0.92	4.09	0.48	0.27
Kirenga—Shorokhovo	46 500	1949–1975	26	12	7.8	5.29	0.28	0.21
Vitim—Bodaibo	186 000	1941–1975	20	38	58	9.83	0.47	0.59
Namana—Myakinda	16 600	1965–1987	20	82	2.4	4.60	0.78	0.23
Buotana—Brolog	12 200	1962–1987	23	20	0.81	2.09	1.17	2.30
Aldan—Tommot	49 500	1943–1987	24	39	20	12.7	1.81	2.88
Aldan—Okhotskiy Perevoz	514 000	1943–1987	22	27	110	6.74	0.37	-0.05
Aldan—GMS Verkhoyanskiy Perevoz	696 000	1962–1987	20	37	200	9.06	0.40	0.40
Timpton—Nagornyi	613	1964–1987	20	4	0.038	1.95	0.70	1.23
Viluy—Suntar	202 000	1964–1987	24	8	6.0	0.94	0.57	0.59
Viluy—Khatyryk-Khomo	452 000	1961–1987	20	32	46	3.21	0.50	0.41

N = number of years;

C_v and C_s are coefficients of variation and skewness respectively.

identify the following shorter cycles: 1938–1954; 1955–1972; 1973–1986. The period of 1938 to 1982 can be assumed to be part of a longer cycle of about 90 years in duration. Checking observation series on stationarity (Bobrovitskaya, 1996) shows that non-stationarity of observation by average values of water discharge and variance is traced, as a rule, for cycles separated in time. For instance, these periods for Lena–Tabaga are 1938–1954 and 1973–1986. Variations in suspended sediment yield are, as a rule, synchronous with those of water discharge. However, the coefficients of variations in sediment yield are 1.5–2.0 times higher than those of water discharge (Table 2).

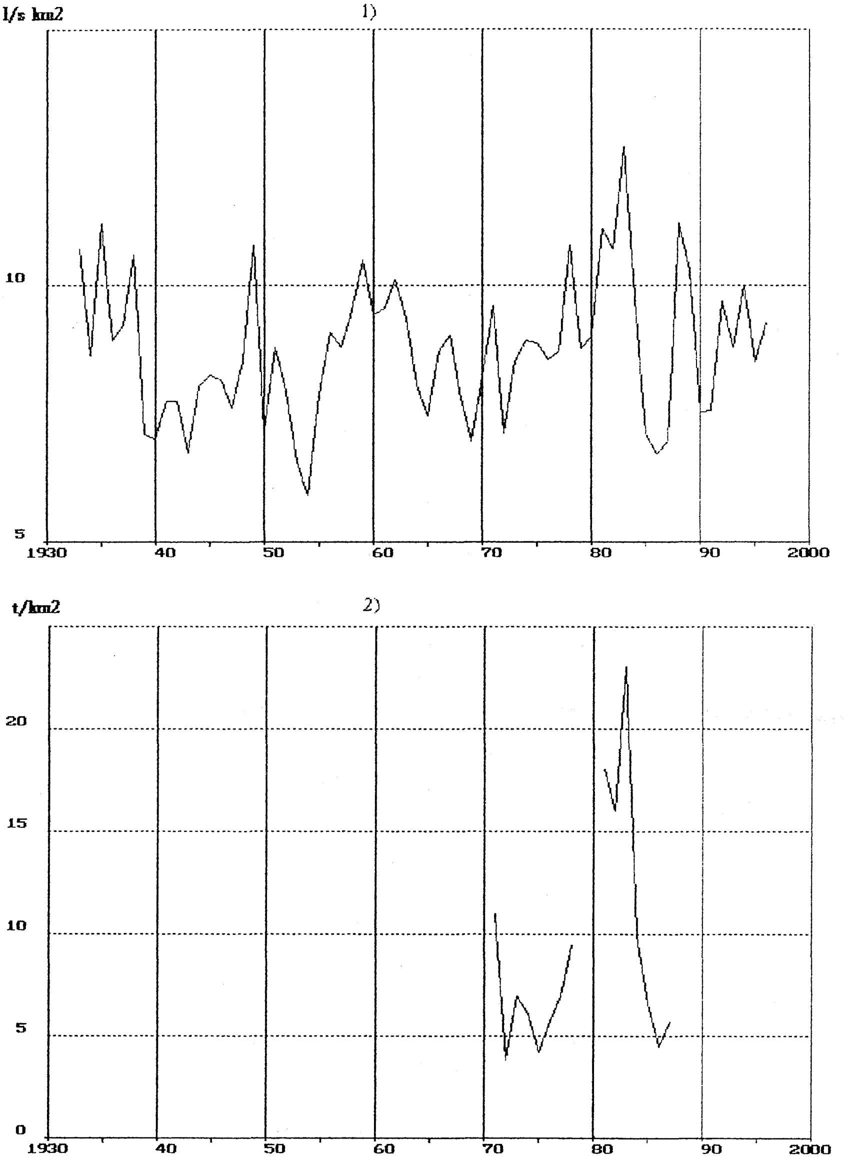

Fig. 2 Long-term variations in annual runoff (l s^{-1} km^{-2}) and suspended sediment yield (t km^{-2}) for the Lena River at Solyanka.

APPLICATION OF TRANSPORTING CAPACITY FORMULAE FOR THE COMPUTATION OF SUSPENDED SEDIMENT YIELD FROM RIVERS

The problems of computing instantaneous and average daily river sediment concentration are filling gaps in the concentration measurement records and computing concentrations for less studied or unstudied rivers. The authors have analysed the different formulae for the transporting flow capacity for the computation of sediment concentration and sediment yield in the Lena basin. The formulae by

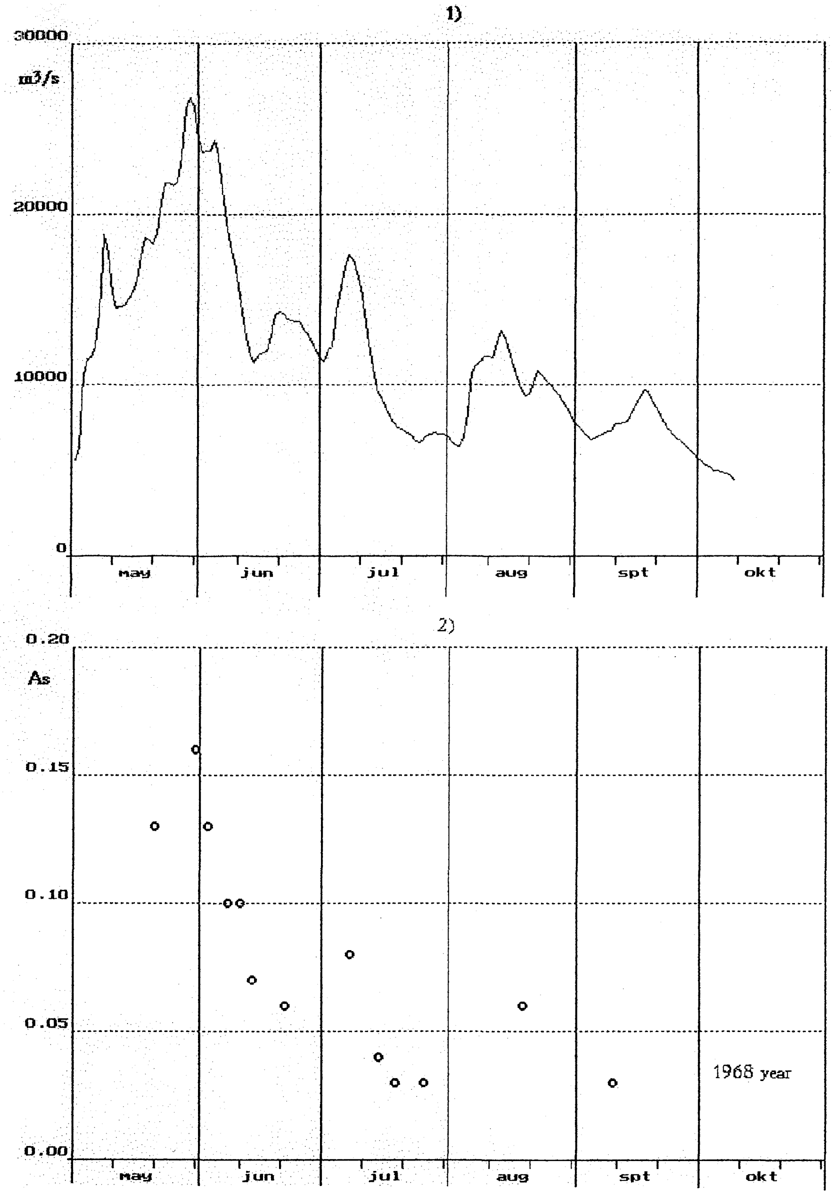

Fig. 3 Chronological variations of daily water discharge (1) and correction coefficients (2) for the Lena River at Solyanka.

Zamarin (1951), Gostunsky (1954), Karaushev (1960) were considered. Analysis has shown that under the lack of information the best results are provided using the empirical formula by Bobrovitskaya & Zubkova (1997):

$$S = A_s V^3 / H \tag{1}$$

where S is sediment concentration (g m^{-3}); V is current velocity (m^3 s^{-1}; H is depth (m). Coefficient A_s is calculated by a reversed way according to measured values of sediment concentration, current velocity and flow depth. Then this coefficient is depicted as a table. Coefficient A_s is a combined correcting coefficient whose values depend on the conditions of sediment concentration formation in a river catchment for a certain site, hydrological phases, and hydrograph shape. An analysis of A_s for the Lena River shows that values range from 0.03 to 1.0 depending on hydrological phases, and differ by comparatively permanent values for every site (Fig. 3, Table 3).

Table 3 The values of coefficient A_s for the Lena River at Solyanka and Tabaga.

River stage	Solyanka	Tabaga
Snowmelt flood. Wave 1		
Rising + peak	0.10–0.15	0.4–1.0
Falling	0.15–0.05	0.6–0.25
Wave 2:		
Rising + peak	0.10–0.20	0.38–0.26
Falling	0.10–0.05	0.38–0.12
Low	0.05–0.03	0.12–0.24
Summer-autumn rain flood	0.05–0.10	0.20–0.28

CONCLUSION

An analysis of water discharge formation, water suspended sediment concentration and sediment yield in the Lena River reveals a variability of these characteristics in time and space. Applying formulae for river transporting capacity with the correcting coefficient whose values depend on the hydrological phase allows the instantaneous computation of average sediment concentrations and suspended sediment yield with an accuracy adequate for hydrological practice.

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