# SUSPENDED SEDIMENT YIELD MAPPING OF NORTHERN EURASIA

**Comment [M1]:** Check the entire file to ensure that our revisions retained all of your intended ideas.

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## Abstract

Mapping of river sediment yield in a global and semi-global scale involves a number of technical difficulties, which are mostly unresolved until now. These maps show the large zonal peculiarities of river sediment yield, as well as level (smoothened) local anomalies. The techniques to design a map on river sediment yield in North Eurasia (within the boundaries of the former Soviet Union $22*10^6$ $km^2$) at a scale of 1:1,500,000 were developed in this study. The source data for the map design were taken from long-term observations in more than 1,000 hydrological stations of Roshydromet complex. These data were collected by a single method mostly during the 20th century. Data on the average area basins (10–100 thousand $km^2$) were used to design the map. The selection of watershed boundary lines that limit river catchments, the calculation of morphometric characteristics of relief, and the assessment of landscape peculiarities on river basin surfaces with remote sensing data were performed on the basis of geographic information system technologies. Using thematic maps and databases (climatic, meteorological, hydrological, geological, soil, etc.) expands the range of analyzed factors, quantifies their contributions, and shows their effects on the developed map in a common view. The creation of this map is a major step in enhancing knowledge of global processes on the mechanical denudation of land, mainly erosion, on the basis of studies on river sediment yield.

**Key words**: suspended sediment yield; GIS; thematic map; watershed boundaries; Northern Eurasia

## Introduction

Mapping of river suspended sediment yield is one of the most significant challenges in the fields of hydrology and geomorphology. This problem, which has yet to be resolved, is attributed to the sparse networks of hydrological stations that systematically observe sediment yield. Interpolation of sediment yield values for unexplored river basins is required. Sediment yield and catchment area have a complex relationship, which requires a careful approach in selecting basins in designing the map. Another challenge is the large number of sediment yield indicators. Each of these indicators can be potentially used for mapping. Furthermore, the discrete nature of sediment yield is necessary for mapping. The sharp volatility within the borders of neighboring catchments limits the number of possible methods to cartographically represent this phenomenon.

Mapping attempts, in which river basins served as territorial units, were performed in the eastern part of the Russian Plain. For example, the following aspects of the study area were investigated: examining the calculated values of the suspended sediment yield in the basins of small rivers with a mathematical–statistical model of the sediment yield, building the map on the spread of the sediment yield, and analyzing the spatial trends of the suspended sediment yield in the basins of small rivers. The areas of study were within the forests, forest steppes, and northern part of the steppe landscape of the Russian Plain, which spans more than 130 thousand $km^2$. The calculated values of the sediment yield module for each of the 3,331 basins of the examined territory were calculated by Yermolaev (2013).
SSY mapping of the Volga River basin was performed with the use of GIS technologies. The total area covered by the study was 757 thousand $km^2$ , which extended 1,000 km from east to west and 1,500 km from north to south, including 110 river basins. SSY mapping involved 53% of the total area of the Volga basin. As a result, the maps on the suspended sediment yield in landscape zones included areas of taiga, mixed, and broadleaf forests; forest steppes; steppes; and semi-deserts in the studies of Maltsev et al. (2012), Yermolaev (2014), and Yermolaev et al. (2012).

**Comment [M2]:** Verify if this is what you mean.

## Methods

The long-term observations served as the source of data to map suspended sediment yield at a scale of 1:1, 500, 000 in the territory of Northern Eurasia (within the former Soviet Union, this territory comprises 22, $402*10^6$ $km^2$). Data collected from more than 1,000 Roshydromet stations and hydrological stations were utilized. These data were obtained during the 20th century with the use of a single method. Riverbed sediment yield was not considered because of the exceptive approximation of its natural definition. Observations mainly covered the European part of the former USSR (3.96 $10^6$ $km^2$), which accounts for almost 60% of the hydrological stations. The average long-term values of sediment yield, *r*, were used when the original data set was processed. These values were expressed in t/$km^2$ $year^{-1}$:

$$r = (R/S) \cdot 31{,}5 \cdot 10^3 , \quad (1)$$

where *r* is the sediment discharge in kg/s, and S is the river catchment area in $km^2$.

This indicator allows the comparison of the hydrological characteristics of different basin areas in common bases. *r* was calculated with an accuracy of up to two decimal places. Doing so is considered adequate because of the relatively low accuracy rate standard (about 8%–10%) in determining suspended sediment (Dedkov & Mozzherin, 1984).

A number of hydrological stations operated from 1940 to 1970. For at least 10 years, these stations were used to process observations on suspended sediment yield. This period is adequate to obtain statistically reliable values of suspended sediment yield. The yield standard (value of the suspended sediment yield) shows good stability over time. Consequently, the map is still useful even if it was developed on the basis of 50-year-old materials. In our opinion, the map reflects the fundamental laws of spatial distribution concerning suspended sediment yield in this large area of the planet with varied landscape conditions.

The boundaries of the catchment basin were determined for each hydrological station, and the data of these stations were used in the mapping study. The entire set of geographic and attribute data was edited in a geographic information database.

The techniques in the automated identification of drainage basin boundaries and their implementing technologies affect the development of geoinformation databases, and they are used as operational-territorial units. Information on water and sediment yield is also obtained from these techniques. At present, identifying the drainage basin boundaries of GIS technology development for large areas is productive in automatic mode, with digital terrain models and vector maps of hydrographic network used as initial data. Several software programs (commercial and free ones), which allow the delineation of build catchment area boundaries in automatic mode, are «ArcGIS», «GRASS», «QGIS», «TAS», «SAGA», «ANUDEM», and «PCRASTER». Note that the boundaries automatically created with different software programs and the same terrain model are not fundamentally different (Zamfir & Simulescu, 2011). Likewise, the quality and details of DTM can significantly affect the quality of the selected (drawing) basin boundaries within a certain area. The most important factors are the peculiarities of the geomorphologic area structure.

**Comment [M3]:** Non-standard acronyms/initialisms that are used more than once in the paper should have their full meaning introduced at first mention.

The following programs were utilized to draw the catchment basin boundaries throughout the area of study: the global digital relief (terrain) model «GTOPO30», the vector map of the hydrographic network, and the map on the location of hydrological stations.

The «GTOPO30» model possesses certain (some) disadvantages. «GTOPO30» contain artifacts in the form of closed local depressions that are false areas of water runoff interception and sediments when a terrain model is used. Consequently, the catchment area and shape are significantly distorted. Preparing a special DTM becomes necessary when an automated technology to identify drainage basin boundaries is used (Maltsev et al., 2012).

This study employs two different approaches in DTM preparation. The first approach is the **total removal** of artificial and actual closed depressions that exist in DTM «GTOPO30», including their areas in the common catchment area. The total removal of depression is justified in the case of more depressions in the terrain model, which are artifacts, compared with the count of real depressions (Lindsay, 2005). This approach was employed at the European part of Russia, which satisfies the condition.

The second approach was used in the territory of Western Siberia with a number of real closed depressions. This approach involves the **selective removal** of the closed depressions that exist in DTM «GTOPO30»; additional information on the location of water bodies in a vector map is used (Maltsev & Yermolaev, 2014).

The results of the research are used to develop a GIS database for catchment basin boundaries; this database was built relative to the locations of gauging points (Yermolaev et al., 2012) and included data on the areas, water runoff, and suspended sediments of 1,579 rivers.

Mapping of the suspended sediments was conducted on the basis of the available database. Different methodological approaches were used. The first approach was implemented in the Volga river basin. The catchments of the gauging station and the suspended sediment value were used as the mapping unit (Maltsev et al., 2012). However, this approach is time consuming and almost impossible to automate.

Another approach in river sediment yield mapping was implemented in Northern Eurasia (in the former USSR). Physiographic (landscape) areas were used as territorial units for mapping. These areas were presented on a thematic map at a scale of 1:15,000,000 in the physical and geographical atlas of the world issued in 1964 and edited in 2007 (National Atlas, 2008). The entire Northern Eurasia was divided into natural zones (from arctic deserts to semi-deserts on temperate zones). Each landscape zone was subdivided into sectors according to climate and orographic conditions. The total number of allocated landscapes was more than 200. Using landscape zones to map the suspended sediment yield was justified by the zonal variation in the flow of suspended sediment yield. The average value of suspended sediments was calculated in natural areas and sectors. If at least ¾ of a basin area belongs to one natural zone, the amount of suspended sediment yield calculated for this basin is used to estimate the average sediment yield within a specific landscape area. Otherwise, the basin is excluded from calculations.

Ideally, the mapping data for the mean values of sediment yield throughout river basin areas within 10–00 thousand $km^2$ range should be used. These data are optimal for the zonal peculiarities of sediment yield. The sensitivity of small catchments to local zonal factors of sediment yield formation, primarily to orography and mountain rock composition that are not typical of this region, can be considered evidence (Bobrovitskaya, 1995; Dedkov & Mozzherin, 1984; Mozzherin, 1994; Karaush, 1977; Shamov, 1959). By contrast, large catchment areas located within a few landscape zones smoothen zonal features, and the volume of sediment yield for these rivers is not typical of any separate landscape zone. However, if such conditions are considered for mapping, the analysis will include 100 basins from 1,579 samples. The lower limits of the basin area were completely removed for mapping, and the upper limits were expanded to $200*10^3$ $km^2$. Therefore, the sample volume involved in determining the suspended sediment yield was 1,500 units.

**Comment [M4]:** Evidence of what? Indicate for clarity of expression.

An electronic vector map of suspended sediment yield with the use of the preceding instructional techniques was prepared for a large area of the earth for the first time (Fig.1).

**Results and discussion**

Analysis of the developed map on river suspended sediment yield in Northern Eurasia shows the following conclusions. Suspended sediment yield is poorly explored at large areas of Northern Eurasia, including the Russian North, Asian part of Russia, Kazakhstan, and Central Asia. These areas are left as white spots on the map because of the absence of reliable mathematical and statistical models that allow the extrapolation of sediment yield value on unexplored rivers (Mozzherin & Mozzherin, 2011).

According to the value of suspended sediment yield, all landscaped areas (zones) and sectors can be divided into five groups: I – areas with very high $r$ values (250 or more t/$km^2$ $year^{-1}$), II – areas with high $r$ values (100–250 t/km2 $year^{-1}$), III – zones with moderate $r$ values (50–100 t/$km^2$ · $year^{-1}$), IV – zones with low $r$ values (10–50 t/$km^2$ $year^{-1}$), and V – zones with very low $r$ values (less than 10 t/$km^2$ $year^{-1}$). The first two groups are presented by axial, mostly elevated zones of young epigeosynclinal mountains (for example, Caucasian mountains, Pamir) and ancient perigeosynclinal mountains (e.g., Tien Shan and others). The intensity of erosion in the basins of this group is entirely controlled by orographic conditions, particularly by absolute altitude and slope steepness. The potential relief and kinetic energies of water that flow in these young epigeosynclinal mountains are so high that these zones are the areas with the most severe erosion (or denudation) and the largest river sediment yield in the world. The third group is composed of moderately high mountains (Carpathians) and is known for its significant suspended sediment yield. However, this yield is lower than those of the preceding categories.

The main factors that affect zonal and sectoral distribution of erosion intensity and sediment yield on the plains and low hills are the degree of economic development and water flow. The latter is an integral representation of climatic conditions. The zonal effect of anthropogenic factors is attributed to differences in the extent of human exploration in geographical zones as a result of natural conditions (climate, soil, vegetation). An increase in exploration level increases erosion and the suspended sediment yield. Azonal factors, such as topography and rock composition, do not significantly affect the zonal distribution of suspended sediment yield on lowland rivers.

The regions with the highest suspended sediment yield on the plains and low hills of Northern Eurasia are confined to zones with intense and prolonged agricultural development. These regions are the southern half of the East European Plain and the northern foothills of the Caucasus. The Southern Siberia mountains have almost the same values of suspended sediment yield. Low $r$ values are typical of middle mountains of the Far East (Kamchatka, Primorye), which are dominated by dense taiga woods. The lowest values of *r* are observed in poorly developed taiga landscapes in the northern part of the East European Plain, which is mostly a part of Siberia. In this area, the zone feature shows a tendency to decrease suspended sediments after a reduction in water flow from the ocean waters to inland.

The key problem in the further improvement of suspended sediment yield maps for the rivers of Northern Eurasia is the calculation of probable *r* values in those areas without direct hydrological observations. In practice, this problem can be resolved on a semi-global or similar level with the use of mathematical and statistical models of erosion and sediment yield.

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