Assessment of soil erosion from rainwater runoff within a small non arable catchment

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Abstract. The article represents the dynamics of erosion-accumulation processes within the test catchment of the Lena basin over two time periods (1985-1990; 2015-2019) from rainfall-runoff, studied using the WaTEM/SEDEM model. The estimate of soil loss from rainfall-runoff was obtained, taking into account the deposition of part of the eroded soil within the catchment. This is one of the first works that estimates the magnitude of soil erosion within a poorly crop developed catchment from rainwater runoff, taking into account the deposition. It was determined that the measured sediment yield from the test catchment decreased over the two studied periods. The decrease in runoff from the studied territory is explained by a decrease in the intensity of agricultural activity in the catchment, as well as the forest area increase and grassland area reduction.

1 Introduction

Currently, climate changes are occurring on the globe in general and in the Arctic zone in particular, which are expressed in the intensification of a wide variety of natural and anthropogenic processes (permafrost degradation, forest fires, etc.). All this leads to a change in the intensity of degradation of the soil cover and the solid matter runoff transported by water streams into the Arctic Ocean [1-4].

The largest rivers in the Asian part of Russia that carry liquid and solid runoff into the Arctic Ocean are the Ob, Lena, Irtysh, and Yenisei, among which the Lena is the largest river in the Arctic. The Lena basin has few times become the object of study of erosion-accumulation processes. It should be noted the researches carried out at the Siberian Branch of the Russian Academy of Sciences [5], Moscow State University [6-7], Kazan University [8-9]. Erosion losses of soil in the Lena River basin were assessed within the framework of the implementation of global models of erosion and sediment yield [10-11]. However, in all these studies, soil losses within catchments were carried out without taking into account the process of accumulation of part of the eroded material and without verifying the results based on observations of the delivery of sediment from the catchment to the river. In addition, in earlier studies of sediment yield from the Lena River catchment, changes in the conditions of soil erosion and the formation of sediment yield in its basin were not assessed. In many parts of the world and Russia, land use and climate changes occurred at

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the border of the 1980s and 1990s [12-13], which should lead to the transformation of erosion-accumulation processes.

Assessing and mapping erosion processes in a catchment, as well as assessing sediment yield from a large area is impossible without the use of erosion models. Nowadays, there are different types of erosion models in the world [14]. The most commonly used are: USLE, RUSLE, MUSLE, WEPP; LISEM; EROSION 3D; EUROSEM, WaTEM/SEDEM; RUSLE2; MMF; SWAT.

To assess erosion soil losses, including the accumulation of part of the washed-off material within the catchment area and the sediment yield into the river, the model must consider the sedimentary connectivity of the study area. Such assessment is possible using one of the following indices: "sediment delivery ratio" (SDR) [15-17]; "index of connectivity" (I.C.) [18-20]; "travel time" [21-22]; "transport capacity" [23-24].

One of the most frequently used indices is "transport capacity" within the WaTEM/SEDEM model [14] due to the small amount of data required for calculations and the high quality of the results obtained. The WaTEM/SEDEM model has been applied within Spain, Italy, Belgium, Mongolia, China.

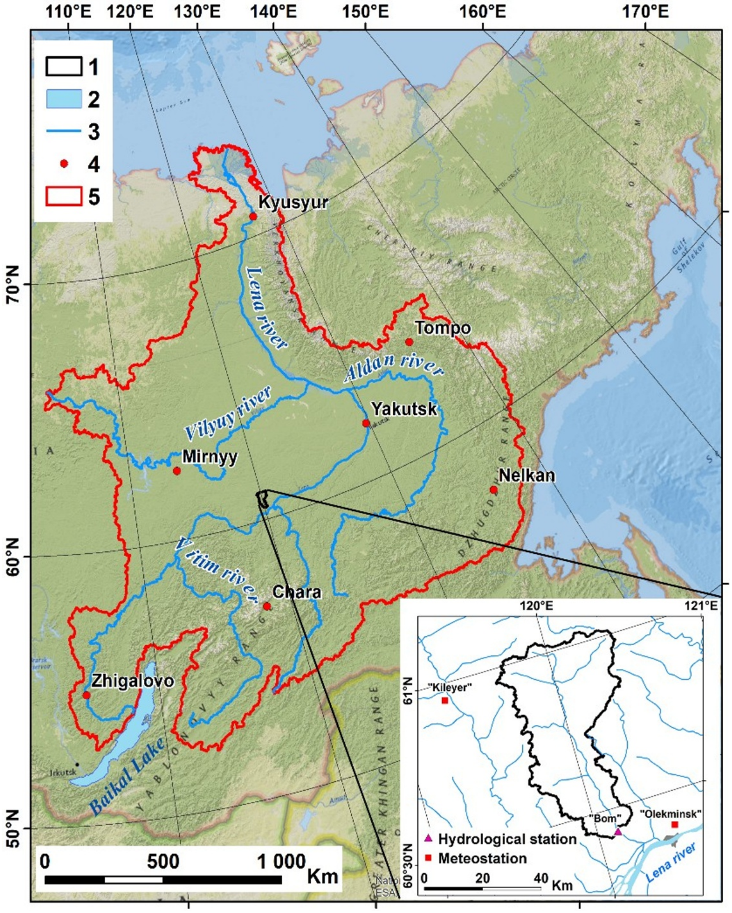
The WaTEM/SEDEM model was also used within the agricultural regions of the south of the European part of Russia [24], the east of the Russian Plain [9]. However, this model has hardly been used within the Asian part of Russia to assess erosion-accumulation processes from rainwater runoff and their dynamics within river catchments. Here could be mentioned only the research of the authors of the article carried out within two small catchments [25]. However, that study only assessed suspended sediment yield and not the dynamics of erosion-accumulation processes in the catchment.

Therefore, the purpose of this work is to assess erosion-accumulation processes from rainfall-runoff using the WaTEM/SEDEM model for the conditions of the Lena plain one small basin and their dynamics over two periods (1985-1990 and 2014-2019). Note that the applicability of the calculation algorithm has been proven primarily for plain areas. Here the model was used for a plain but not plowed catchment area.

2 Materials and Methods

2.1 Study area

The studied catchment is located within the plain relief of the Lena Plateau. The catchment boundaries were built for a hydrographic station in the Bom settlement (Bolshaya Cherepanikha River) (Figure 1). It has an area of 1709 km^2, and its heights vary from 129 to 532 meters. The soils of this catchment are represented by the following (WRB2006): Umbric Albeluvisols Abruptic; Haplic Cambisols Eutric; Haplic Cambisols Dystric; Rendzic Leptosols Eutric. The Bolshaya Cherepanikha River is a left tributary of the Lena River in its middle reaches. The geological structure of the catchment area is mainly represented by carbonate, terrigenous, and mixed sedimentary rocks. The average long-term air temperature within the Bolshaya Cherepanikha River basin is -5.84°C and the average long-term precipitation is 332 mm. The territory was selected considering the availability of monitoring data on suspended sediment yield, which permits verification of the obtained results. The studying catchment is covered by forest by almost 90%, which is typical for the Lena catchment. Despite the negative long-term average annual temperatures, positive temperatures during May, June, July, August, and September are observed here, which allow the formation of surface runoff.



1 – bound of the catchment; 2 – water bodies; 3 – main rivers; 4 – settlements; 5 – bound of the Lena basin

Fig. 1. Location of the studied catchment.

2.2 Methods

For the average long-term assessment and mapping of basin erosion from rainfall runoff, as well as sediment yield from the catchment area the WaTEM/SEDEM was used [23, 26].

The method consists of three stages. At the first stage, the potential soil loss within each pixel is assessed based on the RUSLE equation (1) [27]:

$$\mathrm{E} = \mathrm{R} \times \mathrm{K} \times \mathrm{LS_{2D}} \times \mathrm{C} \times \mathrm{P} \tag{1}$$

Where E is the average long-term soil loss (kg m^{-2} $year^{-1}$), R is the erosion index of rainfall (MJ mm m^{-2} $hour^{-1}$ $year^{-1}$), K is soil erodibility (kg hour MJ^{-1} mm^{-1}), LS_{2D} – erosion potential of the relief (dimensionless), C – soil protection coefficient of vegetation (dimensionless), and P – coefficient of anti-erosion measures.

At the second stage, the transport capacity of each pixel is estimated based on equation 2:

$$\mathrm{TC} = \mathrm{ktcRK}(\mathrm{LS_{2D}} - 4.1\, S^{0.8}) \tag{2}$$

Where TC is transport capacity (kg m^{-2} $year^{-1}$); ktc – transport capacity coefficient (m); S – slope steepness; R (MJ mm m^{-2} $hour^{-1}$ $year^{-1}$) - erosion index of rainfall, K - soil erodibility (kg hour MJ^{-1} mm^{-1}); LS_{2D} (dimensionless) – erosion potential of the relief.

In the third stage, the amount of eroded soil is compared with the transport capacity. In this case, for each grid cell, the amount of sediment delivered from the slopes above is added to the amount of sediment produced by erosion in that grid cell. If the sum of sediments received into the grid cell and sediments formed due to the erosion within this cell is lower than the transporting capacity of the stream, then all sediments are directed further down the slope. If this amount exceeds the transport capacity of the stream, then the sediment yield from the cell is limited by the transport capacity of the stream.

For calculations using WaTEM/SEDEM, the following cartographic models were used: DEM (ALOS3D30 model with a spatial resolution of 1” (about 25-30 m); soil erodibility model; land use model; Rainfall Erosion Index; and model of soil protection coefficient of vegetation (C-Factor).

The average long-term sediment runoff rate obtained by the WaTEM/SEDEM model was compared with the suspended sediment yield at the monitoring station. For a comparative analysis, a monitoring station on the Bolshaya Cherepanikha River in the Bom settlement was used. For the modeling, a raster grid with a resolution of 25 m was used.

To create a spatial model of erodibility (K-factor), spatial and attribute data from the “Unified State Register of Soil Resources” of Russia (data available on http://egrpr.esoil.ru/) were used. This register was primarily created based on the soil map of V.M. Friedland scale 1:2500000 [28]. An alternative source of spatial soil data for this area is the Harmonized World Soil Database [29] as well as the SoilGrids project data [30], but they are less accurate for the study area for several reasons.

Land use for the period 1985-1990 for the Bolshaya Cherepanikha catchment, was created by Landsat 5TM images classification. Pre-processing includes creating multi-band composites as input. For the most accurate recognition, in addition to the spectral bands, it was decided to carry out principal component analysis, and the NDVI vegetation index was calculated for each of the images. Recognition of land use types was carried out in the EnMap Box module for QGIS using the Random Forest algorithm separately for each image. Here, 80% of the training set was used to train the model and 20% to evaluate the recognition accuracy. Recognition accuracy for all classes exceeded 89%.

The Global land cover and land use 2019 model has been used for identificatioan 5 land use classes: forest, grassland, cropland, water bodies, and anthropogenic objects.

The C-factor values for forested areas and grassland were taken from the publication of P. Panagos [31]: forest – 0.011; grassland – 0.043.

According to open data from 2020 on the structure of sown areas of the Republic of Sakha (Yakutia) (“Agriculture in the Republic of Sakha (Yakutia)”): about 61% of sown areas are occupied by silage, annual and perennial grasses; about 17% of the area is under potatoes and other vegetables; about 22% of the area is allocated to leguminous crops. Taking into account the C - factor of each group of crops [32], we can say that the average value will be 0.34.

An analysis of changes in precipitation was carried out based on data from RIHMI-WDC (http://meteo.ru/ accessed on 10 July 2021). Taking into account the data at weather stations, it can be concluded, there was a slight reduction in precipitation by 3.75%. The value of the erosion potential of rainfall was adjusted accordingly for a given time interval within the Bolshaya Cherepanikha catchment.

3 Results and Discussions

In general, for the two considered periods, 1985-1990 and 2015-2019, the entire territory of the Bolshaya Cherepanikha catchment is characterized by very small values of erosion soil losses, which decreased from 0.04 (1985-1990) to 0.035 (2015-2019) t/ha per year. These values are typical for the entire catchment and were obtained taking into account the accumulation of part of the eroded material in its area. For example, for the historical period (1985-1990), the highest intensity of soil loss (0.1 t/ha per year) is characterized by territories covered with Haplic Cambisols Dystric soils, and the lowest intensity (0.01 t/ha per year) is characterized by Haplic Cambisols Eutric. Higher erosion values in the catchment, as a rule, correspond to steep river's coastal sites of tributaries and the main channel of the Bolshaya Cherepanikha River.

Most of the area of the study catchment for two periods is occupied by territories characterized by soil loss less than 0.01 t/ha per year (Table 1).

Table 1. Distribution of territories with different intensity of rainfall erosion and accumulation in the study area.

Ranges of erosion/accumulation (t/ha)	1985-1990, ha	2015-2019, ha
>0.5	195.7	83.9
0.1 – 0.5	983.8	988.2
0.05 – 0.1	1842	1787.6
0.02	0.05	6008.2
0.01– 0.02	9516.3	9219.3
0 – 0.01	99278.3	99795.9
Accumulation	53993.9	54071.3

At the same time, it should be noted that over the two periods considered, there was a more than two fold reduction in the area of land with high soil loss values (>0.5 t/ha per year). It should also be noted that during the period under review, there was a reduction in the area of all lands with erosion in the range of > 0.01 t/ha per year. The area of land with soil loss in the range from 0 to 0.01 t/ha per year has increased.

Territories characterized by accumulation occupy about 31% of the catchment and also slightly increased their area over the study period.

Analysis of modeling data shows a decrease in sediment runoff from the catchment into the Bolshaya Cherepanikha River. So, according to the results, sediment runoff due to rainfall decreased over two periods from 4 t/km^2 to 3.5 t/km^2.

The obtained model data were compared with observation data on suspended sediment yield at the Bom station (Bolshaya Cherepanikha River). Thus, sediment yield over the two periods under consideration (1985-1990 and 2015-2019) decreased from 0.41 t/km2 per year to 0.37 t/km^2 per year. Differences in absolute values of sediment yield from the catchment and in the river can be explained by the need to calibrate transport coefficients when using the WaTEM/SEDEM model for this catchment [8].

Significant reduction in sediment yield from the Bolshaya Cherepanikha catchment from rainfall is explained, in our opinion, by the almost complete disappearance of croplands, the area of which decreased from 151 to 2 hectares (Table 2).

The increase in forest area could have occurred due to the spread of broad-leaved tree species such as birch and alder to the north.

Table 2. Dynamics of the land use structure in the Bolshaya Cherepanikha catchment.

	Area 1985-1990, ha	**Proportion of catchment area 1985-1990, %**	**Area 2015-2019, ha**	**Proportion of catchment area 2015- 2019, %**
Forest	160381.2	89.75	167537.7	93.76
Grassland	17809.1	9.97	10813.5	6.05
Cropland	151.4	0.08	2.1	0.00

4 Conclusions

Based on the modeling of erosion-accumulation processes using the physical-statistical model WaTEM/SEDEM, net erosion maps, considering the accumulation of part of the washed away soil within the study catchment were obtained. The average long-term value of the intensity of soil erosion from rainwater runoff for the two periods in the Bolshaya Cherepanikha catchment decreased from 0.04 to 0.035 t/ha per year. This is explained by a reduction of grassland area, an increase in forest area, and, most importantly, the complete disappearance of arable land in the study catchment. Analysis of the resulting maps shows that about 70% of the catchment is exposed to erosion processes, and accumulation processes are concentrated on 30% of the area.

A comparative analysis of the obtained modeling results and monitoring data allowed us to conclude: that within the middle reaches of the Lena in the conditions of a forested catchment (Bolshaya Cherepanikha River), there is a decrease in sediment yield from the catchment area, and sediment yield measured in the river confirms the dynamics of runoff from the catchment.

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