RESEARCH PAPER

MODELING SEDIMENT PRODUCTION IN URBAN ENVIRONMENTS: CASE OF RUSSIAN CITIES

Andrew V. Shevchenko[1,2*], Andrian A. Seleznev[1,2], Georgy P. Malinovsky[1], Ilia V. Yarmoshenko[1]
[1]Institute of Industrial Ecology, Ural Branch of Russian Academy of Sciences, 620108, Ekaterinburg, Russia
[2]Ural Federal University, 620002, Ekaterinburg, Russia
*Corresponding author: sav@ecko.uran.ru
Received: August 25th, 2023 / Accepted: November 14th, 2023 / Published: December 31st, 2023
https://DOI-10.24057/2071-9388-2023-3022

ABSTRACT. The aim of this study is to provide a tool to assess sediment production in an urban area. The urban environment is affected by a variety of anthropogenic and natural factors that, in particular, lead to the sediment production. The storage of sediments in the urban landscape negatively affects the quality of the urban environment.

The model was developed on the basis of landscape studies conducted in residential areas of six Russian cities. The model takes into account (1) the influence of precipitation, spring snowmelt, and vehicles, (2) the influence of erosion factors for two seasons: warm (t>5°C) and cold (t<5°C), and (3) the presence of disturbed surfaces.

The application of the developed model to Ekaterinburg city conditions returned sediment production equal to 1.2 kg/m^2/y. A comparison of seasonal values shows that sediment production in cold season is 2.5 times higher than in the warm season. In the absence of the disturbed surfaces, sediment production decreases to 0.44 kg/m^2/y. Modeling showed a correlation between sediment production in Russian cities and duration of the cold season. The efficiency of various urban area maintenance practices and cleaning measures were evaluated in terms of sediment production and storage.

The developed model presented in this paper is based on research in Russian cities, but can be applied to assess the formation of sediment and measures to reduce the value of its accumulation in the urban environment in different regions of the world.

KEYWORDS: urban environment, residential area, contemporary sedimentation, urban surface deposited sediments, pollution, accumulation, sediment production, soil, erosion

CITATION: Shevchenko A. V., Seleznev A. A., Malinovsky G. P., Yarmoshenko I. V. (2023).Modeling Sediment Production In Urban Environments: Case Of Russian Cities. Geography, Environment, Sustainability, 4(16), 144-155
https://DOI-10.24057/2071-9388-2023-3022

Conflict of interests: The authors reported no potential conflict of interest.

INTRODUCTION

The large cities are subjected to the constant impact of various negative anthropogenic factors: landscape transformations, construction, motor transport, high population density, concentration of industries, etc. (Silveira et al. 2016; Owens 2020b). The above factors cause the destruction of road surfaces, lawns, sidewalks, abrasion of the road bed by tires (including studded ones), earthwork and repair work and construction (Murakami et al. 2007; Corradini et al. 2019; Pereira et al. 2016; Silveira et al. 2016; Stojiljkovic et al. 2019; US EPA 2022, 2023).

In the natural-technogenic urban landscape catenary complex, the process of sedimentation takes place according to the principle of cascade, and a part of the loose sediment remains deposited on a variety of urban surfaces, including sidewalks, driveways, lawns, playgrounds, and parking lots (Taylor et al. 2007, 2009; Owens et al. 2011; Seleznev et al., 2019a, b; Yarmoshenko et al. 2020). Urban sediment includes particles of soil, leaf litter, atmospheric solid particles, as well as solid material of vehicle emissions, building materials, road salt, road paint, and pedestrian debris (Pereira et al. 2016; Haynes et al. 2020). This object can be referred to as urban surface deposited sediments (USDS) (Seleznev et al. 2021).

The USDS reduces the quality of the urban environment. It causes deterioration of the urban infrastructure, siltation of storm water drainage systems, decrease of the fertility of the urban soils, wearing of mechanisms, vehicles, clothes and shoes, increases financial costs for sediment removal, cleaning of the territories (Pereira et al. 2016; Hewett et al. 2018; Yarmoshenko et al. 2020, Owens 2020b). These aspects of sediment storage cause many people to view sediment as a nuisance and typically have negative connotations (Owens 2020b; Seleznev et al. 2021).

Fine fractions of sediments can accumulate substances potentially harmful for human health (Landrigan et al. 2018; Stojiljkovic et al. 2019; Seleznev et al. 2020; Haynes et al. 2020). The urban sediments represent a secondary, non-point source of pollution and poses a significant risk to the environment due to high content of dust particles and other pollutants (Taylor et al. 2007; Martínez & Poleto 2014; Pereira et al. 2016; Li et al. 2019; Lee et al. 2021). Sediment generated in urban areas can be transported to streams, rivers, and reservoirs (Restrepo & Syvitski 2006; Najafi et al. 2021; Cendrero et al. 2022). These contributes to suspended sediment in water bodies. The potential of sediment as a geo-indicator component in ecological and geochemical studies has recently been under consideration (Kasimov 2013; Crosby et al. 2014; Dias-Ferreira et al. 2016; Owens 2020b).

The problem of sediment production and accumulation on the urban surfaces is of great importance for urban environment quality management. However, there is currently no comprehensive assessment of sediment production in Russian cities. There is also no recommended tool for such an assessment. There are verified models for estimating soil loss on agricultural land due to precipitation, for example Revised Universal Soil Loss Equation (RUSLE), but the experimental assessment of sediment production in urban environments is difficult due to the heterogeneity of the urban landscape. Vehicle traffic is a significant contributor to total sediment production in this type of landscape (Stojiljkovic et al. 2019; Seleznev et al. 2021). There are a number of methods currently available to assess pavement wear, but they assess this wear from a road safety perspective rather than a sediment production perspective. A multi-factorial system such as the urban environment requires an appropriate model that considers all aspects of the environment's erosion potential.

The aim of this study is to develop a model for estimating sediment production in urban areas. In order to achieve the aim, the following tasks were formulated:

1. To create a model object that reflects the typical structure of residential blocks in Russian cities by averaging previous landscape studies.
2. Modify the RUSLE model for use in an urbanized environment and calculate sediment production.
3. To propose a method for estimating the amount of sediment production by pavement wear from studless and studded tires.
4. To perform model estimation of sediment production in urban environments in different climatic conditions.
5. To perform model estimation of sediment production in Ekaterinburg conditions.

MATERIALS AND METHODS

Data source

In recent years, the Institute of Industrial Ecology of the Ural Branch of the Russian Academy of Sciences has collected significant experimental material on surface sediments in the urban environment in a large number of Russian cities: Moscow, Rostov-on-Don, Nizhniy Novgorod, Tyumen, Ekaterinburg, Murmansk, Chelyabinsk, Vladivostok and other. Surface sediments were sampled in residential areas and the adjacent network of streets and roads (Seleznev et al. 2019a, 2019b, 2020, 2021, 2022, 2023; Yarmoshenko et al. 2020). In total, more than 500 samples were taken. The selected samples were analyzed for granulometric, chemical, and mineral composition. In cold season, snow and snow-dirt sludge, which is a mixture of snow and surface sediment from vehicle and pedestrian traffic, were sampled.

A description of the landscape conditions was made at the sampling locations, taking into account the type of use of the landscape areas, the type of pavement, the technical condition, the quality of cleaning and other parameters. Based on the results of the studies, the accumulated stock of surface sediments was estimated. In the fourth populated Russian city Ekaterinburg, the amount of solid sediment storage was found to be 3.2 kg/m^2 (Seleznev et al. 2019).

Elementary Urban Residential Landscape

The paper (Yarmoshenko et al. 2020) describes a study conducted in six Russian cities: Ekaterinburg, Rostov-on-Don, Nizhniy Novgorod, Tyumen, Murmansk, Chelyabinsk. In each city, six experimental sites in residential land use areas in different parts of each city and at different stages of development were selected for field survey. Each site represents a part of the residential yard with an adjacent street and road network area of a block of multi-story apartment buildings. After analyzing the field survey data, which covered about 350,000 m^2, an averaged version of all experimental sites is presented in the paper (Yarmoshenko et al. 2020) and called Elementary Urban Residential Landscape (EURL). The EURL is an elementary part of the typical residential block of most large Russian cities, mostly built during the Soviet era.

The model EURL (Fig. 2.1) was defined as an area of 10 000 m^2 and divided into 14 segments according to the criteria suggested by Yarmoshenko et al. (2020). The typical EURL consists of external (street) and internal (yard) parts and include the following functional zones: road, driveways, parking lots, lawns, sidewalks, playground, and illegal parking. Illegal parking is a part of the city territory that was not originally designed and arranged to accommodate vehicles. During the field surveys the illegal parking were detected on lawns and playgrounds (red cars on Fig. 2.1). The field surveys included the characterization of the segments by several parameters which describe, in particular, the type of pavement, proportion of disturbed surface, state of cleaning, presence of elevation, and others.

The typical EURL includes 50 parking lots and 12 illegal parking lots in the internal part (Yarmoshenko et al. 2020). The intensity of traffic on a three-lane road within the city limits averages 3,000 cars per day, according to the Ekaterinburg city administration. The length of the road adopted in the EURL is 100 m, which is roughly the length of the side of the block.

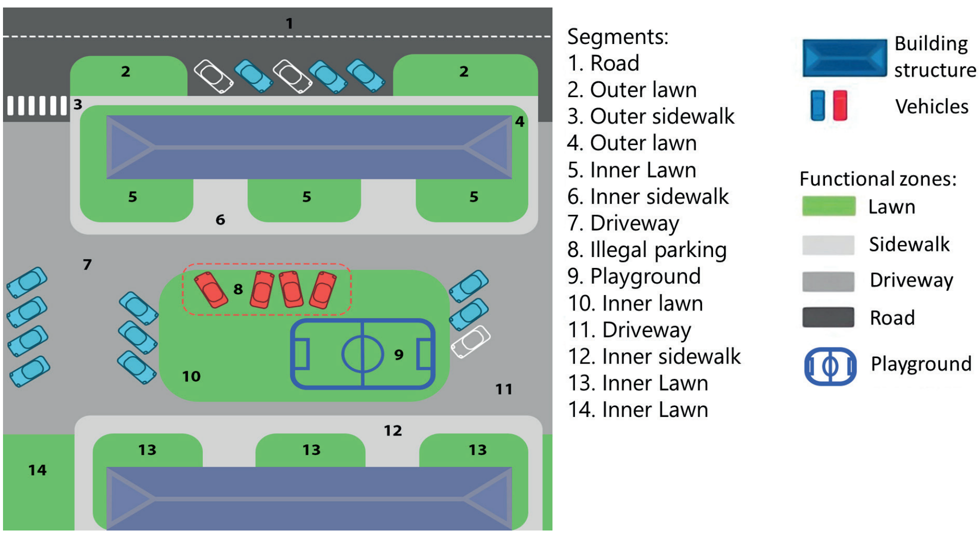


Fig. 1. Scheme of the typical elementary urban residential landscape (EURL) in Russian cities divided into segments and functional zones

Surface types of the elementary urban residential landscape

Three types of surfaces were defined within the EURL: asphalt, lawn, and bare soil. However, this paper considers two variants of the condition and use of functional zone surfaces: real conditions – surfaces are partially disturbed, ideal conditions –surfaces are completely undisturbed. The percentage of the area of each segment that is attributable to disturbed pavement is accepted equal to 16% and 27% for the external and internal segments, respectively. For the road, this percentage is 3.6%. On the average, according to (Yarmoshenko et al. 2020), in the residential areas of the large cities of Russia, the percentage of the disturbed pavement is 24%.

Atmospheric precipitation cannot have a significant effect on undisturbed segments of hard surfaces of roads, driveways, and sidewalks, so there is no natural erosion from the effects of rain and snowmelt. The calculation of erosion from the impact of non-studded tires considers only the segments on which the vehicle is moving. For studded tires, the calculation is for the road only. This is because in the cold season yard driveways are covered with a layer of compacted snow or ice and in most cases are not shoveled to a hard surface, so there is no effect of the studs on them. For ideal conditions, it is assumed that there is no illegal parking and it is an inner undisturbed lawn, and the use of studded tires is prohibited.

Descriptions of the studied cities

As a main object of application of the developed model of estimation of sediment production the city of Ekaterinburg, fourth most populated city in Russia, was chosen. Ekaterinburg is characterized by a high concentration of industrial enterprises, a high traffic load on the road network, and a high population density.

In calculations that take into account temperature and snow cover, two seasons are defined: warm and cold. The warm season is the period when the air temperature is >5°C and the cold season is <5°C. This choice is due to the fact that at air temperatures <5°C it is recommended to equip cars with winter tires. The cold season in Ekaterinburg, lasts on average from November to March (5 months). The average air temperature during this period is -11.2°C. Atmospheric precipitation in the form of snow accumulates at negative temperatures. The average temperature over several years is -15.3°C in January and +17.4°C in July.

In addition, calculations were made for seven major Russian cities located in climatic zones different from Ekaterinburg. For this purpose, cities with cold period duration (t<5°C) from 1 to 9 months were selected: Sochi (1 month), Novorossiysk (2 months), Rostov-on-Don (3 months), Vladivostok (4 months), Khabarovsk (6 months), Novosibirsk (7 months), Salekhard (8 months), Norilsk (9 months).

Ekaterinburg receives an average of 535 mm of precipitation per year, but the RUSLE model considers only liquid precipitation, which is 405 mm/y. For other cities, this value varies from 341 to 1648 mm/y. The average value is about 600 mm/y, against which Sochi stands out with a value of 1648 mm/y.

The average height of the snow cover in Ekaterinburg is 440 mm (Seleznev et al. 2020). This value was used in calculations for such areas as lawns and playgrounds. These areas are not cleared of snow during the cold season. For areas with paved surfaces (roads, driveways, sidewalks) a height of 220 mm of snow cover was used because these areas are subject to regular snow removal. Snow cover height at illegal parking was also assumed to be 220 mm. Parked cars prevent the free accumulation of snow. In other cities, a different snow cover height was selected from reference climate data. The snow cover height on unpaved surfaces is from 100 to 600 mm, on paved surfaces - from 50 to 300 mm.

Soils in urban areas are predominantly altered by human activities. These are urban soils. Therefore, the K-factor for these soils should be determined experimentally for each site for which calculations are made. Sod-podzolic soils containing 20-30% clay and about 40% sand are typical for the Ekaterinburg region (Gafurov 2008). The K-factor of the RUSLE was calculated using these characteristics. This type of soil was used for all cities, because urban topsoil does not differ much in granulometric composition, being an anthropogenically transformed soil.

Empirical model for soil loss assessment

There are three categories of models for the assessment of soil loss on agricultural land: empirical models, conceptual models, and physically based models (Igwe et al. 2017). Empirical models have the advantage that they can be applied to situations with limited data and parameters and are particularly useful as a first step in the identification of sources of sedimentation (Merritt at al. 2003). One of the empirical models is the Revised Universal Soil Loss Equation (RUSLE) (Renard et al. 1991). RUSLE provide a long-term average annual estimate of soil loss due to precipitation. It was developed for small slopes, but can be used to model catchment-scale erosion and sediment transport.

The Revised Universal Soil Loss Equation (RUSLE) model is a soil erosion model that predicts the average annual soil loss due to precipitation and surface runoff from agricultural fields and pastures (Renard et al. 1991). The RUSLE model contains six factors:

$$A_p = R \times K \times LS \times C \times P \quad (1)$$

where A_p is the annual average rainfall soil loss, t/ha/y; R is the rainfall erosivity factor, MJ mm/ha per hour; K is the soil erodibility factor, t ha h/MJ mm, *LS* is the slope length and slope steepness factor (dimensionless), *C* is the land-use (cover management) factor (dimensionless), *P* is the supporting practices factor (dimensionless).

The R-factor depends on the climatic conditions of the area. The key factor is the amount and intensity of atmospheric precipitation that causes erosion (Renard et al. 1991). To calculate the R-factor, data on the average annual liquid precipitation were used for the model site. The following formula is used to calculate the R-factor (Yu et al. 1996; Renard et al. 1997):

$$R = 0.0438 \times P^{1.61} \quad (2)$$

where *P* is average annual liquid precipitation, mm/y.

The K-factor determines the resistance of the soil to erosion under standard conditions. It depends on the granulometric composition of the soil, its sand, clay and silt content (Renard et al. 1997; Knijff et al. 1999). The soil erodibility factor – K-factor, is usually estimated using the nomographs and formulae that are published in for example Wischmeier & Smith (1978). While these equations are suitable for large parts of the USA (for which the USLE was originally developed), they produce unreliable results when applied to soils with textural extremes as well as well-aggregated soils (Romkens et al. 1986). Therefore, they are not ideally suited for use under European conditions.

Romkens et al. (1986) performed a regression analysis on a world-wide dataset of all measured K-values, which yielded the following equation (revised in Renard et al., 1997):

$$K = 0.0034 + 0.0405 \times exp\left[-0.5 \times \left(\frac{\log D_g + 1.659}{0.7101}\right)^2\right] \quad (3)$$

where D_g is the geometric mean weight diameter of the primary soil particles, mm.

D_g is a function of surface texture, and its value can be calculated as follows (Renard et al. 1997; Knijff et al. 1999):

$$D_g = exp\left(f_i \times \ln\left(\frac{d_i + d_{i-1}}{2}\right)\right) \quad (4)$$

where d_i is the maximum diameter, mm; d_{i-1} is the minimum diameter, mm; f_i is the corresponding mass fraction, mm, for each particle size class (clay, silt, sand).

The LS-factor is a factor of the length and slope of a landscape segment, taking into account the effect of sloping processes on erosion (Wischmeier et al. 1978). Eq. 5 was used for the calculation of the LS-factor (Moore et al. 1992):

$$LS = \left(\frac{A_S}{22.13}\right)^m \times \left(\frac{\sin\beta}{0.0896}\right)^n \quad (5)$$

where A_S is the specific catchment area, m^2/m; *sinβ* is the slope angle, deg.; *m* and *n* are constants, 0.4 and 1.3 respectively (Moore et al. 1992).

The C-factor in the soil-loss equation is the ratio of soil loss from land cropped under specified conditions to the corresponding loss from tilled, continuous fallow (Renard et al. 1997). This factor measures the combined effect of all the interrelated cover and management variables. The higher the value, the less the crop stands inhibit erosion.

The P-factor in the soil-loss equation is the ratio of soil loss with a support practice like contouring, stripcropping, or terracing to soil loss with straight-row farming up and down the slope (Renard et al. 1997). If there is no support practice, the P-factor is not used in the calculation and is equal to 1.

RESULTS

RUSLE adaptation for urban environments

The RUSLE model has been used in this study for the estimation of surface solid material production as a result of the impact of precipitation on urban pavements. This model implies the presence of a slope in the study area, but the relief of urban areas is many times more complicated than that of natural areas, since there are a huge number of obstacles in the way of its formation, and at the same time there are even more areas of artificial concentration of runoff. The RUSLE model is designed exclusively for soils that can be used in some form of agriculture. Therefore, the model cannot be used for urban environment without significant modifications. For this reason, the RUSLE model was modified based on a study conducted in the city of Ekaterinburg, one of the objectives of which was to select a C-factor that would allow the model to be transferred to urban conditions (Seleznev et al. 2022). It is important to note that the RUSLE model was used only for areas with ground cover or other forms of open ground, such as road potholes. Any calculations with its help on asphalt and other hard surfaces are meaningless.

In this study, slope angle values are assumed to be 0.5 degrees for areas with hard impervious surfaces (roads, sidewalks, driveways) and 5 degrees for areas with permeable surfaces. These slope angle values have been chosen as examples and approximate the actual slopes of landscape sections in urban environments. If other slopes are present, any value other than zero can be used.

The C-factor reflects the effect of vegetation cover and land use type on erosion rate (Wischmeier et al. 1978; Renard et al. 1991; Renard et al. 1997). The values of the factors range from 0 to 1, depending on the type of land cover. The lower the value, the more resistant to erosion (Lisbôa et al. 2017; Aouichaty et al. 2022; Chen et al. 2023). The C-factor values are in accordance with the paper (Seleznev et al. 2022). Within the framework of this study (Seleznev et al. 2022), two drainless small water bodies were selected in Ekaterinburg. The water bodies are located in different areas of the city, are of anthropogenic origin, the purpose of the water bodies is recreation. The catchment areas are located at the interfaces of different functional zones of the city. In the work was carried out field survey and analysis of cartographic materials of territories of watersheds, determination of bathymetric and morphometric parameters of water bodies, sampling columns of bottom sediments. The assessment of bottom sediments in water bodies was carried out using a three-dimensional triangulation model. Assessment of sediment transport from the catchment area was carried out using the RUSLE model. The parameters of the RUSLE model, in particular the C-factor, were obtained based on the calculated amount of bottom sediments (Table 2.1).

For the C-factor, we used two variants of values reflecting surface condition: undisturbed and disturbed. Disturbed surfaces are surface areas that have been subjected to anthropogenic or other impacts, as a result of which the integrity of the surface has been disturbed. Potholes in roads and other hard surfaces, trampled or unvegetated lawns, illegal parking lots, etc. are examples of such segments.

In urban residential areas, these measures are not implemented, so the P-factor was assumed as 1 (Renard et al. 1997; Lisbôa et al. 2017; Taoufik et al. 2020; Michalek et al. 2021).

A modified Larionov (1993) model of the Russian State Hydrological Institute was used for the estimation of sediment production during snowmelt following the same principles as RUSLE model. Eq. 6 (Larionov 1993; Maltsev et al. 2020) was used for the calculation of material runoff during spring snowmelt:

$$A_{sm} = h \times K \times LS \times C \times P \quad (6)$$

where A_{sm} is the average annual snowmelt soil loss, t/ha/y; *h* is the overland surface flow during snowmelt.

K, LS, C, and P factors are assumed to be the same as for liquid precipitation erosion calculations. The value of surface runoff h is calculated based on Eq. 7 as follows (Larionov 1993; Maltsev et al. 2020):

$$h = H \times D \times I^E \quad (7)$$

Table 1. The values of the C-factor used in the developed model

Functional zone	C-factor	
	undisturbed site	disturbed site
road	0	0.5
driveway	0	0.5
sidewalk	0	0.5
lawn	0.01	0.1
playground	0.1	0.2
illegal parking	0.5	0.5

where H is the water content in snow, mm; D and E are coefficients depending on the landscape zone and soil texture (Table 2.2); I - slope, %.

Methods for estimating sediment production from vehicles

Studless tires

The interaction of a moving vehicle with the road surface results in tire wear and abrasion of the top layer of the road surface. A factor similar to the rainfall erosivity factor (R-factor) of the RUSLE model (Renard et al. 1991) can be used to estimate pavement wear from tire abrasion during warm periods. The R-factor principle has been used to determine the amount of abrasion products from vehicle wheels. It is suggested that instead of precipitation energy, an estimate of the amount of energy transferred from the vehicle to the surface should be used.

The following forces that act on the surface as the vehicle moves are considered to estimate the amount of energy transferred from the vehicle to the surface:

• traction force – resulting from the operation of the engine and the interaction between the drive wheels and the road,

• rolling resistance force – the force that results from the deformation of the tire as it grips the surface of the road,

• friction force – occurs when the vehicle's wheels come into contact with the road surface.

The energy from the engine is transferred to the wheels through the transmission. Part of the energy is used to overcome friction and to move the units. The amount of energy that is lost depends on the efficiency factor of the transmission η_{ts}. According to Turevsky (2005), for passenger cars η_{ts} is taken to be equal to 0.88-0.92, depending on the gear that is engaged.

The torque Tq_s causes the tangential reaction of the road at the point of contact of the wheel with the road, which moves the car, i.e. the traction force F_{tr} (Turevsky 2005):

$$F_{tr} = \frac{Tq_s}{r_{sw}} \tag{8}$$

where Tq_s is the total torque on the driving wheels, N·m; r_{sw} is the static wheel radius, m.

The value of r_{sw} changes under the influence of other forces, but to simplify the calculations, it is considered constant. It is equal to the distance from the axis of the stationary wheel to the road surface (Turevsky 2005). In this case, Tqs equals:

$$Tq_s = \eta_{ts} \times Tq \times r_{gb} \times r_{mg} \tag{9}$$

where η_{ts} is the efficiency factor of the transmission; T_q is the engine torque, N·m; r_{gb} is the gear ratio of the gearbox; r_{mg} is the gear ratio of the main gear.

When a vehicle maneuvers while driving, it generates a rolling resistance force F_r. This force depends on the tire's traction coefficient with the road surface and the load on the wheels (Turevsky 2005; Filkin 2016). The rolling resistance force can be calculated by using the formula:

$$F_r = f \times G_v \tag{10}$$

where F_r is the rolling resistance force, N; f is the rolling resistance coefficient; G_v is the force of gravity acting on the vehicle, N.

According to Filkin (2016), the coefficient of rolling resistance f is considered constant at speeds up to 50 km/h. For roads with asphalt or asphalt cement pavement in excellent condition it is 0.012-0.018, and for roads in satisfactory condition it's 0.018-0.020. For unpaved roads in a dry and rolled condition it is 0.025-0.035 (Turevsky 2005). The characteristics of the vehicle and the accepted speeds for each of the functional zones that are used in the calculations are shown in Table 2.3.

The friction force is a mechanical resistance force that occurs for two reasons: the attraction of the molecules

Table 2. Values of coefficients D and E depending on conditions (Maltsev et al. 2020)

Landscape zone	Soil texture	D	E
forest	clay, loam	2.6953	0.89836
	sandy loam	2.1118	0.63475
forest-steppe	clay, loam	3.1219	0.96103
	sandy loam	2.4472	0.73120
steppe	clay, loam	3.0235	0.99758
	sandy loam	1.37	0.60474

Table 3. Characteristics of the model car and accepted speeds of its movement

Characteristics	Value
weight, kg	1500
engine torque, N·m	155
gear ratio of main gear	4.3
gear ratio of 1st gear	3.769
gear ratio of 2nd gear	2.045
gear ratio of the 4th gear	1.036
tire width, mm	195
driveway, km/h	20
road, km/h	50
illegal parking, km/h	10

to each other at the point of contact and the presence of a surface roughness. The frictional force is calculated according to the following equation:

$$F_{fr} = \mu \times m \times g \quad (11)$$

where μ is the coefficient of friction (adhesion); m is the vehicle mass, kg; g is the gravitational constant, m/s^2.

The coefficient of friction (adhesion) μ was taken from Turevsky (2005) for dry asphalt cement pavement and is equal to 0.7.

Using the data from Table 2.3 to calculate equations 8-11, we obtain the values of the energy transferred to the surface as the car moves. This value corresponds to the size units of the RUSLE model. Table 2.4 shows the values obtained for each functional zone.

In order to take into account the type of surface, it is necessary to introduce into the calculations the coefficient of intensity of wear – I-factor. It depends on the resistance of the surface to various influences. The coefficient was determined by Korsunsky M. B. (Vasiliev 1989) on the basis of the formula for the calculation of the average annual decrease in the thickness of the pavement due to wear:

$$h_{an} = a + b \times \frac{N}{1000} \quad (12)$$

where h_{an} is the annual average value of the reduction in pavement thickness due to wear, mm; a is a coefficient that depends mainly on the resistance of the pavement to adverse climatic conditions (Table 2.5); b is a coefficient that depends on the strength of the pavement material, its moisture content, composition and traffic speed (Table 2.5); N is the traffic intensity, vehicle/day.

Values representing wear per unit of energy transmitted to the pavement were calculated from data on the reduction in pavement thickness due to wear and the energy transmitted to the pavement by the vehicle during travel. The I-factor values for disturbed and undisturbed pavements are shown in Table 2.6. The area of the illegal parking lot is considered to be completely disturbed.

The final equation for calculating pavement wear for studless tires is as follows:

$$A_{sl} = \left(E \times N_w \times P_{us} \times I_{us}\right) + \left(E \times N_w \times P_{ds} \times I_{ds}\right) \quad (13)$$

where A_{sl} is the average annual production of sediment from studless tire abrasion, kg/m^2/y; E is the energy transmitted to the surface during the movement of a car, MJ/m^2/y; N_w is the number of cars per warm season; P_{us} and P_{ds} is the undisturbed and disturbed surface area, respectively, %; I_{us} and I_{ds} is the factor of intensity of wear for undisturbed and disturbed surface area, respectively, kg/MJ (Table 2.6).

Studded tires

Studded tires cause significant road wear (Stojiljkovic et al. 2019). In most parts of Russia in cold season car owners use studded tires. That said, 77% of them are studded (Autostat Omnibus, 2020). Arrojo (2000) and Carlsson (1995) have studied pavement wear for roads with different traffic intensities of vehicles with studded tires. Proposed by Carlsson (1995), SPS index indicates the actual wear from a certain amount of traffic with studded tyres during a particular measuring period, usually one cold season. The SPS index was used in the model without modification.

Table 4. Values of energy transferred to the surface during car movement

Functional zone	Energy of 1 car, MJ/ha/h
road	54
driveway	62
illegal parking	70

Table 5. Values of coefficients a and b depending on the type of pavement (Lugov et al. 2013)

No.	Pavement type	a	b
1	Asphalt-concrete	0.4…0.6	0.25…0.55
2	Crushed stone and gravel, treated with binders with a layer of wear:		
	a) double surface treatment	1.3…2.7	3.5…5.5
	b) single surface treatment	1.4…2.8	4.0…6.0
3	Crushed stone:		
	a) from firm rocks	4.5…5.5	15.0…20.0
	b) from low-strength rocks	5.5…6.5	19.0…25.0
4	Gravel:		
	a) of strong gravel	3.0…4.0	20.0…30.0
	b) gravel of low strength	4.0…6.0	

Table 6. I-factor values by functional zone (kg/MJ)

Functional zone	Undisturbed surface	Disturbed surface
road	0.0000107	0.00128
driveway	0.00000462	0.000555
illegal parking	–	0.000486

The calculations do not take into account cars equipped with studded tires in the warm period, as this is a violation of the law and is rather an exception to the rules. This type of all-season tires is common in the southern regions of Russia, but since this type of tires is not equipped with studs, it is not included in the calculations for the cold period.

The SPS index (Carlsson et al. 1995) can be used to calculate the wear of hard surfaces under the influence of studded tires. The SPS index is the Swedish abbreviation for specific wear. It can be represented as follows:

1. SPS = number of tons of asphalt abrasion per kilometer of road and one million cars with studded tires;
2. SPS = number of grams of asphalt abrasion per kilometer of road and car with studded tires.

The SPS index is based on three different methods of wear measurement: measurement on the road, measurement on slabs laid in the road and measurement on slabs in the VII's road simulator (Carlsson et al. 1995). SPS can be calculated as:

$$SPS = \frac{AW \times LW \times RL \times BD}{AADT \times WP \times SF} \quad (14)$$

where *AW* is the average wear, m/vehicle; *LW* is the lane width, m; *RL* is the road length (1 km), m; *BD* is the bulk density, g/m^3; *AADT* is the average annual daily traffic, vehicles/day, *WP* is the wear period, cold season days/y; *SF* is the stud frequency, %.

The material or type of pavement and the average annual daily traffic will affect the amount of wear. It has also been determined on a road simulator that the weight of a stud can have a 50% increase in wear (Carlsson et al. 1995). Modern studs are mostly lightweight and bi-component. The stud body is made of aluminum instead of steel and the core is made of a hard alloy material.

Developed model for estimating sediment production in urban environments

The final equation for estimating sediment production in an urban area is as follows:

$$USP = \left(\frac{A_p + A_{sm}}{10}\right) + A_{sl} + \left(SPS \times N_c \times k\right) \quad (15)$$

where *USP* is the urban sediment production, kg/m^2/y, A_p is the average annual soil loss from precipitation, t/ha/y; A_{sm} is the average annual snowmelt soil loss, t/ha/y; A_{sl} is the average annual production of sediment from studless tire abrasion, kg/m^2/y; *SPS* is the road wear caused by studded tires, g/km/car; N_c is the number of cars per cold season; *k* is the road length and width correction factor.

Calculations

Sediment production in Ekaterinburg conditions

Estimations of sediment production in warm and cold seasons for different functional zones under real and ideal conditions for Ekaterinburg obtained using the developed model (15) are presented in Table 7. The figures presented in Table 7 refer to areas of the EURL segments that belong to a specific functional zone. The Table 7 includes the areas of different functional zones which are assigned within the EURL model. Under real conditions annual sediment production varies from 0.02 at sidewalks to 6.74 kg/m^2 at roads.

The total sediment production for the entire EURL by seasons for Ekaterinburg is presented in Fig. 2. After summation of the warm and cold seasons estimations the sediment production is equal to 1.2 and 0.44 kg/m^2/y for the real and ideal conditions, respectively. There is a significant difference between estimations obtained for the real and ideal conditions during cold season due to the use of studded tires when considering the real seasonal conditions of sediment production. The model predicts a 3.5-fold increased sediment production in cold season. At the same time, the increase in the sediment production in the warm season is lower – 1.7 times. In the yard part of the EURL, the sediment production under real conditions is 0.34 kg/m^2/y, that is about three times higher than under ideal conditions. The highest sediment production is observed on illegal parking lots. According to the applied model, the sediment production in the legal parking lots and in the driveways of the yards is ten times lower than in the illegal parking lots.

The contributions of the main groups of factors of the sediment production at the model site for Ekaterinburg are shown in Fig. 3. The following groups of factors are considered: 1) ideal conditions of urban land maintenance, 2) exploitation of the urban road network during the cold period, 3) real conditions of internal and 4) external part of the EURL. According to the modeling performed, the exploitation of the urban road network during the cold period contributes 44% to the total annual supply of solid sediment. It can also be noted that 37% of the total sediment production is related to sediment generated even with high requirements to land maintenance are met. The disturbed areas of the functional zones at the external part of the EURL contribute 5% to the total sediment production, while the disturbed areas in the yard part, which mainly include illegal parking lots, contribute 14%. The dynamics of the USDS accumulation can be estimated using a simple differential model:

Table 7. Annual sediment production in warm and cold seasons under real and ideal conditions

No.	Functional zone	Area, m^2	Real conditions		Ideal conditions	
			warm, kg/m^2/y	cold, kg/m^2/y	warm, kg/m^2/y	cold, kg/m^2/y
1	road	1353	1.64	5.10	1.26	1.30
2	driveway	2744	0.08	0.02	0	0
3	lawn (external part)	984	0.07	0.13	0.03	0.05
4	lawn (internal part)	2335	0.10	0.19	0.03	0.06
5	sidewalks (external part)	367	0.01	0.01	0	0
6	sidewalks (internal part)	1348	0.02	0.02	0	0
7	playground	594	0.43	0.85	0.34	0.67
8	illegal parking	275	1.33	1.28	–	–

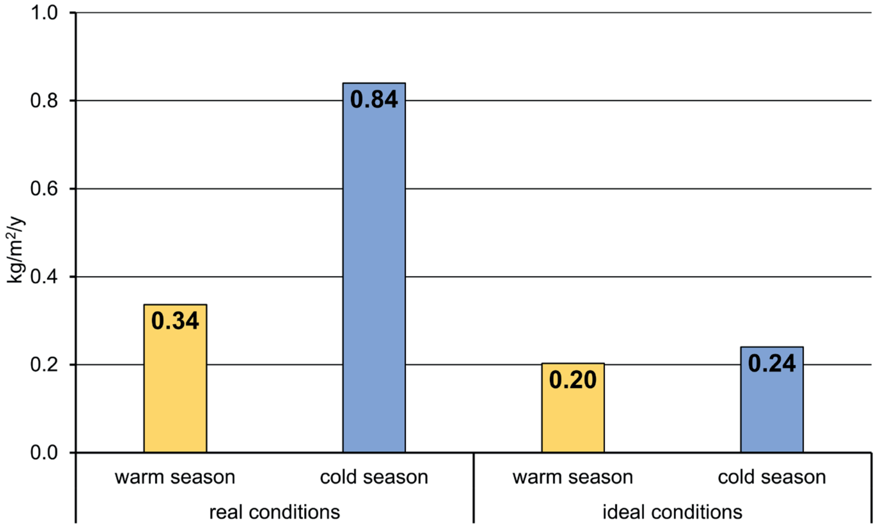


Fig. 2. Total sediment production in typical EURL

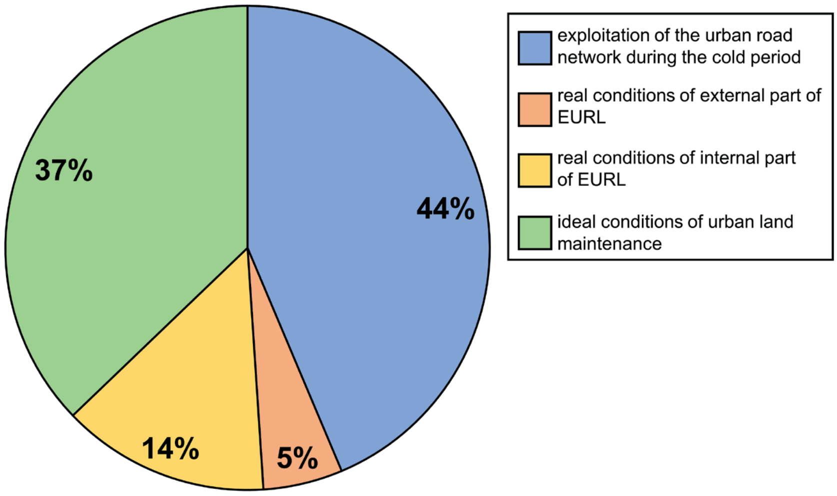


Fig. 3. Contribution of the different groups of factors to the process of sediment production in the urban environment

$$\frac{dC}{dt} = a - b \cdot C(t) \qquad (16)$$

where C is the USDS storage, kg/m^2; t is the time, year; $a = 1.2$ kg/m^2/y is sediment production obtained in current study; b is the removal rate, year^{-1}. Under constant a and b, this function approaches an equilibrium value C_{eq}.

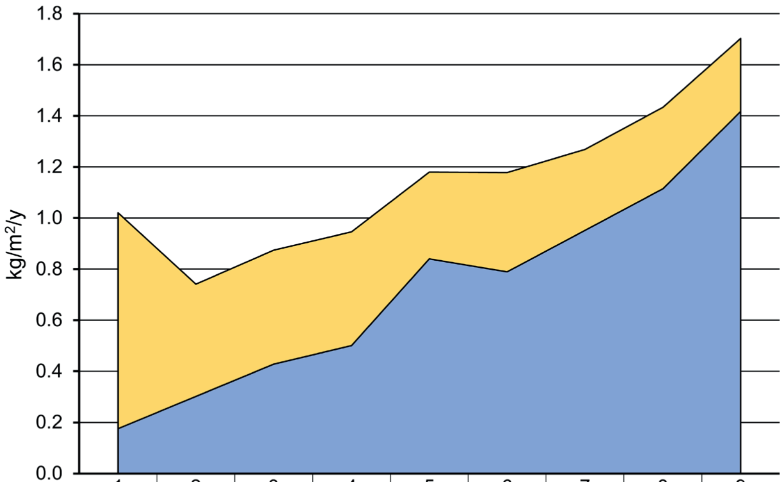
Previously, data on the storage of the USDS in the residential part of Ekaterinburg were obtained based on the study of the content of solid material in snow-dirt sludge sampled during cold season. The value of 3.2 kg/m^2 was obtained (Seleznev et al. 2019). Assuming constant conditions of sediment production and removal this value can be accepted as C_{eq}. Various landscaping activities including earthworks and construction, which may contribute to the sediment production process in the residential areas, are not considered in the developed model (USP). Such a contribution can be tentatively estimated as 10%. Thus, 2.9 kg/m^2 can be accepted as the estimation of sediment storage C_{eq} due to natural and anthropogenic processes, excluding earthworks. Solving equation (16) under such boundary conditions leads to b equal to 0.41 year^{-1}. Thus, the actual rate of removal of the USDS outside the residential area due to both anthropogenic and natural processes is almost two times lower than that required to minimize accumulation. The low removal rate leads to a significant accumulation of the USDS within the residential areas. For new urban landscapes, at such removal rate, an equilibrium between sediment production and removal will be reached in about six years.

Sediment production depending on the duration of the cold period

The results of the calculations of the sediment production in Russian cities with different duration of cold period (winter season) (from 1 to 9 months) are shown in Fig. 4. According to the results of the model calculations, the sediment production in Russian cities is in the range from 0.74 to 1.7 kg/m^2/y. Fig. 3.3 shows a clear correlation between the sediment production and cold period duration. The longer the cold period, the more solid material formed due to the abrasive effect of the studs on the paved surface. Calculations were made for the same traffic intensity (1300 cars per hour). The example of the city of Sochi in Fig. 3.3 shows the influence of atmospheric precipitation on the process of sediment formation. The relative increase in sediment production in this city is associated with the maximum amount of atmospheric precipitation of more than 1500 mm/y, which exceeds the same values in other cities by 2-4 times.

DISCUSSIONS

The factors and conditions of sediment production in Russian cities are considered in the developed model. The model is based on the RUSLE model modified for the urban environment, a model for estimating pavement abrasion production by studless tires based on the general principle of the RUSLE model, and other unmodified models. Using the developed model and the EURL, estimates of sediment production were obtained for the city of Ekaterinburg and



	1	2	3	4	5	6	7	8	9
USP (t>5°C), kg/m²/y	0.84	0.44	0.45	0.45	0.34	0.39	0.32	0.32	0.29
USP (t<5°C), kg/m²/y	0.18	0.30	0.43	0.50	0.84	0.79	0.95	1.11	1.42

Fig. 4. Sediment production in urban environment depending on the cold season duration

seven other large Russian cities located in different climatic conditions. The dependence of sediment production on the duration of the cold period was verified.

Findings in the context of sediment production in urban environments

In the development of the model we have taken into account the conditions that are typical for large cities with a population of millions of people in Russia. The majority of the urban population live in multi-family, multi-storey buildings. A large part of the modern housing stock was built in the period from 1950 to 1991, taking into account the requirements of the building standards valid in the Soviet Union. The predominant part of the buildings has five floors and more that causes a fairly high density of the population. Throughout the country, residential areas of large cities are arranged in a similar manner: residential buildings face the street and road network, several residential buildings limit the common yard area. The basic elements of the residential block landscape (EURL) are the yard, the residential buildings, and the nearby street and road network. On average, such an element has an area of 10000 m^2, as shown in (Yarmoshenko et al. 2020). The developed modification of the sedimentation model is designed to be applied to such an element of the landscape. It is assumed that for territories of residential blocks of a large city the calculations for one element of the landscape are representative for estimation of sediment production in the entire residential land use area.

For the modification of the model of sediment production in the urban landscape, both experimental data and model results of vehicle impact on different types of pavements under different operating conditions have been used. The fact that in Russian cities a large number of cars are parked in internal parts of the blocks of multi-storey buildings is taken into account when modeling the impact of vehicles on different parts of the landscape. Before 1991, a small number of parking lots in yards was provided in standard projects of improvement of development with multi-storey buildings. In the modern conditions with the explosion of automobilization, which took place in the last decade, the yards were overcrowded with cars, even though the underground parking lots and the surface parking lots were organized away from the residential blocks. With the overcrowding of yards, some cars are parked in yards in the areas that are not intended for this purpose. Self-parking on lawns and playgrounds is widespread in all the cities surveyed, despite the fact that Russian society perceives such parking practices negatively.

A specific condition of the sediment production in the cities of Russia is the long period of cold weather. Temperatures below 0°C and permanent snow cover are established over a large area during the cold period. During the long cold period, most vehicles are equipped with studded tires. The height of the snow cover can reach several tens of centimeters. In spring, the snow melts intensively for 1-2 weeks, which significantly intensifies the weathering process.

According to the results of the calculation made for Ekaterinburg, the average sediment production in a modern Russian city is 1.2 kg/m^2/y. According to Russel et al. (2017) the sediment yield in urban areas without pronounced cold season conditions is defined in the range up to 1.8 kg/m^2/y with a median of 0.33 kg/m^2/y. During the active period of construction - up to 27 kg/m^2/y with a median of 5.4 kg/m^2/y (Russel et al. 2017). More than 1 kg of sediment is found along 1 meter of road curb in a study conducted in British Columbia, Canada (Owens et al. 2011). Though the relationship between the sediment production and sediment yield is indirect, it can be noted that these estimates are close to the results obtained in this paper, while the average sediment production in large Russian cities is above the median and close to the maximum sediment yield in other countries.

The use of studded tires in cold period, illegal parking, disturbed lawns, asphalt and other pavements are the main causes of increased sediment production. Sedimentation is increased by a factor of 2.7 due to the intense anthropogenic impact associated with these factors. In the absence of these causes, the sediment production would be 0.44 kg/m^2/y. This is close to the median value obtained by (Russel et al. 2017).

Yards contribute approximately 14% of solid sediment. In internal parts of the EURL, parking on lawns and the poor condition of asphalt and lawn surfaces are the main causes of higher than ideal sediment production.

In general, Russian cities have a high sediment production. As shown by the modeling, the structure of the causes of the sediment production is to a large extent attributed to negative anthropogenic impacts. The intensive sediment production occurs both on the network of streets and roads, and in the areas of yards.

Increased sediment production is one of the major factors reducing the quality of the urban environment. The sediment storage is associated with negative environmental, medical, infrastructural, psychological and other issues. Reduction of sediment production is an important task of urban environment improvement and, more generally, of modern urbanism as a trend of social life.

Sediment surface storage depends on the rate of sediment production and removal of stored sediment. In the urban catena, the sediment removal is assumed to occur by two ways – natural and anthropogenic. Applying catena simplification, the EURL is located within the hill top and hill slope parts. The lower part of the urban catena is represented by a storm drain system and a waterway bed which is located outside of the EURL. In this way, sediment removal occurs through natural runoff. Wind lifting of the dust sediment fraction also contributes to surface sediment removal. The anthropogenic way involves the removal of the surface sediments during cleaning and other landscaping services. Anthropogenic removal also includes the transport of the USDS by the wheels of vehicles.

Measures to reduce sediment production in urban environment

The developed model of sediment production in the urban environment and further estimations allow to evaluate the effectiveness of various measures for the reduction of sediment production in the cities.

The restriction on the use of studded tires can be considered as a priority measure for the reduction of sediment production in regions with long cold season. In situation when studded tires are banned, the sediment production will decrease from 1.2 kg/m^2/y to 0.44 kg/m^2/y However, this solution involves a number of organizational and technical difficulties. Currently, there are no sufficiently inexpensive innovative type road pavements that can be used to provide the necessary grip with studless tires in freezing and icy conditions. The studless tires do not provide the necessary grip on icy parts of roads and yard driveways. If cold season traffic is reduced, the impact of studs will also be reduced. For example, total sediment production can be decreased from 1.2 to 0.92 kg/m^2/y and the contribution of studded tires would decrease from 44% to 28% if the proportion of cars (or the number of cars in the city) with studded tires is reduced by half. In general, it should be noted that a change in cold season vehicle use practices requires further researches and technological innovations.

Qualitative performance of pavements and lawns repairs on time can reduce the sediment production through the reduction of anthropogenic and natural influences on the disturbed surfaces. In Ekaterinburg, sediment production can be reduced by 19% if the technical conditions of all pavements are properly maintained.

One of the measures for reduction of the USDS accumulation in residential areas can be the increase of the cleaning efficiency. Calculations based on the model (16) show that the amount of the USDS will be reduced to 0.5 kg/m^2 in about 4 years if additional cleaning with the intensity of 1.2kg/m^2/y (i.e. equal to the annual supply) on the territory with the initial level of accumulation of 3.2 kg/m^2 is organized.

Introducing a total ban on parking in residential yards will reduce the anthropogenic impact on surfaces, exclude parking on lawns, and consequently reduce the sediment production of disturbed surfaces. For complexes of new residential buildings, this approach to solving the problem of pollution of residential yards with sediment material is widely used. In this case, such complexes are equipped with large underground and external parking lots. In the residential areas that were built earlier, e.g. before the year 2000, surface and underground parking lots were often not provided. Therefore, measures to restrict vehicle access to internal parts of the EURL designed before 2000 will cause a negative response of car owners, and thus are unlikely to be accepted by the majority of society.

As can be seen from solving equation (16), proper organization of surface runoff plays a certain role in sediment transport and deposition processes. A part of the USDS can be transported out of the yards and get into the storm water drainage system and into other artificial and natural streams. The proper organization of surface runoff is usually a consideration at the design stage of construction of new residential complexes. Previous landscape surveys (Yarmoshenko et al. 2020) have shown that, in general, in most courtyards of multi-storey buildings in Russian cities the runoff is properly arranged, especially the formation of huge puddles is prevented. However, the formation of local low-lying areas (relief depressions) with small puddles and the accumulation of the USDS is not excluded.

Sediment reduction measures must be applied to different parts of the urban landscape. In modern Russian cities, streets and adjacent sidewalks and lawns are the responsibility of the city government. The quality of internal parts and yards are under the responsibility of homeowners. The lack of consistency in environmental quality management may be one of the reasons for the ineffectiveness of sediment production reduction measures.

Full implementation of strict requirements for reduction of sediment production in urban conditions is equivalent to approaching the ideal conditions. Achieving the ideal conditions allow the pollution of the urban environment with the USDS to be reduced to 0.44 kg/m^2/y in Ekaterinburg.

Limitations of the developed model

A number of assumptions and simplifications were made in constructing the model and modeling the sediment production process in this study. These assumptions and simplifications are associated with the uncertainty in the estimates obtained. The main sources of uncertainty of the model are the following ones:

- uncertainty of the coefficients R, K, LS, C, P, h in RUSLE model;
- uncertainty of coefficients describing the dependence of warm season pavement wear on warm and cold seasons vehicle loads;
- lack of qualitative data on vehicle loadings and traffic;
- the variability of the landscape characteristics of the yards and roads.

In general, the above sources of uncertainty can have a significant impact on the results of sediment production estimation for specific real sites. At the same time, with the help of the developed model, the average characteristics for the residential areas of the city can be returned correctly enough for the estimation of the total amount of generated USDS and the contribution of different functional zones and factors.

Generally, there is no strong limitation to apply the developed model of sediment production in the urban environment in other regions of the world. However, not all countries have a residential block organization similar to the Russian one. The situation is quite different in some countries where people live mainly in single-family homes in the suburbs. In this case, it is necessary to apply another model of elementary urban landscape developed in accordance with the conditions of the area under study. The use of different model sites does not change the principles of the model structure, if all estimated factors are taken into account. It is important to note that many factors in the models are also necessary to be adjusted for a specific territory.

CONCLUSIONS

1. A model of sediment production in the urban environment has been developed. The model takes into account both natural and anthropogenic factors and

processes. The model is built using empirical coefficients that take into account the characteristics of natural and anthropogenic influences.

2. According to the results of the modeling, the sediment production in Ekaterinburg is about 1.2 kg/m^2/y and, in other Russian cities, varies from 0.74 to 1.7 kg/m^2/y.

3. The sediment production in a modern Russian city estimated using the model corresponds to the previous assessment of the USDS storage taking into account a reasonable equilibrium between production and removal. The obtained results of the modeling logically explain the differences in the rates of sediment production in the Russian cities and the data on other regions, taking into account the climatic conditions, the greater anthropogenic load in the blocks of multy-storey buildings and the quality of urban management.

4. The quantitative contribution of the different factors in the sediment production in the urban conditions has been determined. It was found that cold season exploitation of vehicles equipped with studded tires account for 44% (about 0.51 kg/m^2/y) of the sediment production. At the same time, even in the case of high requirements for the territory maintenance, the expected sediment production reaches 0.44 kg/m^2/y.

5. Measures to reduce the sediment production in the modern urban environment have been analyzed: restriction on the use of studded tires, cold season traffic reduction, reduction of vehicle load on yard spaces, higher requirements for the technical condition of infrastructure and maintenance of residential areas, etc.

6. The reference USDS removal rate that ensures a high efficiency of the measures to reduce the sediment accumulation is defined.

Declarations All authors certify that they have no affiliations with or involvement in any organization or entity with any financial interest or non-financial interest in the subject matter or materials discussed in this manuscript.

REFERENCES

Aouichaty N., Bouslihim Y., Hilali S., Zouhri A., Koulali Y. (2022). Estimation of water erosion in abandoned quarries sites using the combination of RUSLE model and geostatistical method. Scientific African, 16, e01153, DOI: 10.1016/j.sciaf.2022.e01153.

Arrojo G.M. (2000). Pavement wear caused by the use of studded tyres. DIVA. https://urn.kb.se/resolve?urn=urn:nbn:se:vti:diva-1204.

AUTOSTAT OMNIBUS – 2020. Winter car tires: car owners' preferences (fourth wave). Surveys | AUTOSTAT. Available at: https://www.autostat.ru/research/product/384/.

Basic Information about Nonpoint Source (NPS) Pollution | US EPA. (2022, December 22). US EPA. Available at: https://www.epa.gov/nps/basic-information-about-nonpoint-source-nps-pollution.

Carlsson A., Centrell P., Öberg G. (1995). Studded tyres: socio-economic calculations. Statens väg- och transportforskningsinstitut, Linköping.

Cendrero A., Remondo J., Beylich A.A., Cienciala P., Forte L.M., Golosov V., Gusarov A.V., Kijowska-Strugała M., Laute K., Li D., Navas A., Soldati M., Vergari F., Zwoliński Z., Dixon J., Knight J., Nadal-Romero E., Płaczkowska E. (2022). Denudation and geomorphic change in the Anthropocene; a global overview. Earth-Sci Rev, 233, 104186, DOI: 10.1016/j.earscirev.2022.104186.

Chen C., Zhao G., Zhang Y., Bai Y., Tian P., Mu X., Tian X. (2023). Linkages between soil erosion and long-term changes of landscape pattern in a small watershed on the Chinese Loess Plateau. CATENA, 220, 106659, DOI: 10.1016/j.catena.2022.106659.

Chin A., Beach T., Luzzadder-Beach S., Solecki W. (2017). Challenges of the "Anthropocene." Anthropocene, 20, 1–3, DOI: 10.1016/j.ancene.2017.12.001.

Corradini F., Meza P., Eguiluz R., Casado F., Huerta-Lwanga E., Geissen V. (2019). Evidence of microplastic accumulation in agricultural soils from sewage sludge disposal. Sci Total Environ, 671, 411-420, DOI: 10.1016/j.scitotenv.2019.03.368.

Crosby C.J., Fullen M.A., Booth C.N., Searle D.E. (2014). A dynamic approach to urban road deposited sediment pollution monitoring (Marylebone Road, London, UK). J Appl Geophys, 105, 10–20, DOI: 10.1016/j.jappgeo.2014.03.006.

Di Miceli Da Silveira A., Pereira J.A., Poleto C., De Lima J., Gonçalves F.S., Alvarenga L.A., Isidoro J. (2016). Assessment of loose and adhered urban street sediments and trace metals: a study in the city of Poços de Caldas, Brazil. J Soils Sediments, 16:2640–2650, DOI: 10.1007/s11368-016-1467-5.

Dias-Ferreira C., Pato R.L., Varejão J.M., Tavares A.O., Ferreira A. (2016). Heavy metal and PCB spatial distribution pattern in sediments within an urban catchment—contribution of historical pollution sources. J Soils Sediments, 16(11), 2594–2605, DOI: 10.1007/s11368-016-1542-y.

Filkin N.M., Shaikhov R.F., Buyanov I.P. (2016). Teoriya transportnyh i transportno-tekhnologicheskih mashin: Uchebnoe posobie [Theory of transport and transport-technological machines: Textbook], Perm: FGBOU VO Perm State Agricultural Academy, 230 p. (in Russian)

Gafurov F.G. (2008). Pochvy Sverdlovskoj oblasti [Soils of the Sverdlovsk Region], Ekaterinburg: Urals-University Publishing House, 396 p. (in Russian)

Golosov V., Tsyplenkov A. (2021). Factors Controlling Contemporary Suspended Sediment Yield in the Caucasus Region. Water, 13(22), 3173, DOI: 10.3390/w13223173.

Haynes H.M., Taylor K.G., Rothwell J.J., Byrne P.J. (2020). Characterisation of road-dust sediment in urban systems: a review of a global challenge. J Soils Sediments, 20(12), 4194–4217, DOI: 10.1007/s11368-020-02804-y.

Hewett C.J.M., Simpson C., Wainwrigh J., Hudson S. (2018). Communicating risks to infrastructure due to soil erosion: A bottom-up approach. Land Degrad. Dev., 29(4), 1282–1294, DOI: 10.1002/ldr.2900.

Igwe P.U., Onuigbo A.A., Chinedu O.C., Ezeaku I.I., Muoneke M.M. (2017). Soil Erosion: A Review of Models and Applications. IJAERS, 4(12), 138–150, DOI: 10.22161/ijaers.4.12.22.

Kasimov N.S. (2013). Ekogeohimiya landshaftov [Ecogeochemistry of Landscapes], Moscow, IP Filimonov M.V., p. 208 (in Russian).

Knijff J.M., Jones R.J.A., Montanarella L. (1999). Soil erosion risk assessment in Italy. European Soil Bureau, 19044, 52.

Landrigan P.J., Fuller R.A., Acosta N.J.R., Adeyi O., Arnold R.M., Basu N., Baldé A.B., Bertollini R., Bose-O'Reilly S., Boufford J.I., Breysse P.N., Chiles T.C., Mahidol C., Coll-Seck A.M., Cropper M.L., Fobil J.N., Fuster V., Greenstone M., Haines A., Zhong M. (2017). The Lancet Commission on pollution and health. The Lancet, 391(10119), 462–512, DOI: 10.1016/s0140-6736(17)32345-0.

Larionov G.A. (1993). Eroziya i deflyatsiya pochv: osnovnyye zakonomernosti i protivoerozionnykh meropriyatiy [Experience in calculating soil erosion for the construction of a set of anti-erosion measures], Eurasian Soil Sci., 4, 92–104.

Li X., Liu B., Zhang Y., Wang J., Ullah H., Zhou M., Peng L., He A., Zhang X., Yan X., Yang T., Wang L., Yu H. (2019). Spatial Distributions, Sources, Potential Risks of Multi-Trace Metal/Metalloids in Street Dusts from Barbican Downtown Embracing by Xi'an Ancient City Wall (NW, China). IJERPH, 16(16), 2992, DOI: 10.3390/ijerph16162992.

Lisbôa É.G., Blanco C.J.C., Maia R., Bello L.L. (2017). A stochastic estimation of sediment production in an urban catchment using the USLE model. Hydrolog Sci J, 62(15), 2571–2586, DOI: 10.1080/02626667.2017.1395031.

Lugov S.B. (2013). Vozmozhnosti raschetnoj ocenki iznosa pokrytij pri prognozirovanii koleeobrazovaniya [Possibilities of Calculated Assessment of Wear of Coatings in Predicting Rutting], Bulletin of the Moscow State Automobile and Road Technical University (MADI), No. 4(35), 53-59. (in Russian)

Maltsev K.A., Yermolaev O. (2020). Assessment of soil loss by water erosion in small river basins in Russia. CATENA, 195, 104726, DOI: 10.1016/j.catena.2020.104726.

Merritt W., Letcher R., Jakeman A. (2003). A review of erosion and sediment transport models. Environ Modell Softw, 18(8–9), 761–799, DOI: 10.1016/s1364-8152(03)00078-1.

Michalek A.J., Zarnaghsh A., Husic A. (2021). Modeling linkages between erosion and connectivity in an urbanizing landscape. Sci Total Environ, 764, 144255, DOI: 10.1016/j.scitotenv.2020.144255.

Moore I.D., Wilson J. (1992). Length-slope factors for the Revised Universal Soil Loss Equation: simplified method of estimation. J Soil Water Conserv, 47(5), 423–428. https://www.jswconline.org/content/47/5/423.

Murakami M., Nakajima F., Furumai H., Tomiyasu B., Owari M. (2007). Identification of particles containing chromium and lead in road dust and soakaway sediment by electron probe microanalyser. Chemosphere, 67(10), 2000–2010, DOI: 10.1016/j.chemosphere.2006.11.044.

Najafi S.K., Dragovich D., Comiti F., Sadeghi S.H. (2021). Sediment connectivity concepts and approaches. CATENA, 196, 104880, DOI: 10.1016/j.catena.2020.104880.

Owens P.N. (2020b). Soil erosion and sediment dynamics in the Anthropocene: a review of human impacts during a period of rapid global environmental change. J Soils Sediments, 20(12), 4115–4143, DOI: 10.1007/s11368-020-02815-9.

Owens P.N., Caley K.A., Campbell S.N., Koiter A.J., Droppo I.G., Taylor K.G. (2011). Total and size-fractionated mass of road-deposited sediment in the city of Prince George, British Columbia, Canada: implications for air and water quality in an urban environment. J Soils Sediments, 11(6), 1040–1051, DOI: 10.1007/s11368-011-0383-y.

Pereira Pa.A., Ferreira A., Sarah P., Cerdà A., Walsh R.P.D., Keesstra S. (2016). Preface. J Soils Sediments, 16(11), 2493–2499, DOI: 10.1007/s11368-016-1566-3.

Polluted Runoff: Nonpoint Source (NPS) Pollution | US EPA (2023, March 16) US EPA. Available at: https://www.epa.gov/nps.

Renard K.G., Foster G.R., Weesies G.A., Porter J.I. (1991). RUSLE: Revised universal soil loss equation. J Soil Water Conserv., 46(1). 30–33.

Renard K.G., Foster G.W., Weesies G.A., McCool D.K., Yoder D.C. (1997). Predicting soil erosion by water: a guide to conservation planning with the Revised Universal Soil Loss Equation (RUSLE).

Restrepo J.M., Syvitski J.P.M. (2006). Assessing the Effect of Natural Controls and Land Use Change on Sediment Yield in a Major Andean River: The Magdalena Drainage Basin, Colombia. AMBIO, 35(2), 65–74, DOI: 10.1579/0044-7447(2006)35.

Romkens M.J.M., Baumhardt R.L., Parlange M.B., Whisler F.D., Parlange J.Y., Prasad S.N. (1986). Rain-induced surface seals: their effect on ponding and infiltration. Annales Geophysicae, 4, B(4), 417–424.

Russell K.M., Vietz G., Fletcher T.D. (2017). Global sediment yields from urban and urbanizing watersheds. Earth-Sci Rev, 168, 73–80, DOI: 10.1016/j.earscirev.2017.04.001.

Seleznev A.A., Ilgasheva E., Yarmoshenko I.V., Malinovsky G. (2021). Coarse Technogenic Material in Urban Surface Deposited Sediments (USDS). Atmosphere, 12(6), 754, DOI: 10.3390/atmos12060754.

Seleznev A.A., Shevchenko A.V., Gluhov V.S., Malinovsky G.P. (2022). Assessment of the sediment supply from the catchment into a water body in an urban area. TR-MNT, 4, 13–29, DOI: 10.56564/27825264_2022_4_13.

Seleznev A.A., Teterin A., Yarmoshenko I.V. (2020). Meteorological conditions of surface sediment runoff formation during spring snowmelt in urban areas. IZVESTIYA, DOI: 10.18799/24131830/2020/2/2476.

Seleznev A.A., Toropov A.S., Okuneva T.G., Kiseleva D.V., Yarmoshenko I.V., Ryanskaya A.D. (2023). Migration of natural radionuclides in the system «hydrocriogenic components - water - ground waters of born waters» in citizens' waters. Proceedings of Tomsk Polytechnic University, 334(5), 189-204, DOI: 10.18799/24131830/2023/5/3969.

Seleznev A.A., Yarmoshenko I.V., Malinovsky G. (2019a). Assessment of Total Amount of Surface Sediment in Urban Environment Using Data on Solid Matter Content in Snow-Dirt Sludge. Environ. Process., 6(3), 581–595, DOI: 10.1007/s40710-019-00383-w.

Seleznev A.A., Yarmoshenko I.V., Malinovsky G. (2020). Urban geochemical changes and pollution with potentially harmful elements in seven Russian cities. Sci Rep, 10(1) , DOI: 10.1038/s41598-020-58434-4.

Seleznev A.A., Yarmoshenko I.V., Malinovsky G., Ilgasheva E., Baglaeva E., Ryanskaya A., Kiseleva D., Gulyaeva T. (2019b). Snow-dirt sludge as an indicator of environmental and sedimentation processes in the urban environment. Sci Rep, 9(1) , DOI: 10.1038/s41598-019-53793-z.

Stojiljkovic A., Kauhaniemi M., Kukkonen J., Kupiainen K., Karppinen A., Denby B., Kousa A., Niemi J.K., Ketzel M. (2019). The impact of measures to reduce ambient air PM10 concentrations originating from road dust, evaluated for a street canyon in Helsinki. Atmos. Chem. Phys., 19(17), 11199–11212, DOI: 10.5194/acp-19-11199-2019.

Syvitski J., Ángel J.R., Saito Y., Overeem I., Vörösmarty C.J., Wang H., Olago D. (2022). Earth's sediment cycle during the Anthropocene. Nat Rev Earth Environ, 3(3), 179–196, DOI: 10.1038/s43017-021-00253-w.

Taoufik M., Loukili I., Hadi H.E, Baghdad B. (2020). Soil erosion risk assessment in an extraction area: Case of abandoned quarries in the Akreuch region (Morocco). IEEE International conference of Moroccan Geomatics (Morgeo), DOI: 10.1109/morgeo49228.2020.9121910.

Taylor K. (2007). Urban environments. In: Perry C, Taylor K (eds) Environ Sediment, Wiley-Blackwell, Hoboken, 190–222.

Taylor K.G., Owens P.N. (2009). Sediments in urban river basins: a review of sediment–contaminant dynamics in an environmental system conditioned by human activities. J Soils Sediments, 9(4), 281–303, DOI: 10.1007/s11368-009-0103-z.

Turevsky I.S. (2005). Teoriya avtomobilya: Ucheb. posobie [Car Theory: Textbook], Moscow: Vyssh. shk. 240 p., ISBN 5-06-004615-X.

Vasiliev A.P., Balovnev V.I., Korsunsky M.B. (1989). Remont i soderzhanie avtomobil'nyh dorog: Spravochnik inzhenera-dorozhnika [Repair and maintenance of highways: Handbook of road engineer], edited by A. P. Vasiliev, M.: Transport, 287 p. (in Russian)

Waters C.N., Zalasiewicz J., Summerhayes C., Barnosky A.D., Poirier C., Gałuszka A., Cearreta A., Edgeworth M., Ellis E.C., Ellis M., Jeandel C., Leinfelder R., McNeill J.R., Richter D.D., Steffen W., Syvitski J., Vidas D., Wagreich M., Williams M., Wolfe A.P. (2016). The Anthropocene is functionally and stratigraphically distinct from the Holocene. Science, 351(6269) , DOI: 10.1126/science.aad2622.

Wischmeier W.H., Smith D.J. (1978). Predicting rainfall erosion losses: a guide to conservation planning. In Predicting rainfall erosion losses - a guide to conservation planning, vol. 537, p. 62.

Yarmoshenko I.V., Malinovsky G., Baglaeva E., Seleznev A.A. (2020). A Landscape Study of Sediment Formation and Transport in the Urban Environment. Atmosphere, 11(12), 1320, DOI: 10.3390/atmos11121320.

Yu B., Rosewell C. (1996). Rainfall erosivity estimation using daily rainfall amounts for South Australia. Soil Res, 34(5), 721, DOI: 10.1071/sr9960721.