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Opportunities and Prospects of Suspended Sediment Source Tracing for Urban Catchment Management

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ABSTRACT

Relevance. Assessment of contribution of various sources (processes, territories), in particular suspension, to river pollution is an essential component of developing measures for reducing the negative impact on the river system. In Russia, this approach is only being developed though it has long been a key one in municipal services of many countries. The paper reviews application of the sediment source tracing method (also known as "fingerprinting") and its adjustment to an urbanized catchment area using different statistical algorithms, typical sources of pollution of urban rivers being analyzed. **Methods.** The method tested on the Setun River basin located within the Moscow agglomeration is based on sampling substrates from sources and at a control point, laboratory suspended sediments trace analysis, selection of representative tracers, as well as direct modeling of source contribution using statistical models of mixture separation, such as FingerPro, simmr, MixSIAR, Sed_SAT, SIFT. **Results.** Unification of terms used when employing this method is proposed. The authors consider the results of a three-pronged division of samples in the catchment area: soils in open ground areas, road dust, and riverside erosion, concluding that in most urbanized basins, riverside ledges are the main source of suspension, the process of riverside erosion being a key factor in the formation of suspension, which determines the relevance of measures for stabilizing the bank line.

KEYWORDS: suspended sediment source tracing method, fingerprinting, suspended sediments, pollution sources, mixing models, FingerPro, MixSIAR, simmr, tracers, source contribution, urban area.

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INTRODUCTION

The worldwide increase in the rate of soil erosion due to both changes in the structure of land use [1] and growing frequency of extreme hydrological and meteorological phenomena [2, 3] affects the increased transport of fine sediment fractions (suspensions) accompanying the movement of the main pollutants to river systems [4]. One of the urgent tasks of practical importance in developing catchment management schemes is to assess the source contribution to river pollution.

Sediments mobilized in a catchment area can have various physico-chemical characteristics (concentrations of macro- and microelements, granulometric composition, organic matter content, radioactivity, etc.); their mixtures at the "target" points, in accumulative bodies in the lower parts of catchments, in the mouths of watercourses, and the bottoms of reservoirs often making it possible to determine fractional contribution of sources in the catchment area to the supply of sediments to the target. The corresponding statistical analysis technique is called fingerprinting in the international literature. It should be noted that the technique is applied specifically to suspensions taking into account the predominant transfer of pollutants in finely dispersed fractions of suspended sediments. In Russian studies, the method is called either fingerprinting or "search for feeding provinces" (in the geological literature), which does not correspond to the scale of the study of redistributing suspensions in river basins.

Taking into account the meaning of the method, in this work, the term – *suspended sediment source tracing method* – is understood as a set of procedures for identifying and quantifying the contribution of suspended matter sources to rivers. The suspended sediment source tracing method includes a number of stages from sampling sources and a target to statistical evaluation of source contributions. *Sources* are defined as homogeneous areas or substrates in a catchment area from which sediments enter a water body and form *a mixture* by mixing materials from different sources. *Tracers* are quantitative physical or chemical characteristics that make it possible to distinguish statistically sources by their contribution to suspension transfer. A separate sample of the mixture is *the target sample*. *A target* is a lithodynamically homogeneous object or medium in which a mixture is formed (for example, a water mass in a channel at a river station, bottom sediments or an accumulative body). The place of sampling the target is called a *control station or a control site*. To quantify the contribution of sources, mixing/unmixing models are used, which include both mixing models

(the mixture composition is estimated based on information about sources) and unmixing models (the sources are determined based on the mixture data). Contribution modeling is the last stage in the implementation of the suspended sediment tracing method. The procedure for statistical decomposition of a mixture into contributions from sources is *unmixing*.

This method plays a key role in the development of strategies for protection of land and water resources, sustainable landscape management within catchment areas, and management of the water management complex of territories [5]. In Russia, the suspended sediment source tracing method is much less widespread. It was used in works on the Western Dvina [6] where the integrated approach including hydrological modeling (SWAT), separation of runoff sources using EMMA analysis and fingerprinting using geochemical elements and radionuclide ^{137}Cs was applied. The method was used to identify the sources of pollutants entering the Avacha Bay (Kamchatka) [7].

One of the key tasks of the method is its adaptation to the conditions of an urbanized landscape. The suspended sediment source tracing method in cities uses a standard list of sources, the combinations of which vary depending on the specific study: riverside ledges, surface soil layer, road dust, as well as sediments from construction sites [8-11]. For the first time in Russia, this method is used to assess the impact of urbanization on pollution of Moscow rivers along with other approaches to assessing sediment redistribution in small river catchments of the city [12, 13]. It is applied to the located within the city Setun River basin, which includes fundamentally different territories of different economic use: residential, public and industrial zones, as well as relatively small unchanged natural landscapes.

The purpose of this work is to review the world experience in using suspended sediment source tracing method (urban areas included) and to develop a concept for investigating the contribution of potential sediment sources in the small river basin of the Setun River (Moscow) on this basis. The differentiation of sources of suspended sediments entering the mouth of the Setun River from its catchment area, which is the first stage in the application of the methodology, is considered.

OBJECT AND METHOD OF RESEARCH

The history of the sediment source tracing method

Initially, the sediment source tracing method was applied in the second half of the 20th century [14, 15] and aimed at identifying sources using mineral composition of suspended sediments [14]. The approaches used were largely qualitative,

i.e. they consisted in describing and visually comparing properties of sediments to identify sources of pollution. This laid the foundation for the formation of a future methodology for tracing suspension sources, the main English-language term of the technique 'fingerprinting' had not been introduced yet. The method began to develop when radioactive isotopes, in particular ^{137}Cs, were used as tracers [16, 17]. Both anthropogenic (^{137}Cs) and natural radionuclides (^{210}Pb, ^{7}Bc) approaches were proposed to use as tracers, their characteristics minimally depend on the lithology of rocks [16].

Transition from qualitative to quantitative approaches in tracing suspension sources was in the study [17] in which characteristics of suspended sediments were correlated with their potential sources – soils and riverbed sediments. Mineralogical and magnetic parameters of sources, the content of radionuclides, organic carbon and nitrogen, phosphorus were used as tracers; the granulometric composition of sediments being analyzed. The key stage in the development of the method was the work of E. Collins [18], where the system identification of sediment sources was implemented for the first time (Fig. 1). Using the example of watersheds in Great Britain (the Severn River), the researcher considered various eroded soils and riverbed sediments as sources; a wide range of tracers(geochemical elements, radionuclides, and organic carbon) also used .The criteria for selecting tracers included availability of analysis, stability (conservativeness) during transportation, and distinguishability of sources (discrimination with tracers). At the initial stage, selecting tracers for sediment identification was based on hypotheses rather than statistical procedures.

Since the late 1990s and early 2000s, the sediment source tracing method has been rapidly developing both theoretically and practically. The set of tracers for identifying sources has expanded, and statistical approaches to estimating the contribution of sources have been actively developed. Geochemical markers have become widely applied [18], radioactive isotopes used to estimate the transit time of sediments in the riverbed network [19].

A significant contribution to unification of the sediment source tracing method was the study [20] that proposed three stages of selecting the most informative tracers: 1) range test – stability of the marker during transportation: when moving from the source to the control point the tracer must retain its properties; 2) statistical distinguishability of tracers between sources – verification using Mann–Whitney tests (for two sources) or Kraskel–Wallis (for three or more sources); 3) based on the λ Wilkes criterion, discriminant function analysis

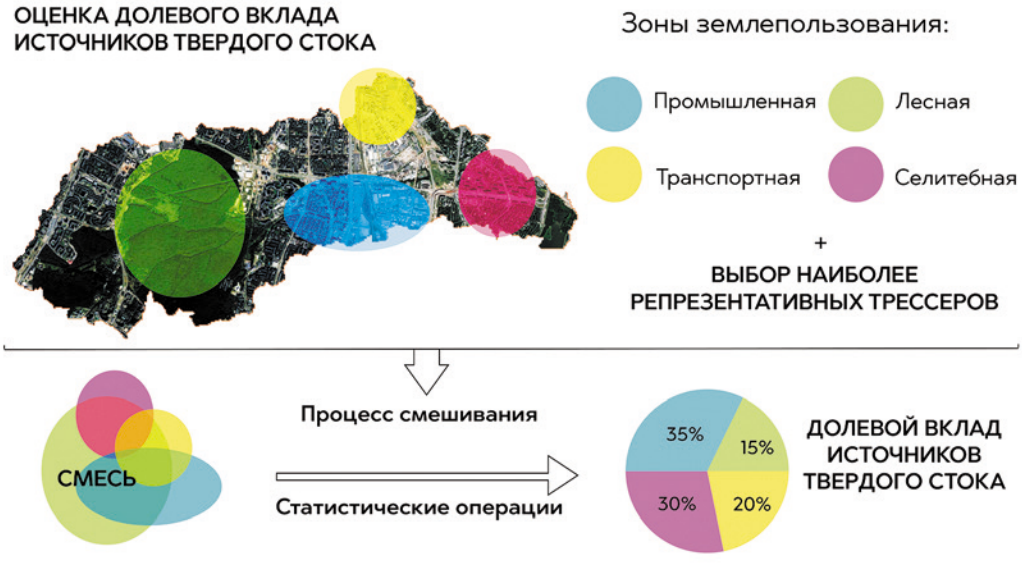


Figure 1. Graphic representation of the fingerprinting method.

(DFA) performing a step-by-step selection of the minimum number of tracers that can distinguish all sources. However, some authors criticize the use of DFA since using a large number of markers reduces the contribution of non-conservative tracers to the overall result [21, 22], therefore parallel verification with and without DFA is recommended [23].

From the 2010s to the 2020s, environmental DNA (eDNA) began to be used as a tracer in the sediment source tracing technique [24], unmixing models were created, and the first attempts to form global databases were made (Collins et al., 2017; Owens et al., 2016). The Isosource and MixSIAR models [27] were difficult to apply. They were improved with SIAR in R [28] using Markov Chain Monte Carlo algorithms (MCMC). The MixSIAR model [29], an R package based on the Bayesian approach, was a breakthrough in the quantitative analysis. This approach made it possible to describe uncertainty in sediment sources and processes correctly, the model providing a significant narrowing of confidence intervals of estimates, which indicates an increase in the accuracy of calculations. MixSIAR was originally developed to evaluate animal food chains. Later it was successfully adapted for solving sediment fingerprinting tasks.

Concurrently, classical probabilistic models were actively developing, in particular the FingerPro model in R with the open source on GitHub used for estimating the solid matter sources contribution to river systems [30]. The model was subsequently improved by switching from the three-stage method (TSM) of tracer selection (the initial version) to the Consensus Method (CM) including the following methods of tracer selection: Conservative Index (CI), Consensus Ranking (CR) and Consistent Tracer Selection (CTS) leading to increased accuracy and stability (Lizaga et al., 2020). The current stage of fingerprinting is characterized by the development of a new Bayesian simmr (Stable Isotope Mixing Model in R). It appeared in 2023 making it possible to use both the classical Markov Chain Monte Carlo algorithm (MCMC) with JAGS, and Fixed-Form Variational Bayes (FFVB) – an accelerated procedure for obtaining an approximate solution [27].

The sediment source tracing method is applied ranging from individual slopes and small watercourses to basins with an area of over 10,000 km^2 [5]. The most intense growth in interest to the method has been in the UK, the USA, China, Spain, Iran, France, Brazil and Australia [5]. In China, a large number of studies are devoted to desert zones [32-34]. In Iran, lowland territories exposed to anthropogenic influences are studied [35]. Great Britain and Spain have foothill and agricultural areas, partly with anthropogenic disturbed catchments [18, 36]. In each region, the method adapts to local physical and geographical conditions, the latter affecting the choice of tracers. The present stage of the method development is characterized by a tendency towards the integrated use of various groups of tracers and mixture separation models based on Bayesian statistics [27-29, 37].

Sediment source tracing technique

The implementation of the method consists of several key stages: testing sources and targets, laboratory processing and analysis, choosing a mixture separation model, selecting the most representative tracers that take into account the specifics of the landscape, as well as interpreting the results obtained using models evaluating the contribution of sediment sources. The method of sampling, laboratory data analysis, the approach to selecting representative tracers and the model of estimation of source contribution should be considered as elements of a unified system.

Field and laboratory work

The source selection program is determined by the type of landscapes, soil and geological conditions, spatial and temporal variability of sources, etc. [5]. Three main approaches are considered as sources of sediment intake: different substrates, catchments (subbasins), and land use zones. Sources can be allocated according to the following land use zones: transport, industrial, residential, natural, recreational, a zone without residential real estate [8, 38-40]. In addition, sources are determined by the type of substrate, for example, surface soils, road dust, riverside ledges, suspended sediment from sewage collectors, etc. [41, 42]. There is also an approach based on allocation of sources by subbasins, i.e. small catchments that are parts of the catchment area under study [43]. Each of these options has both pros and cons. Therefore, the choice of approach should be based on the specifics of a particular watershed and the tasks assigned in the study (Fig. 2).

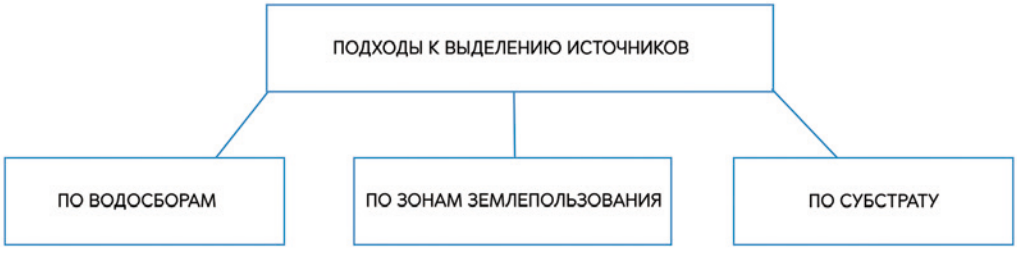


Figure 2. Approaches to identifying sources of suspended sediment from the catchment to the river system.

As a substrate in the target there are used suspended sediments, alluvial soils, bottom sediments, and fresh accumulative strata (silt) [44-46]. As a rule, fine-grained sediments of < 63 microns are analyzed. They concentrate the largest amount of pollutants [5, 47]. The data are pre-filtered, e.g. parameters of high uncertainty are discarded [23]. Recording the granulometric composition of sediments (PSC correction, SSA) is an important aspect of the sediment source tracing method [48]. In most of mixture separation models under study, there is no block including particle compensation, therefore one should take this limitation into account and prepare data before starting the modeling process.

Selecting tracers for identification of pollution sources

Identification of tracers that can reflect spatial differentiation and composition of suspended matter sources to the best advantage [5, 49, 50] is the most important task of the first stage of the method. When choosing tracers, the key factor is their conservativeness. Conservative tracers (e.g. heavy metals and metalloids, rare earth elements, radionuclides) have stable behavior during transportation in the riverbed system making them preferable when evaluating determination of suspension sources. In contrast, organic tracers are characterized by non-conservative behavior, which requires additional adjustments in calculations [25].

There are used different groups of tracers:

1. Macro- and microelements – inorganic indicators (Al, Fe, K, Mg, Ti, heavy metals and metalloids, rare earth elements). The advantage is high accuracy of their analytical determination even at low concentrations of elements in samples due to the use of inductively coupled plasma mass spectrometry (ICP-MS) or X-ray fluorescence analysis (XRF).

2. Organic markers – bioindicators (biomarkers and stable carbon isotopes $\delta^{13}C$ и nitrogen $\delta^{15}N$ used to assess vegetation and soil sources). The isotopic composition of carbon and nitrogen is highly informative in assessing differences in vegetation sources, it particularly widely used in agricultural landscapes [51]. Organic matter contains biomarkers that consistently reflect the specifics of soil and vegetation cover or anthropogenic sources of pollution.

3. Radionuclides. They include both anthropogenic isotopes (for example, ^{137}Cs) and natural ones – ^{210}Pb used to assess erosion processes [19, 52]. Anthropogenic radionuclide ^{137}Cs, which appeared after the nuclear tests of the 1950s and 1960s, is widely used as an indicator of surface erosion due to its stable fixation in the upper soil horizon (0-20 cm) [53].

4. Magnetic susceptibility (χ) characterizes the ability of materials to respond to an external magnetic field. An essential feature of magnetic susceptibility is its relation to the granulometric composition of sediments. Different fractions of sediments possess different magnetic properties, the latter facilitating measurements in narrow granulometric ranges [54].

5. Specific markers, such as compounds $\delta^{13}C$ and isotopic signatures of fatty acids (CSSI), definite radionuclides [5]. There are used colour indicators, isotopic signatures of CSSI fatty acids, environmental DNA (eDNA), stable ratio of oxygen isotopes (^{18}O) in phosphate ($\delta^{18}O_p$). There is also a

method for determining the spectral properties of substrates, which is based on the analysis of reflection spectra and optical density in the visible, ultraviolet and infrared ranges [55]. With the help of colour characteristics, it is possible to identify the level of organic matter, heavy metals and metalloids, and also use them to identify both types of land use (forest, pasture, arable land) and sediments from various soil horizons.

Stable results are achieved by combining different groups of tracers [51]. Modern studies demonstrate dynamics of an increase in the number of tracers used, as well as a steady trend towards combining groups of markers to identify sources [56]. Increasing the number of tracer groups can raise reliability of calculating contributions using mixture separation models [5]. However, the a priori choice of tracers has a fundamental impact on accuracy and reliability of estimates with the help of models because inclusion of non-conservative markers can reduce the overall quality of model estimates [23].

The choice of tracers can be based on both statistical methods and an expert assessment of their chemical and physical properties [25]. For example, to identify sources of suspended matter in an agricultural landscape, one had better give preference to organic markers, whereas in a forest fire zone one had better choose magnetic susceptibility [57].

Numerical implementation of the calculation

The numerical implementation of the sediment source tracing method is determined by the separation procedure (unmixing), on the basis of which the composition of suspended sediments in the sources in the catchment area is compared with the composition of the suspension at the control point using statistical methods. The optimal ratio between the sources is being searched for. The relative contribution of each sediment source is determined by equation (1) which satisfies the constraints of equation (2) [58].

$$\sum_{j=1}^{m} a_{i,j}\,\omega_j = b_i, \tag{1}$$

$$\sum_{j=1}^{m} \omega_j = 1 \qquad 0 \le \omega_j \le 1, \tag{2}$$

where b_i is the concentration of tracer i in the target sample;

$a_{i,j}$ represents the concentration of tracer i in source j;

w_j is the unknown relative contribution of source j;

m is the number of potential sediment sources;
n is the number of selected tracers.

The models are based on the Markov Chain Monte Carlo algorithm to implement the separation procedure. Unlike models using the classical probabilistic approach, models on Bayesian statistics, such as simmr or MixSIAR, are based on different versions of the initial a priori proportion of sources, i.e. they verify correctness of the separation procedure – how accurately the prediction of source contributions is done. Artificial [59] or virtual mixtures [60] are used for this purpose. An artificial mixture is a mixture from several real sources modeled in the laboratory, proportions being specified; then it is checked whether the model can correctly restore the specified proportions. A virtual mixture represents a statistical reconstruction of the separation process allowing scientists to do model calibration based on simulation data. This makes it possible to assess the level of uncertainty of results and provides a more reliable solution [27-29, 37].

The quality of the model approximation is determined with the GOF consent criterion on the FingerPro. It should be noted that despite the high values of the model fit criterion (GOF) [61], this indicator is not a guarantee of prediction accuracy [56]. It is the checks on artificial or virtual mixtures that make it possible to verify that the model determines contributions of sources of suspended matter to the river network correctly.

$$GOF = 1 - \frac{1}{n}\sum_{i=1}^{n}\left\{\left(\frac{b_i - \sum_{j=1}^{m} x_i a_{i,j}}{\Delta_i}\right)^2\right\}, \quad (3)$$

where $a_{i,j}$ is the average concentration of tracer i in source j (j = 1 to m);
b_i is the concentration of tracer i (i = 1 to n) in the target sample;
x_j is the relative contribution of source j to the target sample;
m is the number of potential sediment sources;
n is the number of tracers.

Software implementation of the sediment source tracing method is performed in different complexes SIFT [62], Sed_SAT [65], FingerPro [31], MixSIAR [29], and simmr [27, 28, 37] (table).

The SIFT model based on the classical probabilistic approach implements the standard stages of fingerprinting [62]. The Sed SAT model additionally in-

Table. Software packages for suspended sediment source tracing

Model	Statistical approach	Research examples	Source
FingerPro	Classical statistics	[36] https://doi.org/10.1016/j.jenvman.2020.111020 (agricultural catchment area), [64] https://doi.org/10.3390/su151511856 (mining-influenced catchment)	[31] (https://doi.org/10.1007/s11269-020-02650-0)
Sed_SAT	Classical statistics	[41] https://doi.org/10.1002/rra.3325 (urbanized catchment)	**[65]** (https://doi.org/10.3133/ofr20171062)
SIFT	Classical statistics	[66] https://doi.org/10.1002/hyp.13736 (four contrasting catchments)	**[62]** (https://doi.org/10.1016/j.scitotenv.2018.04.126)
MixSIAR	Bayesian approach, MCMC – complex with random and fixed effects	[67] https://doi.org/10.1016/j.geoderma.2017.12.008 (arable lands in Austria)	**[29]** (https://doi.org/10.7717/peerj.5096)
SIMM	Bayesian approach, simplified MCMC	[67] https://doi.org/10.1016/j.geoderma.2017.12.008 (arable lands in Austria)	**[28]** (https://doi.org/10.1371/journal.pone.0009672), [37] (https://doi.org/10.1002/env.2221), [27] (https://doi.org/10.48550/arXiv.2306.07817)

cludes a block where corrections for the organic matter content and the granulometric composition of sediments, as well as filtering emission points tests are done [65]. Besides, FingerPro, based on the classical probabilistic approach with a three-step method (TSM) of tracer selection and visualization of the results is a widely applied model. The latest version of the FingerPro model integrates the consensus method (CM), which is considered an improved alternative to the three-step method (TSM) [31]. The advantage of FingerPro is the data visualization unit available, which helps researchers to pre-evaluate differentiation of sediment sources and see the presence of abnormal measurements or emissions. However, the model does not have a block including correction for the granulometric composition of sediments, and there is no block for calibrating data using virtual mixtures.

Of the Bayesian statistics models, the MixSIAR model used in R with JAGS [29] is the most widespread. It provides a posteriori estimation of source contributions based on Markov Chain Monte Carlo algorithms (MCMC). The advantage of the model is the ability to fine-tune it for a specific study, as well as calibrate data on sets of virtual mixtures that simulate all possible combinations of sediment source contribution at the control point [56, 60]. A similar statistical approach is used by the simmr model [27].

RESULTS AND THEIR DISCUSSION

Global experience in applying the sediment source tracing method to an urbanized landscape

Papers [9, 38, 42, 68] study tracing suspension sources in pollution of urbanized rivers [9, 38, 42, 68]. The specific character of applying the method in these conditions is the following: the predominant sources of sediments entering the river network or accumulating them in intermediate reservoirs are often technogenically transformed soils: construction sites, accumulations of road dust, man-made flower beds, sediments from filled-in erosion forms, etc. [9]; some sediment sources may be difficult to account for due to the high spatial mosaic character of urban surfacing; artificial drainage systems, storm water sewers, and industrial waste can make a significant, and sometimes decisive, contribution.

Using riverbed [44-46] (rather than accumulative bodies) suspended sediment samples as a target substrate is typical of urban rivers. This is explained by the fact that riverbeds can be cleared, whereas accumulative surfaces along

river banks can characterize either a long-term picture or individual extreme events, but do not correspond to the current background sediment runoff from the catchment area. High seasonality of contribution of certain suspension to urban rivers can be considered its specifics. It is necessary to take into account seasonality among other things due to the use of deicing reagents in winter [42].

Classical approaches to selecting representative tracers are retained for watersheds located in urbanized landscapes. Most studies employ a sequence of tests: range test, Kruskal-Wallis test (KW) and DFA. Principal component analysis (PCA) is often used to make a preliminary assessment of the data structure. In an urbanized landscape, due to the high concentrations of pollutants accumulating on fine particles, it is extremely important to adjust the granulometric composition of suspended solids, as well as the content of organic matter (TOC) [69].

Examples of regional research indicate applying the sediment source tracing method to small catchment areas of the order of the first tens of km^2 [9, 70] and prove the predominant role of riverside erosion [8, 10, 38, 41, 71]. In the urbanized catchment area of the Dead Run Stream, VA (the USA), riverside ledges were found to form from 70 to 76 per cent of suspended sediments in the upper and, accordingly, in the lower reaches of the river, especially during periods of high water content [71]. In the upper reaches of the Difficult Run Stream, VA (the USA), riverside contribution to suspended sediments reached 91per cent and bottom sediments – up to 98 per cent [41]. The degree of overregulation of the riverbed was considered separately in a number of papers [38, 41], indicating that contribution of riverside ledges was no more than 40 per cent under conditions of strong regulation and increased to 45-85 per cent in the natural channel of the urban environment [8].

The contribution of road dust becomes especially noticeable after rains [8, 41]. So, in the urbanized basin of the Dead Run Stream, VA (the USA), more than 50 per cent of suspended solids after heavy rainfall accounted for road dust, but sediments from roads do not settle in the riverbed [41]. In the Anacostia River basin, Maryland (the USA), contribution of road dust was 13 per cent [38]. A high contribution of road dust (25-45 per cent) was registered in the urbanized catchment area of the Dead Run Stream, Baltimore, MD (USA) in the sewer outlet area. Downstream, the contribution of dust decreased to 15 per cent in the suspension, erosion of riverside ledges being the dominant source [42]. Drainage and filtration systems have reduced the contribution of

road dust from 35 to 23 per cent. However, dust remains a priority source of pollutants in the catchment area [42].

A number of publications emphasize the importance of including construction sites in the list of potential sources [39, 40, 68]. In the urbanized catchment area in Alabama (the USA), fine fraction from construction sites in suspended sediments had 30-40 per cent higher concentrations of a number of heavy metals (Ni, V, Pb). Contribution of construction sites to suspended sediments reached up to 100 per cent for the fine fraction [68], and up to 91 per cent in bottom sediments in the lower reaches [39]. This indicates that excluding construction sites from the list may lead to incorrect assessment of source contribution and the absence of a granulometric correction may underestimate the contribution of man-made sources of pollution.

Many researchers include surface soils in the list of sources of urban pollution [8, 40, 72]. However, the share of surface soils in the city even in urbanized landscapes including agricultural zones does not exceed 10 per cent [72]. At the same time, as a rule, in agricultural territories, soils determine the intake of suspensions and remove up to 70 per cent of pollutants [43].

Applying the sediment source tracing method to the Setun River basin

The review made allowed us to develop a conceptual framework for studying the sources of suspended matter in the basin of the Setun River, which is the largest tributary of the Moskva River within the agglomeration experiencing a constant increase in the degree of urbanization of the territory. About a third of the area of the Setun River basin is occupied by the administrative and residential sector, industrial zones ("Ochakovo", the largest brewery in Moscow) and the roadway (MKAD section). The soil cover in urban areas is fragmented and best preserved in forests and forest-park zones [63].

During the period of 2019-2023 there were collected 211 samples from sediment sources in the basins of the Setun River and its tributaries – the Navershka and Ochakovka rivers: 124 – surface soil layer, 77 – road dust, 10 – sediments from riverside ledges. Suspended sediment samples were taken at the mouth of the Setun River – 76 samples over four years, about once per month. Samples from the sources were separated, all mineral grains of the size bigger than sand were screened out. In the target, such separation is actually carried out by the river itself. In laboratory conditions, with the help of the method of fractional precipitation in a centrifuge samples from sources and targets were divided into fractions of different sizes: less than 1 micron (PM1), 1-10 microns

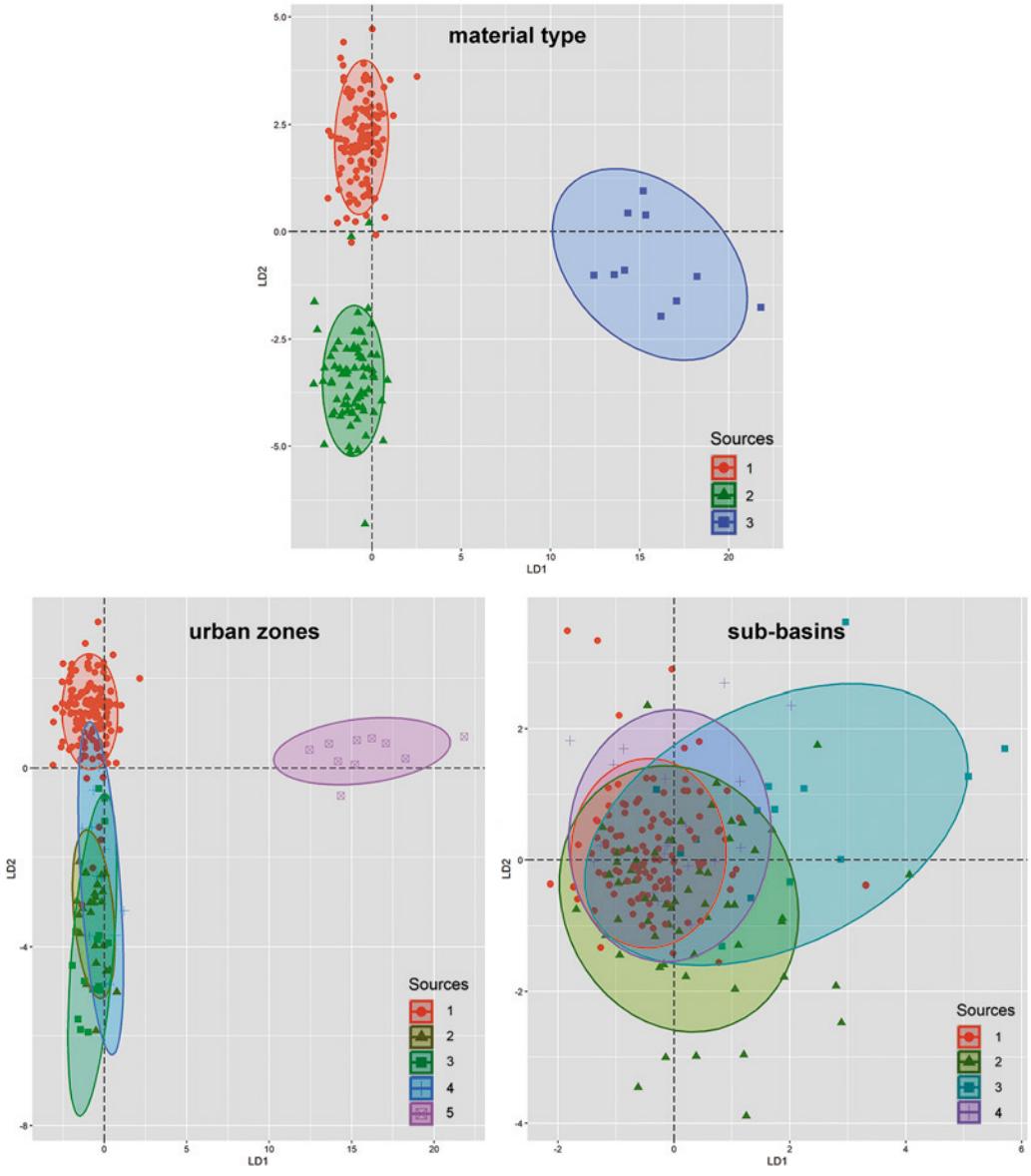


Fig. 3. Separability of potential sediment sources in the Setun River catchment according to three different approaches: material types – 1) soils, 2) road dust, 3) river alluvium; urban zones – 1) transport zone, 2) residential and mixed-use zone, 3) slightly modified areas and anthropogenic green zones, 4) industrial zone, 5) valley bottoms; sub-catchments – 1) The Upper Setun basin, 2) the Navershka basin, 3) the Ochakovka basin, 4) the Lower Setun basin.

(PM1-10) and gross fraction. Using the method of inductively coupled plasma mass spectrometry (ICP-MS) there was made chemical analysis in all three dimensions; concentrations of micro- and macronutrients determined, a total of 54 chemical elements uniformly calculated.

There were analyzed three possible approaches to the classification of sediment sources in the catchment area of the Setun River: the basin, urban land use zones, and the "substrate" . The latter was the basic one when developing the study design. When projecting the entire data set for sources into a two-dimensional space with the linear discriminant analysis method there was evaluated separability of different classes, with visual interpretation provided (Fig. 3).

When differentiating by substrate type, there was obtained a clear separability of classes. The division into sub-basins, each of which includes both sections of the moraine plain and man-made processed surfaces in the interfluves, as well as slopes and bottoms of preserved river valleys that were not destroyed by urbanization, did not turn out to be successful due to the uniformity of the relief and geological structure of the territory. When differentiating the complete set of 214 sampling points by land use zones, only two zones were well isolated: the transport one, which includes mainly samples of road dust, and the natural one (alluvium of the bottom of the valley of the Setun River and its tributaries). The other zones – residential (together with the public and business zone similar in geochemical spectrum), industrial, and slightly modified sections of parks and public gardens – turned out to be very close in the multidimensional space of the tracers. The intuitively expected patterns were not found here. Moreover, some of the 'most polluted' samples were found in parks and public gardens.

Thus, the substrate type and land-use zones are considered to be the main types of sources for identifying pollution within the catchment area of the Setun River. Further statistical processing will make it possible to obtain estimates of contribution of soils, road dust and riverside ledges and justify measures to reduce river pollution; for the first time the task involving implementation of the sediment sources tracing method for different fractions: less than 1 microns (PM1), 1-10 microns (PM1-10) and gross fraction.

CONCLUSION

The paper provides an overview of the history of developing and applying the sediment source tracing technique, which is an effective tool for identifying sources of suspended solids in an urban landscape. It is reasonable to use macro- and microelements as the most informative tracers.

The revealed principles of the methodology implementation determined the approach to differentiating the sources of suspended sediments entering the mouth of the Setun River from its catchment area. The approaches of sources differentiation (their classification schemes) according to sub-basins or urban land use zones proved ineffective. In the context of the basins of the tributaries of the Setun Rivers (the Ochakovka and Navershka rivers) and direct catchments of the main river (the upper and lower sections of the Setun), the process of mixing natural quaternary and pre–quaternary geological formations and man-made soils, their geochemical characteristics averaged, does not significantly differentiate these parts of the entire basin in terms of soil composition. Similarly, in the context of land use zones (social and business, industrial, residential, transport, recreational): differences in the chemical composition of soils in these zones are not statistically differentiated, their internal diversity is much higher than differences between the average values for the zones, which leads to an almost complete loss of effectiveness of the approach when using such a model of watershed differentiation. Only the three-pronged division of samples in the catchment area by the substrate type has proved to be effective: soils in open ground areas, road dust, and riverside erosion.

Thus, the suspended sediment source tracing method is aimed at developing measures to manage river basins and limit the flow of pollutants into river systems. The method has extensive prospects. It can be adapted to various catchments of small rivers flowing in urban or industrial areas. The findings that in most of the world urbanized basins riverside ledges are the main source of suspended matter entering rivers determine the relevance of measures to stabilize and strengthen bank slopes.

CONFLICT OF INTERESTS

The authors declare no relevant conflict of interests.

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