Application of the method of random additions for the simulation of radioactive contamination

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Abstract. The article considers the possibility of using the method of random addition to simulate radioactive contamination of the area under conditions of significant uncertainty of the wind in the surface layer during the spread of radioactive substances. The analogy between the existing methods of construction of relief surfaces and the construction of a model of radioactive contamination is considered. The algorithm allowing to build the specified surfaces on known values of density of radioactive pollution in a small number of set points is described. The values characterizing forecast errors are estimated in advance. The article concludes a possibility of application of random additions algorithm for simulation of radiation contamination in the accident at radiation-hazardous objects (RHO). The considered modification of the algorithm makes it possible to build a model of the density of radioactive contamination by known fixed points.

Keywords: method of random addition, radioactive contamination, radiation-hazardous objects.

1. Introduction

Despite the significant improvement in the state of safety at radiation facilities in recent years, it is impossible to exclude the possibility of emergency situations, including the release of radioactive substances outside the sanitary protection zones. The reasons for such emissions can vary from natural disasters in the areas of radiation-hazardous facilities to sabotage and terrorist activities.

Currently existing approaches to radiation environment modeling are based on various solutions of the semi-empirical equation of turbulent diffusion [1-5]. Various solution methods give more or less satisfactory results for nuclear explosions and the spread of radioactive substances in a relatively stable surface air layer [6-11].

In case of accidents on radiation-hazardous objects, in conditions when the uncertainty of the space-time characteristics of the wind in the surface layer is high, other approaches to the modeling of radioactive contamination of the area are necessary. It is difficult to take into account a large number of independent causes acting on the bulk source of radioactive contamination in one or another analytical form [12-14].
Note that the appearance of the resulting level of contamination of the territory according to the results of measurements presented in figure 1a is similar to the measuring-altitude (hypsometric) map of the area (figure 1b).

![Figure 1](image1.png)

Figure 1. Appearance of maps: a) radioactive contamination density of a part the territory of the Republic of Belarus $^{90}$Sr, kBq/m$^2$, source: [4]; b) altitude, source: hypsometric map of the European part of the Russian Federation.

The reason for this similarity is clear – the formation of the relief is influenced by a large number of factors, including those associated with weathering and movement of rocks under the influence of gravity, water, etc. Accurate account of the totality of factors is impossible, but the methods of constructing surfaces that simulate the relief are known [15-17].

Their advantage is that, ignoring from the physical processes that determine the appearance of the real landscape and without giving any information about their features, they allow to describe the landscapes of a rather complex structure using a small number of variables [18-21].

2. Methods
One of these methods is the algorithm of successive random additions proposed by Foss and used in the simulation of generalized Brownian motion [22-23]. As shown by Foss, this algorithm is easy to generalize to a large number of measurements. Figure 2 shows the surfaces constructed using this algorithm, for which the program was written. Initially, the heights $Z = 0$ were fixed in four corners of the grid of 512×512 elements. Afterwards, dimensionless coordinates are used, in which the side of the area is 1. The program uses a subroutine that generates independent Gaussian random numbers $\xi_n$ with zero mean and unit variance. At the first step we get one value $\xi$ and use it as the surface level in the center of the grid (at the $\left(\frac{1}{2}, \frac{1}{2}\right)$ point). In accordance with the proposed algorithm, interpolation is performed at the second stage and elevations are found at four points with dimensionless coordinates $\left(\frac{1}{4}, \frac{3}{4}\right)$, $\left(\frac{3}{4}, \frac{1}{4}\right)$, $\left(\frac{1}{4}, \frac{3}{4}\right)$ and $\left(\frac{3}{4}, \frac{3}{4}\right)$. E.g., the elevation at the point $\left(\frac{1}{4}, \frac{1}{4}\right)$ is equal to $Z\left(\frac{1}{4}, \frac{1}{4}\right) = \frac{1}{4} \left( Z\left(0,0\right) + Z\left(\frac{1}{2}, 0\right) + Z\left(\frac{1}{2}, \frac{1}{2}\right) + Z\left(0, \frac{1}{2}\right) \right)$, which would mean that the result of the
interpolation is simply the arithmetic mean of the elevations at the nearest diagonal points. Elevations at the nearest two points on the border \( \left( 0, \frac{1}{2} \right) \) and \( \left( \frac{1}{2}, 0 \right) \) were taken equal to the arithmetic mean of elevations in the nearest corners of the area. In the developed program, changes were made to this algorithm, and the elevations at the boundary points were found as an arithmetic mean of 3 points, including \( Z \left( \frac{1}{2}, \frac{1}{2} \right) \). At this stage of the process, interpolated elevations were set at 13 points – five starting positions, four new interior points and four new boundary points. At the next step, 13 independent values \( \xi_{n} \) were added to the elevations that were already calculated. In this case, Gaussian random numbers have the following dispersion at each stage:

\[
\xi_{n}^{2} = \sigma_{n}^{2} = r^{2nH},
\]

where \( r = 1/\sqrt{2} \) is the scale factor.

This procedure continues and in the next cycle points \( \left( \frac{1}{2}, \frac{1}{4} \right), \left( \frac{1}{4}, \frac{1}{2} \right), \left( \frac{3}{4}, \frac{1}{4} \right) \) and \( \left( \frac{1}{4}, \frac{3}{4} \right) \) are added. Elevations at these points are defined as the arithmetic mean of elevations at the nearest nodes, that is, at nodes that lie in directions parallel to the axes. At the points lying on the border, elevations are again determined in a special way, taking into account the central point. After each cycle, this algorithm doubles the number of points at which the elevation is set and reduces it by the factor \( r = 1/\sqrt{2} \) – the distance between such points. The surfaces shown in figure 2 were obtained after 9 cycles of application of this algorithm.

The arguments describing the surface in this algorithm are the Hurst exponent \( H \) and the scale factor \( r \). For two-dimensional surfaces, the scale factor is \( 1/\sqrt{2} \), and thus the only parameter describing the surface is the Hurst exponent, which will determine the “indentation” of the landscape.

3. Results

Examples of construction of three surfaces for different Hurst indicators – \( H \) are shown on the figure 2.

![Figure 2](image)

**Figure 2.** Construction of surfaces by random addition for three different values of the Hurst exponent \( H \): a) \( H = 0.9 \), b) \( H = 0.5 \), c) \( H = 0.2 \).

The transition to the modeling of radioactive contamination of the area is carried out by using an obvious correlation of the density of radioactive contamination of the territory with the surface height.
As the initial data for the consideration of such a model, one could take the nature of radioactive contamination of the area, modeled in accordance with the above algorithm. If the pollution densities at some points are known, it can be assumed without loss of generality that densities at nodal points are known, for example, with relative coordinates \(\left(\frac{3}{4}, \frac{1}{2}\right)\); \(\left(\frac{1}{2}, \frac{1}{2}\right)\) and \(\left(\frac{3}{4}, \frac{1}{2}\right)\), which are, respectively, 2.0; 6.0 and 2.0 relative units (if densities at other [non-nodal] points are known, this will be reduced to a change in the scale of the grid). The densities in the corners are assumed to be small, i.e. far from the density source they are almost equal to zero, which can be guaranteed by setting sufficiently large negative densities at points (0,0), (0,1), (1,0), (1,1).

Next, the construction algorithm remains the same with the following changes: for example, a point with coordinates \(\left(\frac{1}{2}, \frac{3}{4}\right)\) and \(\left(\frac{3}{4}, \frac{1}{2}\right)\) will be taken into account when finding densities in points \(\left(\frac{1}{2}, 0\right); \left(1, \frac{1}{2}\right)\) as a weighted arithmetic mean according to the formula (1), taking into account the distance of the point from the one in which the density is calculated:

\[
P(X) = \frac{\sum_{i=1}^{N} W_{(x,y)}^i P_i}{\sum_{i=1}^{N} W_{(x,y)}^i}, \quad (1)
\]

where \(P(X)\) is the density of radioactive contamination at the design point \(X\); \(P_i\) are the densities at the nodal points; \(W_{(x,y)}^i\) are the weighting coefficients inversely proportional to the relative distance to the calculated point.

Thus, for point \(X\) the value of \(X_{(0,0)} = W_{\left(\frac{1}{2}, \frac{1}{2}\right)} = 1\) and \(W_{\left(\frac{1}{2}, \frac{1}{2}\right)} = 1\), \(W_{\left(\frac{1}{2}, \frac{1}{2}\right)} = \frac{1}{\sqrt{2}} = \sqrt{2}\) – this factor is greater than 1 due to the point \(\left(\frac{3}{4}, \frac{1}{2}\right)\) being closer to point \(X\). Similarly, it will be taken into account to find the pollution density at the point \(\left(\frac{1}{2}, \frac{1}{2}\right)\) and the density value at the point \(\left(\frac{1}{2}, 1\right)\). Then random normally distributed points (except fixed ones) are added to the found points \(\xi\) with the corresponding variance. Afterwards, the algorithm continues to find the values of the pollution density in all nodal points of the initial grid, while the specified densities remain unchanged. When at some (in this case, the 2nd) stage there will be no nodes in which densities are not determined, the dispersion decreases and the calculation is carried out according to the usual algorithm.

Due to the random nature of this model, the type of this or that implementation of the algorithm will be different from the original one that is selected. We will estimate the difference between the base model and the working one by the standard deviation \(\sigma\) of the power values from the base by the formula (2):

\[
\sigma = \frac{\sum (P_{0i} - P_i)^2}{N}, \quad (2)
\]

where \(P_{0i}\) and \(P_i\) are the values of dose rates at the \(i\)-th point, respectively, the base and the working model.
Figure 3. Results of construction of the map of density of radioactive pollution of the district, and-base model, b and c – settlement models. The number of repetitions is 9, the Hurst exponent is 0.9, a scaling factor of 1.41. Circles indicate points with a given pollution density – for point (1, 1) 6.0 relative units, for peripheral points - 2.0 relative units.

As a result of modeling, the average deviation for 10 runs was obtained — 2.4 relative units (0.38 maximum scale) for three fixed points with Hurst exponent H = 0.9. Obviously, as the number of points with a known pollution density increases, the accuracy of the model should increase.

4. Conclusions

1. The random addition algorithm can be used to simulate radiation contamination of the area as a result of an accident at a radiation-hazardous facility (RHO).

2. The considered modification of the algorithm makes it possible to build a model of the density of radioactive contamination by known fixed points.

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