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Digital Modeling of Relief for Tasks of Preliminary Analysis

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ABSTRACT: The article proposes a method of digital modeling of relief for areas called quarters. By defining the plane of quarters, it is possible to display the formation of a stack of surface waters in the form of a slope vector, as well as the visualization of the slopes of the relief in the form of a cartogram. Quarters of relief also contribute to a quantitative assessment of the relief – to determine the degree of complexity of the relief. The digital elevation model based on the planes of quarters contributes to the preliminary analysis of the relief for various engineering design tasks.

KEYWORDS: relief, quarter, quarter surface, average slope line, quarter plane, relief plane, stingray line, slope vector, relief complexity.

I. INTRODUCTION

Most engineering design tasks require the most comprehensive analysis of the terrain to make optimal decisions. In particular, in the tasks of carrying out optimal – auto and railway lines of communication with regard to the requirements imposed on the project, in the tasks of carrying out optimal hydraulic engineering (canals and drainage) facilities, in the tasks of designing vertical planning of ameliorative agricultural land, in design of industrial and civil structures, taking into account natural drainage, in making decisions of the rapid deployment of military forces and equipment for crossing terrain, in the determination of mudflows areas in settlements of the foothill massif, etc.
The software application "Геоанализатор" (Geo-analyzer) was developed in the development of which the following goals were set:

- determination of the average slope of the surface of the relief in areas;
- determination of the average slope of the relief surface as a whole;
- a visual representation of the formation of runoff of surface water in the form of arrows of the slope line on the sections and as a whole;
- representation of the relief in the form of cartograms of slopes.
- representation of the relief in the form of a cartogram of the complexity of the relief.

II. THEORETICAL BASIS

The definition of the average slope line [1,2] contributed to the definition of the average slope plane [3]. The development of the theoretical foundations of the degree of complexity of the relief [4,5] became a prerequisite for determining the relief area as a quarter [4].
The program «Geo-analyzer» was developed on the basis of the program «Сложность рельефа» (Complexity of relief) [6]. The core of the program for constructing isolines was the “Test Tri_Dll” program [7].

III. METHODOLOGY

The program «Geo-analyzer» works on the basis of the primary source data (measurements) conducted on a rectangular regular network. The method of research was chosen: methods of descriptive geometry, methods of analytical geometry and differential-geometric handling of data.

ISSN: 2350-0328
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Vol. 5, Issue 10 , October 2018

$$A = \left[z_{ij}\right] = \begin{pmatrix} z_{11} & z_{12} & \cdots & z_{1n} \\ z_{21} & z_{22} & \cdots & z_{2n} \\ \cdots & \cdots & \cdots & \cdots \\ z_{m1} & z_{m2} & \cdots & z_{mn} \end{pmatrix} \tag{1}$$

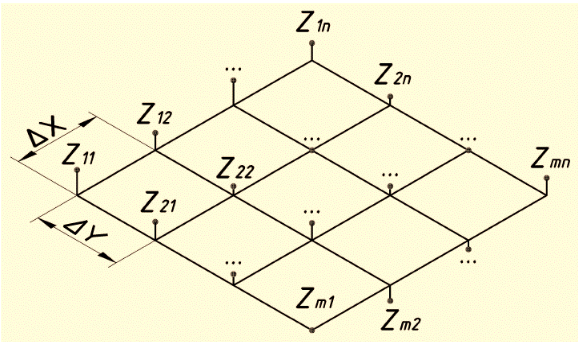

Figure 1. The initial data of relief on the rectangular regular network

Definition-1. Nine adjacent nodes of a regular 3×3 network will be called «квартал» (a quarter) consisting of four cells, called «квадрант» (quadrant) (Fig. 2):

Nine adjacent knots of a regular network 3×3 we name «квартал» (quarter) consisting of four cells called «квадрант» (quadrant) (fig. 2):

$$[A] \equiv \begin{bmatrix} Z_{11} & Z_{12} & Z_{13} \\ Z_{21} & Z_{22} & Z_{23} \\ Z_{31} & Z_{32} & Z_{33} \end{bmatrix} \equiv \left[Z_{ij}\right] \tag{2}$$

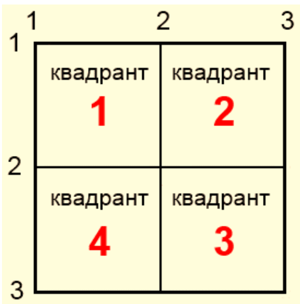

Figure 2. Disposition scheme of quadrants and definition of quarter of surface

To the main geometrical characteristics of the quarter of the surface of the relief we take the following:

1. The spatial position of the plane of the quarter;
2. Determination of the vertical angle of inclination of the plane of the quarter relative to the horizontal plane;
3. Determination of the slope line and identification of the position of the slope vector.

ISSN: 2350-0328
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Vol. 5, Issue 10 , October 2018

Definition-2. The plane drawn by the average values of the source data of a quarter in the form of a 3×3 matrix is called the «quarter plane».

Determining the position of the slope vector means determining the coordinates of the beginning and end of the arrow for its subsequent visualization in digital models. In this case, the beginning is always in the center of gravity of the plane, and the end is directed perpendicular to the horizontal trace of the plane or its horizontals. The projection of the slope vector on the horizontal plane will also be perpendicular to the horizontal wake of the plane (Fig. 3).

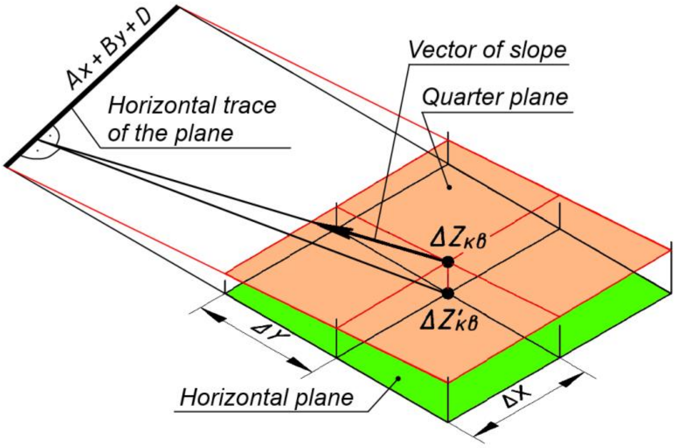

Figure 3. Determination of the plane of the quarter and the slope vector

The plane of the quarter, by definition, passes through the point $\Delta Z_{\kappa в}$ – the average value of the source data of the quarter:

$$\Delta Z_{\kappa в} = \frac{\sum_{i=1}^{3}\sum_{j=1} Z_{ij}}{9}; \tag{3}$$

The coordinates $\Delta Z_{\kappa в}$ are x = ΔX, y = ΔY – the center of the quarter. The orthogonal projection of $\Delta Z_{\kappa в}$ on the horizontal plane is $\Delta Z'_{\kappa в}$.
It is known that the position of a plane in space is determined by three points that are not lying on one straight line or by two intersecting straight lines. Since the position of one point ($\Delta Z_{\kappa в}$) is known, it is necessary to determine the position of two points of the plane of the quarter, for which we will make a series of iterative calculations.
Let a flat curve be given – a profile section of the relief in the form of a linear matrix of one row *m* or one column *n*:

$$m = \begin{pmatrix} Z_{11} & Z_{12} & \ldots & Z_{1j-1} & Z_{1j} \end{pmatrix} \quad \text{or} \quad n = \begin{pmatrix} Z_{11} \\ Z_{21} \\ \ldots \\ Z_{i-11} \\ Z_{i1} \end{pmatrix} \tag{4}$$

where Z – values of the exceedances of discrete points of a flat curve - the source data.
As is known, the approximation of a flat curve into a linear function is:

$$z = f(k) = ak + b \tag{5}$$

ISSN: 2350-0328
International Journal of AdvancedResearch in Science, Engineering and Technology
Vol. 5, Issue 10 , October 2018

Function (5) should not be considered as a function of plotting a straight line with a factor *a*. In this function, the variables are the coefficients *a* and *b* which should be determined, and *k* is the iteration counter for determining new values of Z_{ij}.
The coefficients of function (5) are determined by the solution of the system both for a single row and for a single column using the least squares method:

$$\begin{cases} a\sum_{i=1}^{n} k_i^2 + b\sum_{i=1}^{n} k_i = \sum_{i=1}^{n} k_i Z_i \\ a\sum_{i=1}^{n} k_i + bn = \sum_{i=1}^{n} Z_i \end{cases} \tag{6}$$

The coefficients *a* and *b* of system (6) can be determined by the substitution method or the Cramer method.
The average value of the elements of a single row – *m* and one column – *n* 3×3 matrices will be:

$$\Delta Z_{m1} = \frac{\sum_{j=1}^{3} Z_{1j}}{3} \text{ for row,} \qquad \Delta Z_{n1} = \frac{\sum_{i=1}^{3} Z_{i1}}{3} \text{ for column} \tag{7}$$

Setting the average value for each row and each column of the 3×3 matrix, we form a pair of new flat curves – one column and one row:

$$u = \begin{pmatrix} \Delta Z_{m1} \\ \Delta Z_{m2} \\ \Delta Z_{m3} \end{pmatrix}; \qquad \text{and} \qquad v = (\Delta Z_{n1} \quad \Delta Z_{n2} \quad \Delta Z_{n3}); \tag{8}$$

Having the initial data of two flat curves *u* and *v*, they should be approximated to linear functions in the form:

$$z_u = ak + b \qquad \text{for column} \tag{9}$$

$$z_v = a'k' + b' \qquad \text{for row} \tag{10}$$

where k, k'= 1, 2, 3 are iteration counters.
Iterative calculus of equations (9) and (10) will determine the new values of the curves *u*, *v* which will lead them to the straight lines drawn from the average values of the rows and columns of the quarter (Fig. 4).

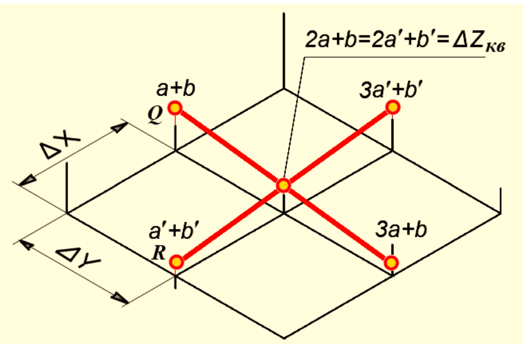

Figure 4. Straight lines drawn by the average values of rows and columns of the quarter

ISSN: 2350-0328
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Vol. 5, Issue 10 , October 2018

For $k = 2$ and $k' = 2$, equations (9) and (10) have the same values, which means the straight lines of average slopes of the rows and columns have a common point of intersection and form a plane. It is characteristic that the intersection point of two straight lines is also equal to $\Delta Z_{кв}$ (or $\Delta Z^0_{кв}$) – the average value of the source data of the quarter. Therefore, this plane is a quarter plane drawn from the average values of rows and columns of a 3×3 matrix and determines the overall slope of the quarter surface.

To determine the equation of a quarter plane, it is enough to have the coordinates of three points that do not belong to one straight line. Equations (9) and (10) contribute to the determination of the coordinates of five points (see Fig. 4).

The coordinates of three points that do not belong to one straight line, were selected points Q, R, $\Delta Z_{кв}$ (Fig. 5):

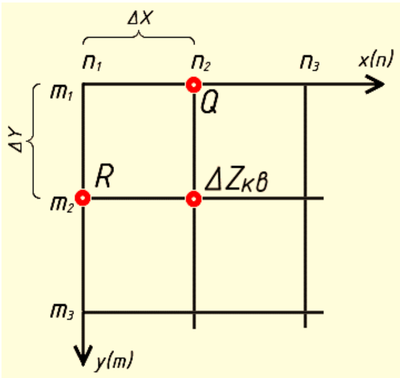

Figure 5. The choice of three points Q, R, $\Delta Z_{кв}$ taking into account the coordinate system of the computer monitor

After a series of calculations and transformations, the general equation of the plane was defined as:

$$Ax + By + Cz + D = 0 \quad (11)$$

where $A = \Delta Y(2a + b - a' - b');$

$B = \Delta X a;$

$C = -\Delta X \Delta Y;$

$D = \Delta X \Delta Y(a' + b' - a).$

The general equation of the quarter plane in the form of (11) helps to determine the slope line, the line of greatest slope in the form of an arrow of the slope vector indicating the direction of the slope of the plane.

To determine the slope vector, 3 consecutive calculations were performed:

1. Derivation of a horizontal trace of a quarter plane by solving a problem on the intersection of two planes – the quarter plane and the horizontal plane passing through the level $z = 0$:

$$\begin{cases} Ax + By + Cz + D = 0 \\ z = 0 \end{cases} \Rightarrow Ax + By + D = 0 \quad (12)$$

2. Derivation of the horizontal plane of the relief passing through the level of $\Delta Z_{кв2}$ satisfying visualization of the arrow within the boundaries of the quarter.

$$\begin{cases} Ax + By + Cz + D = 0 \\ z = \Delta Z_{кв2} \end{cases} \Rightarrow Ax + By + D_2 = 0 \quad (13)$$

where D_2 is a free term different from equation (12).

ISSN: 2350-0328
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Vol. 5, Issue 10 , October 2018

$$\Delta Z_{\kappa в2} = \Delta Z_{\kappa в} - \frac{r \cdot \Delta Z_{\kappa в}}{d} \tag{14}$$

where *r* is the limit value of the boundaries of the plane of the quarter from the center of the plane. $r = \Delta X$ or $r = \Delta Y$, the smallest value of them.

Note: in practice engineering design often $\Delta X = \Delta Y$.

Systems of equations (12) and (13) are – the mutual intersection of the plane of the quarter and horizontal planes (Fig. 6):

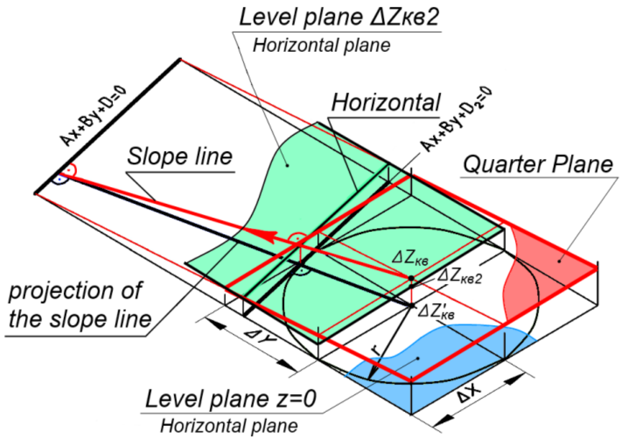

Figure 6. Determination of the horizontal line of the plane of the quarter within the boundaries of the quarter

3. The mutual intersection of the horizontal line (13) and the perpendicular line conducted through the $\Delta Z'_{\kappa в}$ will determine the point of their intersection:

$$\begin{cases} Ax + By + D_2 = 0 \\ \pm Bx + Ay + D_3 = 0 \end{cases} \Rightarrow E'(x, y) \tag{15}$$

Thus, the projection of the slope vector $V_{c\kappa}$ (Fig. 7) will have the coordinates:

$$V_{c\kappa} \begin{cases} \Delta Z'_{\kappa в}(\Delta X, \Delta Y) - \text{start of the arrow} \\ E'(x, y) - \text{end of the arrow} \end{cases} \tag{16}$$

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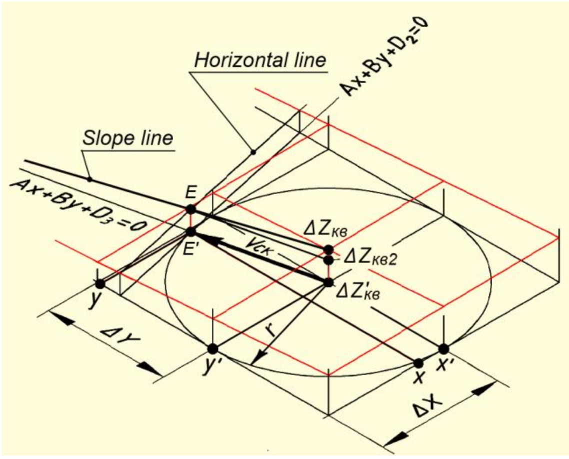

Figure 7. Visualization of the arrow of the slope vector within the boundaries of the quarter

According to the method of determining the plane of the quarter, the plane of the relief was also determined based on the average values of the rows and columns of the source data (1). The plane of the relief contributes to the determination of the average slope of the surface of the relief.
The quantitative characteristics of the relief in the form of a complexity coefficient are no less important. It contributes to the definition of the convexity or concavity of the relief relative to the plane for which the degree of complexity is zero [8].
The determination of the coefficient of complexity is based on the differentiation of the source data of the quarter in the form of a 3×3 matrix.
A certain relationship was established between the nine members of the matrix by the finite difference method:

1. We summarize the absolute values of the difference of the elements of the rows and differentiate:

$$m = \frac{|(Z_{11} - 2Z_{12} + Z_{13})| + |(Z_{21} - 2Z_{22} + Z_{23})| + |(Z_{31} - 2Z_{32} + Z_{33})|}{\Delta X} \tag{17}$$

where ΔX is the pitch of a rectangular regular network along the rows.

2. We summarize the absolute values of the difference elements of the columns and differentiate:

$$n = \frac{|(Z_{11} - 2Z_{21} + Z_{31})| + |(Z_{12} - 2Z_{22} + Z_{32})| + |(Z_{13} - 2Z_{23} + Z_{33})|}{\Delta Y} \tag{18}$$

where ΔY is the pitch of a rectangular regular network along the columns.

3. We summarize the absolute value of the difference of the elements of the diagonal and also differentiate:

$$d = \frac{|(Z_{11} - 2Z_{22} + Z_{33})| + |(Z_{13} - 2Z_{22} + Z_{31})|}{\sqrt{\Delta X^2 + \Delta Y^2}} \tag{19}$$

Equations (17–19) are summed up and get some value – ξ for the quarter of the surface:

$$\xi = m + n + d \tag{20}$$

Equation (20) satisfies the definition of the degree of complexity of the plane $\xi = 0$ and has different values if the surface (quarter) under consideration is not a plane.

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Vol. 5, Issue 10 , October 2018

IV. CONCLUSION

Based on the above, the Geo-Analyzer program makes visualization of the formation of surface water runoff by quarters in the "Стрелки кварталов" (Arrows of Quarters) mode and the whole territory in the "Стрелка плоскости рельефа" (Arrow of the relief plane) mode (Fig. 8), identifying sections by the inclination of the planes in the «Картограмма уклонов» (Cartogram of slopes) mode (Fig 9), as well as the degree of complexity of the relief in the mode «Картограмма сложности» (Cartogram of complexity) (Fig. 10).

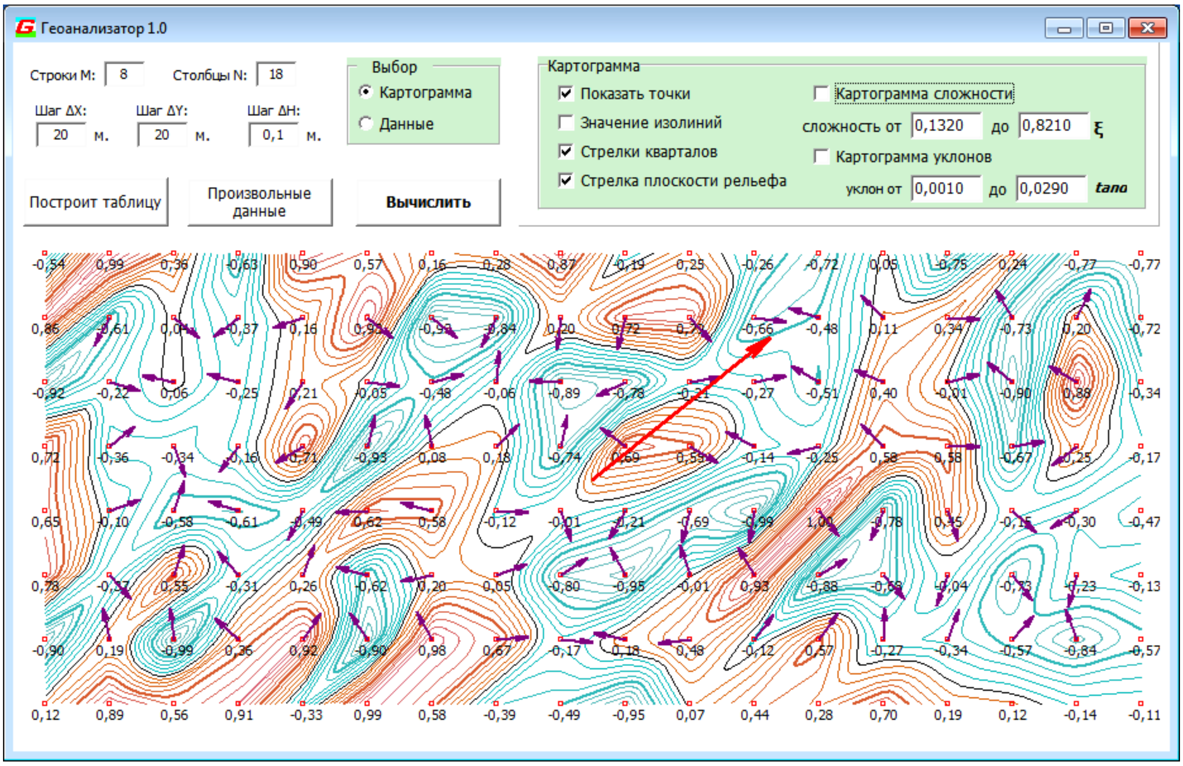

Figure 8. Formation of runoff of surface water by quarters and the entire territory of the relief as a whole

The modes “Cartogram of complexity” and “Cartogram of slopes” contribute to the choice of the borders of cartogram quadrant filling according to the criteria set by the user. In an arbitrary selection, they take from minimum to maximum values.

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Vol. 5, Issue 10 , October 2018

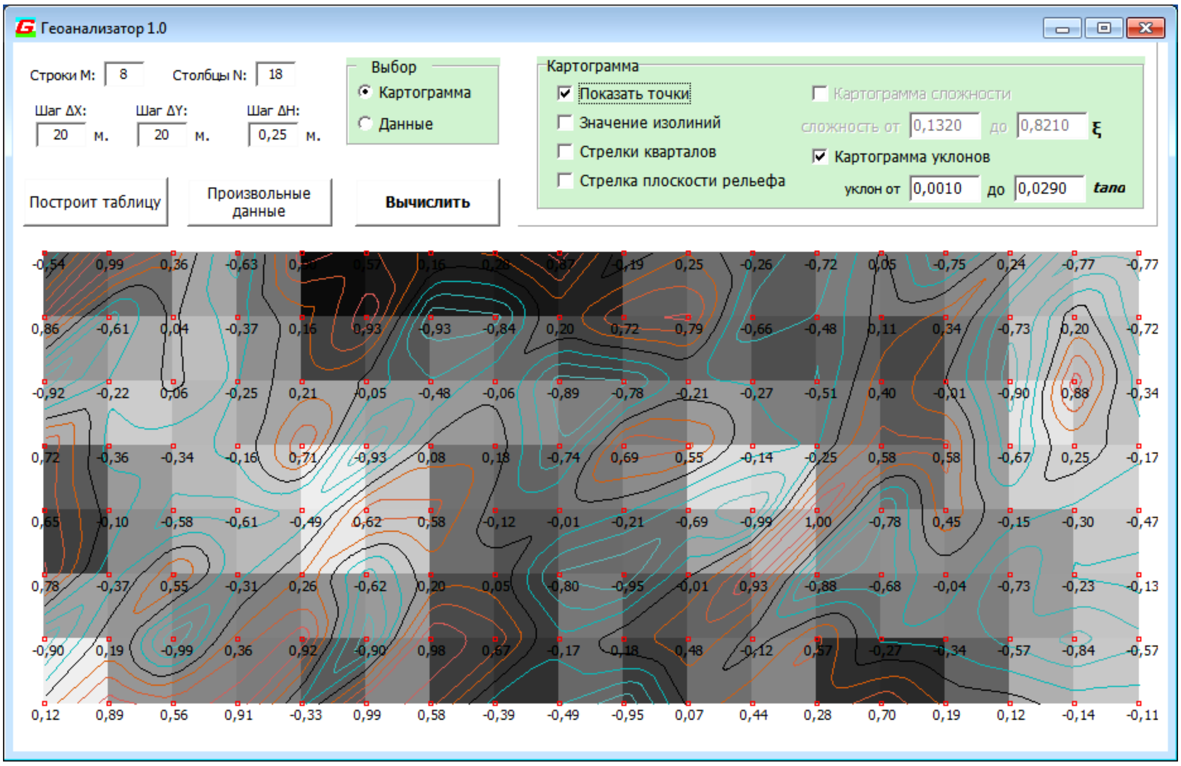

Figure 9. Displaying cartogram of slope

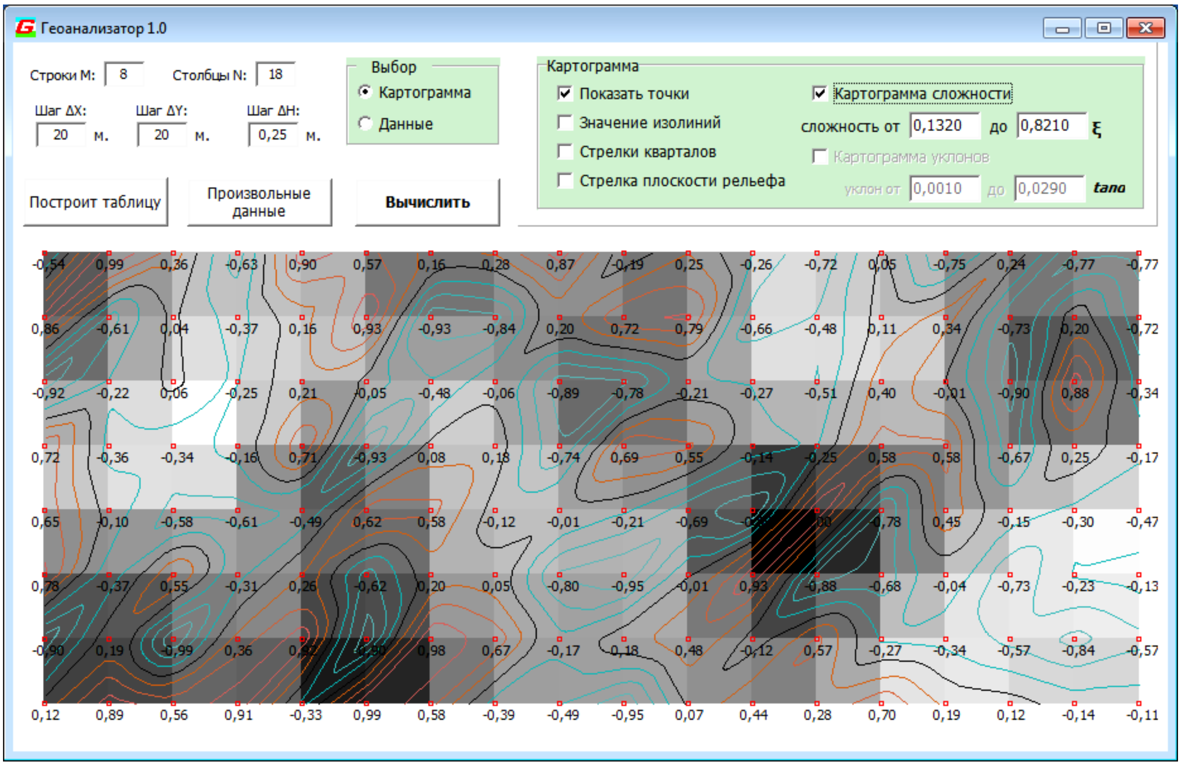

Figure 10. Displaying cartogram of complexity

ISSN: 2350-0328
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Vol. 5, Issue 10 , October 2018

In fig. 8, 9 and 10 selected arbitrary relief data for presentation and training purposes.
The “Geo-Analyzer” program contributes to the preliminary analysis of various terrain areas and the selection of optimal solutions among the many options of the vertical planning project in the tasks associated with water disposal and in the tasks of carrying out the optimal route of dislocation, taking into account the terrain.

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