Computer Science Journal of Moldova, vol.**3**, no.1(7), 1995

Digital Elevation Model for Republic of Moldova

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Abstract

The creation of Digital Elevation Model technique is proposed. The initial data preparation requirements, the ideology of elevation matrix construction and absolute marks values interpolation, search optimization of obtained values are elucidated. The procedures of obtaining of cartographic models of steepness and expositions, based on concept of gradient are described.

1 Introduction

The Digital Elevation Model (DEM) [2] is the basis for solution of various problems arising when the strategy of Geographical Informational Systems (GIS) [1] on maintenance of natural–resources data banks is elaborated, for solution of classical problems of physical geography, construction of models and expert evaluations and others.

Availability of DEM for Republic of Moldova on medium and large scales becomes more and more vital. Such kind of model can form the basis for various geomorphological definitions, modern exogen processes research. It also can help to build topoclimatical maps to analyse the particularities of soil distribution and landscape division into regions. The significant volume of information and processing complexity determine the necessity and expediency of use of computers on all stages of creation and operation of DEM.

2 Initial data

Digital Elevation Model is two dimensional array of absolute elevation values, each element of which has strict geographical location. Space photo [3] and topographical maps [3] serve as initial data for building of DEM. The proposed concept is based on use of large–scale topographical maps. In this case, the scale of initial complete set of maps defines both the step of discretisation (cell or pixel size) and the accuracy of absolute marks calculation. So, for example, to obtain a valuable Digital Elevation Model for scale 1 : 200000 the scale of given topographical maps should not be less than 1 : 100000 and for scale 1 : 50000 — not less than 1 : 25000.

Another problem which has to be decided at the stage of creation and implementation of DEM, is connected with nonrectangularity of topographical sheets depended on geographical coordinates. The topographical maps are made on the basis of Crasovskii cylinder [5] on Gaus–Krüger projection, which is the particular case of Universal Traversal Mezcator projection (UTM), when $k = 1,0$ (the cylindrical surface is tangent with the earth surface along the equator).

The coordinate variation of latitude is within 120 and 1340 meters, and of longitude 0 – 1430 meters for map sheets of scale 1 : 100000. For sheets of scale 1 : 25000 they are equal to 7,5 – 388 meters of latitude and 0 – 380 meters of longitude respectively. The sheets arrangement for scale 1 : 100000 and for scale 1 : 25000 is presented on a Fig 1.

The completeness of DEM is determined by initial data. The models differ from the principle points distribution and surfaces description according to the form of representation they can be attributed to one of four types [6, 7]:

- Geometricaly ordered, in which the surface is given by points being a vertex of geometrical regular network;
- Geomorphological ordered (analog), containing points, located on structural lines (level level), local extremum of a surface;
- Half–regular (combination of the first two models);

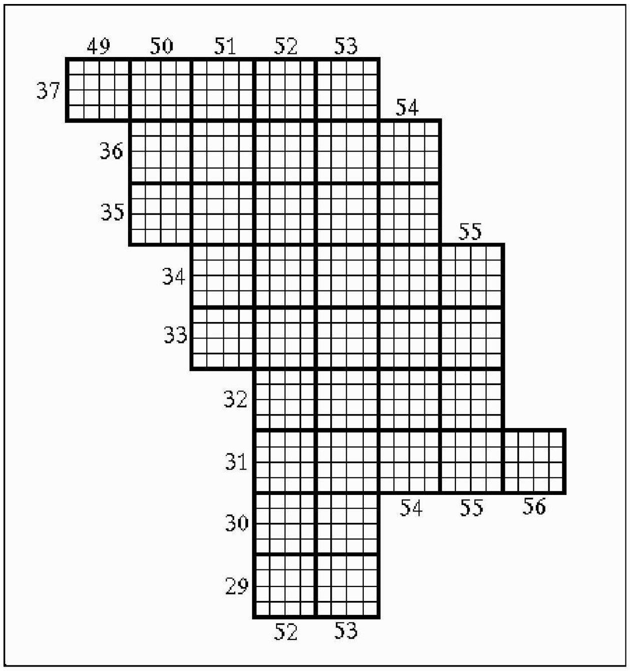

Figure 1: Sheets placing on the map

- Chaotic.

The most optimal is geomorphological ordered model. The same point of view is accepted in [6]. The sufficient size of pixel for scale 1 : 100000 is equal to 200 meters, for scale 1 : 25000 — 50 meters. The accuracy of calculation of absolute marks is affected by the level lines tracing step.

The transformation of cartographical images to the digital form is reduced to its reading, i.e. to determinate coordinates of graphic elements that compose image. The procedure of generation of digital elevation model is submitted on the following steps:

a) Preparation of initial information;

b) Tracing:

– scanning

or

– digitizing;

c) Elevation matrix obtaining;

d) Presenting of results.

The necessary data processing is executed in a geodesic system of coordinates and the results are transformed to Krasovski ellipsoid that makes the obtained model universal.

The data preparation and reduction, contained on topo maps for use in automatic (computer) construction of DEM is rather labour–consuming and a responsible part of work. This stage includes a number of consecutive nonproduction work:

- Drawing on a tracing–paper of level lines, contained on topomaps with the indication of absolute marks;
- Cheching of the drawing information and its editing for joining of toposheets;
- Scanning of the information and saving it into image file (scanning by parts and compound the final image in the case when working parameters of a scanner are less than size of sheets);
- Trace the image file (with sufficient accuracy), choice of methods and parameters in order to obtain vector form;
- Editing the vector form of images (removal of redundant points, arising as a result of scanning);
- Geographical location of vector form of images and managing of their storage on magnetic devices.

Scanning and obtaining vector forms of image file are executed by ready programs or using our own means. Essential significance has sufficient accuracy (there can be redundant) of vector form of image file and mutually unequivocal conformity between the image of a line and its vector representation. For level lines two cases are possible: the beginning and the end of a line coincide or the beginning and the end of a line do not coincide, i.e. the line continues on other sheets.

The geographical location of vector form consists of recalculation of local coordinates of all points according to the projection and the measure unit chosen. So, following the mathematical basis of topographical maps a meter system of coordinates and Gaus–Krügher projection was accepted for develop DEM of the Republic of Moldova.

For exact joining on borders exceptions of imposes or breakages at simultaneous processing of the information, the coordinates of corners of topo maps are required. The topographical maps of scale $1:100000$ have the sizes of $20'$ on latitude and $30'$ on longitude and of scale $1:25000$ $5'$ and $7,5'$ respectively . When the exact values of corner coordinates are absent it will be necessary to calculate them.

Let us describe the corners meter coordinates determination procedure for one photosheet. The initial data are geographical coordinates of a number of (no less than two) reper points. Then meter coordinates of each corner of toposheet satisfy the following system of equations

$$\sqrt{(x_r - x_i)^2 + (y_r - y_i)^2} = \rho_{ri}, i = 1, 2, \ldots, n, \tag{1}$$

where $r = \{SW, NW, NE, SE\}$ – index of a corner of a sheet, x_i, y_i – meter coordinates of i–point, ρ_{ri} — distance (in meters) between point i and an appropriate corner of toposheet which is measured on a map. In the $n > 2$ case the system is redundant and then the criterion for optimum determination of (x_r, y_r) can be condition

$$\sum_{i=1}^{n} \sum_{r} (\rho_{ri} - \rho_{ri}^*)^2 = min, \tag{2}$$

where $\rho_{ri}^* = \sqrt{(x_r^* - x_i)^2 + (y_r^* - y_i)^2}$ — calculated distance between point i and a corner r with coordinates (x_r^*, y_r^*). Condition (2) express (natural) requirement of a minimum error determination of distance between reper points and every corner of a map. Essential difference of a root–mean–square deviation $\sum(\rho_{rk} - \rho^*_{rk})^2$ for point k indicates (for certain) on a error in its coordinates determination.

Such points are excluded from consideration and the system (1)–(2) is solved again. Recurrence of a procedure for some sheets permits to specify required coordinates of corners.

The use of meter and geodetic coordinates requires a procedure of mutual coordinate recalculation [5].

After obtaining of vector form the corner coordinates together with local coordinates of appropriate corners are necessary and sufficient data for geographical location of lines of a level.

Really, the geographical location mathematically is reduced to the mapping rectangular area from one system of coordinates into another. In the case of choice of a meter system of coordinates the mapping should be linear, i.e. the line in one system should remain the line after mapping. The functions executing mapping will be linear concerning each variable and, therefore, they can be written as:

$$\begin{aligned} x(\xi,\eta) &= \alpha_0 + \alpha_1(\xi - \xi_0) + \alpha_2(\eta - \eta_0) + \alpha_3(\xi - \xi_0)(\eta - \eta_0), \\ y(\xi,\eta) &= \beta_0 + \beta_1(\xi - \xi_0) + \beta_2(\eta - \eta_0) + \beta_3(\xi - \xi_0)(\eta - \eta_0), \quad (3) \end{aligned}$$

where ξ, η are the coordinates of point in given (local) coordinate system; x, y are given (metric) coordinates of a point.

For determination of unknown factors α_i, β_i we take the advantage of known map corners coordinates and then we need their exact calculation under formulae (3). As a result we obtain two independent systems of linear equations relatively to α_i and β_i:

$$\alpha_0 + \alpha_1(\xi_r - \xi_0) + \alpha_2(\eta_r - \eta_0) + \alpha_3(\xi_r - \xi_0)(\eta_r - \eta_0) = x_r, \quad (4)$$

$$\beta_0 + \beta_1(\xi_r - \xi_0) + \beta_2(\eta_r - \eta_0) + \beta_3(\xi_r - \xi_0)(\eta_r - \eta_0) = y_r, \quad (5)$$

for $r = \{SW, NW, NE, SE\}$.

Notice that the function (3) will be mutually unequivocal, if $\alpha_1/\beta_1 \neq \alpha_2/\beta_2$.

If we take (ξ_{SW}, η_{SW}) instead of point (ξ_0, η_0) the solution of systems (4) and (5) can be written in the following form:

$$
\begin{aligned}
\alpha_0 &= x_{SW}, \\
\alpha_1 &= ((\xi_{NW}-\xi_{SW})(\eta_{NW}-\eta_{SW})((\xi_{NE}-\xi_{SW})(\eta_{SE}-\eta_{SW}) \\
&\quad -(\xi_{SE}-\xi_{SW})(\eta_{NE}-\eta_{SW}))-(\xi_{NE}-\xi_{SW})(\eta_{NE}-\eta_{SW}) \\
&\quad ((\xi_{NW}-\xi_{SW})(\eta_{SE}-\eta_{SW})-(\xi_{SE}-\xi_{SW})(\eta_{NW}-\eta_{SW})) \\
&\quad +(\xi_{SE}-\xi_{SW})(\eta_{SE}-\eta_{SW})((\xi_{NW}-\xi_{SW})(\eta_{NE}-\eta_{SW})- \\
&\quad (\xi_{NE}-\xi_{SW})(\eta_{NW}-\eta_{SW})))/Dxh, \\
\alpha_2 &= ((\xi_{NW}-\xi_{SW})(\eta_{NW}-\eta_{SW})((\xi_{NE}-\xi_{SW})(\xi_{SE}-\xi_{SW})- \\
&\quad (\xi_{SE}-\xi_{SW})(\xi_{NE}-\xi_{SW}))-(\xi_{NE}-\xi_{SW})(\eta_{NE}-\eta_{SW}) \\
&\quad ((\xi_{NW}-\xi_{SW})(\xi_{SE}-\xi_{SW})-(\xi_{SE}-\xi_{SW})(\xi_{NW}-\xi_{SW})) \\
&\quad +(\xi_{SE}-\xi_{SW})(\eta_{SE}-\eta_{SW})((\xi_{NW}-\xi_{SW})(\xi_{NE}-\xi_{SW})- \\
&\quad (\xi_{NE}-\xi_{SW})(\xi_{NW}-\xi_{SW})))/Dxh, \\
\alpha_3 &= ((\xi_{NW}-\xi_{SW})((\xi_{NE}-\xi_{SW})(\eta_{SE}-\eta_{SW})- \\
&\quad (\xi_{SE}-\xi_{SW})(\eta_{NE}-\eta_{SW}))-(\xi_{NE}-\xi_{SW}) \\
&\quad ((\xi_{NW}-\xi_{SW})(\eta_{SE}-\eta_{SW})-(\xi_{SE}-\xi_{SW})(\eta_{NW}-\eta_{SW})) \\
&\quad +(\xi_{SE}-\xi_{SW})((\xi_{NW}-\xi_{SW})(\eta_{NE}-\eta_{SW})- \\
&\quad (\xi_{NE}-\xi_{SW})(hW-\eta_{SW})))/Dxh; \\
\beta_0 &= y_{SW}, \\
\beta_1 &= \{(\xi_{NW}-\xi_{SW})(\eta_{NW}-\eta_{SW})((y_{NE}-y_{SW})(\eta_{SE}-\eta_{SW})- \\
&\quad (y_{SE}-y_{SW})(\eta_{NE}-\eta_{SW}))-(\xi_{NE}-\xi_{SW})(\eta_{NE}-\eta_{SW}) \\
&\quad ((y_{NW}-y_{SW})(\eta_{SE}-\eta_{SW})-(y_{SE}-y_{SW})(\eta_{NW}-\eta_{SW})) \\
&\quad +(\xi_{SE}-\xi_{SW})(\eta_{SE}-\eta_{SW})((y_{NW}-y_{SW})(\eta_{NE}-\eta_{SW})- \\
&\quad (y_{NE}-y_{SW})(\eta_{NW}-\eta_{SW}))\}/Dxh, \\
\beta_2 &= \{(\xi_{NW}-\xi_{SW})(\eta_{NW}-\eta_{SW})((\xi_{NE}-\xi_{SW})(y_{SE}-y_{SW})- \\
&\quad (\xi_{SE}-\xi_{SW})(y_{NE}-y_{SW}))-(\xi_{NE}-\xi_{SW})(\eta_{NE}-\eta_{SW})
\end{aligned}
$$

$$
\begin{aligned}
& ((\xi_{NW} - \xi_{SW})(y_{SE} - y_{SW}) - (\xi_{SE} - \xi_{SW})(y_{NW} - y_{SW})) \\
& +(\xi_{SE} - \xi_{SW})(\eta_{SE} - \eta_{SW})((\xi_{NW} - \xi_{SW})(y_{NE} - y_{SW}) - \\
& (\xi_{NE} - \xi_{SW})(y_{NW} - y_{SW}))\}/Dxh, \\
\beta_3 \quad = \quad & \{(y_{NW} - y_{SW})((\xi_{NE} - \xi_{SW})(\eta_{SE} - \eta_{SW}) \\
& -(\xi_{SE} - \xi_{SW})(\eta_{NE} - \eta_{SW})) - (y_{NE} - y_{SW}) \\
& ((\xi_{NW} - \xi_{SW})(\eta_{SE} - \eta_{SW}) - (\xi_{SE} - \xi_{SW})(\eta_{NW} - \eta_{SW})) \\
& +(y_{SE} - y_{SW})((\xi_{NW} - \xi_{SW})(\eta_{NE} - \eta_{SW}) \\
& -(\xi_{NE} - \xi_{SW})(\eta_{NW} - \eta_{SW}))\}/Dxh, \\
Dxh \quad = \quad & (\xi_{NW} - \xi_{SW})(\eta_{NW} - \eta_{SW})((\xi_{NE} - \xi_{SW})(\eta_{SE} - \eta_{SW}) - \\
& (\xi_{SE} - \xi_{SW})(\eta_{NE} - \eta_{SW})) - (\xi_{NE} - \xi_{SW})(\eta_{NE} - \eta_{SW}) \\
& ((\xi_{NW} - \xi_{SW})(\eta_{SE} - \eta_{SW}) - (\xi_{SE} - \xi_{SW})(\eta_{NW} - \eta_{SW})) \\
& +(\xi_{SE} - \xi_{SW})(\eta_{SE} - \eta_{SW})((\xi_{NW} - \xi_{SW})(\eta_{NE} - \eta_{SW}) - \\
& (\xi_{NE} - \xi_{SW})(\eta_{NW} - \eta_{SW})).
\end{aligned}
$$

When we save the data on magnetic devices it should be taken into account, that their volumes will be significant (especially for scale $1 : 25000$).

The reduction is reached first, by exception of redundant quantity of points determining the level lines with saving of accuracy (the point is excluded, if it is on distance less than given d from segment which connects previous and the next point); secondly by compact storage (record of relative coordinates in degrees with a fractional part south-western corner of a sheet as a base point taking).

3 Computation of absolute elevations

The task of determination of absolute elevations on the basis of geomorphological model for each (separate) sheet of a map includes two stages:

- structuring of initial data;
- calculation of absolute elevations in the knots of a regular network.

For describe the procedure it is necessary to introduce the concept of the working area, as lines of level in vector form, contained into a rectangular environment (geodesic system of coordinates), including also an environment. The structure of data should provide the most effective way for solving of main image proceeding tasks. Each level line is given by a sequence of points and coresponding value of absolute elevation on line. So, the line of level is approximated by poligon.

It is supposed, that they satisfy the following natural conditions:

a) level line is closed; if it is presented an open–ended (i.e. the line proceeds outside of limits of the considered area), it is closed on a border of the working area;

b) lines of level are not crossed within themselves.

Then the set of closed isolines in the working area can partially be ordered under the relation of inclusion: the polygon M_1 is contained in the other polygon M_2 if at least one point of M_1 is an internal point for M_2.

On the base of this relation the graph is building as a hierarchical tree (Fig. 2), the vertexes of which are level lines. The root of a tree is a polygon that correspond to the working area. For any current vertex of a tree its "sons" are those vertexes (lines of level) and only those, which are contained in current and at the same time are not contained in another son of the tree current vertex.

Current line is chosen and its place concerning the vertexes of a tree is determined. If the line is contained into the considered vertex, its place relatively to "sons" is analyzed. When the current line is contained in one vertex of a tree and is not contained in any of "sons", the new vertex of a tree is created for it, which is "son" of the found vertex.

To find out the arrangement of isolines it is possible to use the elementary method of testing if the point belong to a polygon [9]. Let's consider the polygon. It is necessary to test whether one point on the plane belongs to it. Drawing through the given point a straight line and, moving on it from infinity, we calculate the number of crossings

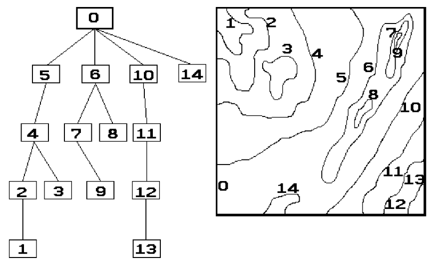

Figure 2: The nodes of the tree (a) and corresponding level lines (b)

with the border of polygon. At first crossing straight line enters into polygon, at next — leaves it.

If the number of crossings is odd then the point belongs to polygon, if it is even — does not belong. All specific cases are considered and are analysed in [9]. This is one of elementary methods of construction of a tree of inclusions, possessing order $O(N)$, where N — number of the polygon vertexes.

On the following stage a rectangular grid is placed upon the working area, in knots of which the values of absolute elevation are calculated. The knot needs to be located on the tree constructed above and the value of elevation needs to be calculated via interpolation, using the values of appropriate isolines. The localization of the point consists in finding of minimum on inclusion polygon M, in which the given point is included, and also in finding of all maximum on inclusion polygons contained in M, for which the given point does not belong to them.

The procedure of search on the tree is very similar to the procedure of its construction:

- An arbitrary point on a plane — knot of a grid is considered;
- If the point belong to the area (top of a tree), limited by current isoline, all "sons" of the current vertex are considered.

The procedure is finished when the vertex is found for which the point is contained inside of the area limited by appropriate isoline and is not contained in any polygon coresponding to "sons".

The search procedure is very laborious and the optimization of algorithm costs is important. The calculation of absolute elevations once for a grid dense enough is reasonable.

In order to optimize the search procedure it is possible the following simplification. At consecutive proseeding of the neighbour knots of the net by big probability the next knot will belong close to the located vertex of a tree for the previous knot and then, for each following knot the search begins not from a root of a tree, but from the current vertex. Especially appreciable gain of this approach is reached for knots of a grid, which belong to the vertex of a deep levels of the graph.

After grid knot localization on the level lines tree the interpolation of absolute elevation values is carried out. The minimum distances between the given point and polygons are determined and the value is calculated under the formula [10]:

$$H_{ij} = \frac{\sum_{m\in\Omega} p_m H_m}{\sum_{m\in\Omega} p_m}, \tag{6}$$

where H_{ij} — is the value of absolute elevation in the knot, H_m — value of an absolute elevation of a line of level m, p_m — return distance between knot (i, j) and a line m, Ω — set of polygons.

This formula of a Gauss type gives considerably best results, than other formulae [11,12].

The coordinates of knot (i, j) in (6) are calculated under formulae: $x_i = x_0 + (i-1)h, y_j = y_0 + (j-1)h$, where $x_0 = \min\{x_{SW}, x_{NW}\} +$

$h/2, y_0 = \min\{y_{SW}, y_{SE}\} + h/2$. The step of interpolation h depends on initial scale.

The results of building of DEM are prezented as a hypsometric map (Fig.3), which forms the basis for determining the morphological complexes of landscape and their quantitative parameters.

Figure 3: The altitudes

4 Computation of slope and of expozitions

After absolute mark values determination in the net knots by any given step we can construct a number of cartographical models of territories, begining with morphometrical one. As universal tool for determining morphometrical characteristics of landscape can be the concept of gradient of scalar field, which is, in the fact, the normal vector to a surface.

Let the surface is given by an equation $z - H(x, y) = 0$, where x, y — coordinates on a plane, and z — hight of a surface. A gradient of the surface has the following coordinates:

$$g = \{g_x, g_y, g_z\} = GRAD\{z - H(x, y)\} = \{-\frac{\partial H}{\partial x}, -\frac{\partial H}{\partial y}, 1\}$$

.

Let $i = 1, \ldots, n_x$ — the number of a column, $j = 1, \ldots, n_y$ — the number of a row of a rectangular network. Then, for calculation of their gradient components with the second order of approximation, the next formulae are used:

$$g_{x,ij} = -0.5\frac{h_{i+1,j} - h_{i-1,j}}{h_x}, \quad g_{y,ij} = -0.5\frac{h_{i,j+1} - h_{i,j-1}}{h_y}, \quad g_{z,ij} = 1,$$

for $i = 2, \ldots, n_x - 1, \quad j = 2, \ldots, n_y - 1$.

On the boundary the following formulas ensuring also the second order of approximation are used:

$$g_{x,1j} = -0.5\frac{-3h_{1,j} + 4h_{2,j} - h_{3,j}}{h_x},$$

$$g_{y,i1} = -0.5\frac{-3h_{i,1} + 4h_{i,2} - h_{i,3}}{h_y},$$

$$g_{x,n_xj} = -0.5\frac{3h_{n_x,j} - 4h_{n_x-1,j} + h_{n_x-2,j}}{h_x},$$

$$g_{y,in_y} = -0.5\frac{3h_{i,n_y} - 4h_{i,n_y-1} + h_{i,n_y-2}}{h_y}.$$

The most frequently used morphometrical parameters of landscape are the slope and the exposition of the surface. Their availability enables us to characterize land and surface of landscapes.

The determination of a slope by classical methods is a long and labour–consuming process and is carried out by use of detailed toposheets for quite large contours.

Using a geometrical interpretation of the gradient, the slope of a surface α is defined by the formula:

$$\alpha = Arctan(\sqrt{g_x^2 + g_y^2}),$$

Depending on the purpose of cartographical model of surface slopes the appropriate scale is set. An evaluation of agricultural use for the territory model of slopes of separate region is presented on the Fig.4.

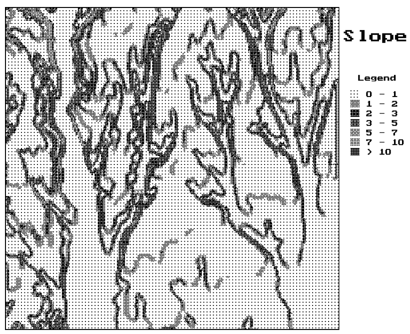

Figure 4: The slopes

The concept of a gradient is applied also when an exposition (orientation of a surface concerning the parties of light) is calculated, the information about which is necessary, for example, for study of microclimate energetical characteristics redistribution of solar radiation and of thermal balance. Under the previous notations an exposition e is calculated by the next formula:

$$\alpha_e = Arctan(\frac{g_y}{g_x})$$

.

The positive direction of x–axis corresponds to the east exposition, negative — to the western. At $g_x = 0$ a sign of the components g_y is considered: at positive significance exposition is northern, at negative — southern. If g_x, g_y are close to zero the surface has not an exposition at all (on Fig.5 they are painted by colour, which corresponds to letter O).

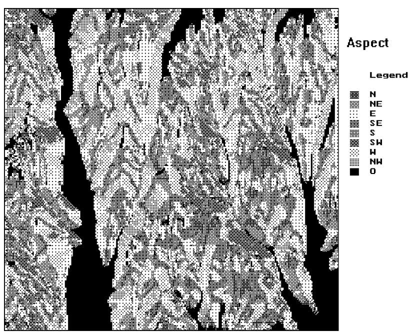

Figure 5: The aspects

As a rule, exposition is defined by four or eight directions.

The exposition is defined by following rules:

a) by four directions —

$$\text{if } \frac{7}{4}\pi \le \alpha_e \text{ or } \alpha_e < \frac{1}{4}\pi, \text{ then expozition is eastern } (E - East),$$
$$\text{if } \frac{1}{4}\pi \le \alpha_e < \frac{3}{4}\pi, \text{ then expozition is northen } (N - Nord),$$
$$\text{if } \frac{3}{4}\pi \le \alpha_e < \frac{5}{4}\pi, \text{ then expozition is western } (W - West),$$
$$\text{if } \frac{5}{4}\pi \le \alpha_e < \frac{7}{4}\pi, \text{ then expozition is southern } (S - South).$$

b) by eight directions —

$$\text{if } \frac{15}{8}\pi \le \alpha_e \text{ or } \alpha_e < \frac{1}{8}\pi, \text{ then expozition is eastern } (E),$$
$$\text{if } \frac{1}{8}\pi \le \alpha_e < \frac{3}{8}\pi, \text{ then expozition is north-east } (NE),$$
$$\text{if } \frac{3}{8}\pi \le \alpha_e < \frac{5}{8}\pi, \text{ then expozition is northen } (N),$$
$$\text{if } \frac{5}{8}\pi \le \alpha_e < \frac{7}{8}\pi, \text{ then expozition is north-west } (NW),$$
$$\text{if } \frac{7}{8}\pi \le \alpha_e < \frac{9}{8}\pi, \text{ then expozition is western } (W),$$
$$\text{if } \frac{9}{8}\pi \le \alpha_e < \frac{11}{8}\pi, \text{ then expozition is south-west } (SW),$$
$$\text{if } \frac{11}{8}\pi \le \alpha_e < \frac{13}{8}\pi, \text{ then expozition is southern } (S),$$
$$\text{if } \frac{13}{8}\pi \le \alpha_e < \frac{15}{8}\pi, \text{ then expozition is south-east } (SE).$$

The interpretation of slope angles and expositions permits us to receive the cartographical models, which find the application in various fields scientific researches. Specially follows to note the necessity of data and models constructed on their base at geoecological evaluation of territory of republic and forecast its change.

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Received 13 January, 1995

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