MULTIVARIATE APPROACH TO RELIEF CLASSIFICATION AND TYPOLOGY - THE EXAMPLE OF NORTH-WESTERN CROATIA

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Abstract:
This work deals with the multivariate approach to the relief classification and typology from the applied-geomorphological aspect on the example of North-Western Croatia. The researched area is covered by 4495 samples analyzed according to 9 criterion variables (quantitative, geomorphological pedological and lithological variables).

Consonant with the research purposes, a multivariate approach has been approved. It is based on generalization of a larger number of attributes pointing out characteristic features and relations. All this enables the establishment of a hierachial structure and construction of the corresponding models, on the basis of which we realize typology and get an insight into the causes of the relief type differentiation.

Key Words:
classification, typology, North-Western Croatia, multivariate methods

MULTIVARIJANTNI PRISTUP KLASIFIKACIJI I TIPOLOGIJI RELJEFA - PRIMJER SJEVEROZAPADNE HRVATSKE

Izvadak:
U radu je, na primjeru Sjeverozapadne Hrvatske, razmotren multivarijantni pristup klasifikaciji i tipologiji reljefa s primijenjeno-geomorfološkog aspekta. Istraživano područje podijeljeno je na 4495 uzoraka (padina) analiziranih prema 9 kriterijalnih varijabli (kvantitativne geomorfološke, pedološke i litološke varijable).

U skladu s ciljevima istraživanja, odabran je multivarijantni pristup koji se temelji na generalizaciji većeg broja atributa uz
INTRODUCTION

Problems of the applied quantitative research in geomorphology connected with slopes and slope processes are exceptionally important. The slope processes are considered as risks because of their connection with soil erosion and slope instability (Mihalić, Stanić, 1995). The ecological aspect of this problem is also very significant. Evidently, it is necessary to apply the exact research methods with the purpose of corresponding quantification, typification and evaluation of the relief with regard to the mentioned differences, and with little subjectivity.

The research starting point is the analysis of the modifying influence of the relief on the exogenic geomorphological processes activity, which is expressed to such a degree that its quantitative parameters, together with the basic pedological and lithological features, can be significant assessors of the risk of the slope processes.

Consonant with the basic starting point, the fundamental quantitative parameters of the denudation-tectonic and denudation-accumulative relief of North-Western Croatia have been analyzed (Bognar, 1987), with the purpose of estimating and predicting the slope conditions and planning activities with a minor risk of the slope processes. Besides, the quoted quantitative variables were analyzed as well as their ability to explain, together with the pedological and lithological parameters, the spatial variability of various relief types on the researched area.

North-Western Croatia represents the key region of the Republic of Croatia with regard to its geographical position, role and importance. Its area amounts 19,665 km² approximately, i. e. it occupies about 35 % of the area of the Republic of Croatia (Žulić, 1974). The researched area is somewhat smaller because it occupies the denudation-tectonic and denudation-accumulative relief, i. e. the slope inclinations > 2⁰ (Fig. 1). All together, 4495 samples were analyzed according to 9 quantitative variables of relief, soil and lithology.

APPROACH AND METHODS

Classification and typology of particular relief forms are important tasks in geomorphological research, and they are indispensable for organization of often an
exceptionally large number of numerically expressed relief features. The notions of classification and typology are often used as synonyms, but Horváth (1997), on the basis of researching a large number of various concepts, considers that these two notions must be clearly distinguished and relevantly interpreted. Classification represents the first step in analysis, i.e. identification of categories by a detailed division of the relief units according to the clearly defined quantitative and qualitative criteria. On the contrary, typology represents the integration phase of the data achieved by classification, which implies grouping, i.e. the synthesis of the relief categories defined by the classification method into new units.
according to a defined common criterion.

In other words, the relief types represent the parts of the researched area distinctly determined in the region, with characteristic features of the group they belong to (e.g. the distance measures). The notion of a relief type can be understood as a theoretical model representing a group of the mutually similar spatial units, but, on the other hand, of the common features essentially different from another relief type.

Connection of forms and processes is one of the fundamental principles of geomorphological research. This connection can be cause-effect and correlative. The correlative connection is marked with simultaneous changes of certain parameters which do not have to be necessarily casually connected (MiHljević, 1995). For that reason, in the analysis of the quoted problems, there are multivariate methods which can quantify the relations among all elements of the geomorphological slope system and, in that way, point to the importance of the processes taking part in their formation (Peh, 1990, 1992). Moreover, through a simultaneous analysis of a larger number of variables, these methods contribute to discovering of the relief features variability cause, and, similar to the system analysis, on the basis of generalization of a larger number of attributes, stress the characteristic features and relations establishing a hierarchical organization. Likewise, these methods enable the construction of the corresponding mathematical models (Mather, Doornkamp, 1970) based on the fundamental variables or functions as optimal descriptors, on the basis of which one can deduce conclusions about the relief dynamic balance condition, which represents the basis of the rational approach to typology and evaluation.

Such an approach aims for the most possible elimination of subjectivity in estimation of features and makes the basis of the exact approach to the relief evaluation from a certain aspect.

When using multivariate methods, a special attention must be paid to the selection of the attributes which are going to be analyzed, and determination of the types must be based on a detailed and homogenous system of criteria, which should, if possible, include the remaining elements of the geographical environment for the sake of a more complex cognition of the relations in lithosphere, hydrosphere, pedosphere and atmosphere (Horvath, 1991, 1997).

Among significant works dealing with the problems of classification, typology and regionalization, it must be mentioned Linton's work about the delimitation of morphological regions (1951) and also "A method for deriving multi-factor uniform regions" (1961) by B. J. L. Berry, where the author singles out the regions of the USA on the basis of the cluster and factor analyses. The classification by means of the cluster analysis was worked out in detail by A. J. Parsons (1977) in his work "A technique for the classification of hillslope forms", on the example of the slope-profiles of several isolated hills of the N. J Wales in Australia. S. Leel-Össy (1984)
is preoccupied with the relief typology in Hungary according to the genetic criteri-
on. F. J. Dent, in his work "Land suitabil-
ity classification" (1978, according to D.
A. DAVIDSON, 1986), considers a param-
eter multivariate approach to the land class-
ification according to the favour for ag-
ricultural using. A cluster classification
has been carried out according to the charac-
teristics of particular kinds of soil, as
well as the soil fertility evaluation on the
basis of the main component and factor
analyses. In his work "Morphometric ana-
lysis of montain drainage basins in the
Basin and Range Province, USA" (1989),
W. N. Engstrom, on the basis of the cluster
analysis classifies the drainage basins in
Arizona and brings the results into con-
nection with the relief evolution. G. Hor-
váth (1991, 1997) works out the problems
of the relief classification and typology in
Hungary.

RELIEF CLASSIFICATION OF
NORTH-WESTERN CROATIA

Three groups of criteria make the basic
starting point of the analysis: a) morpho-
metric criteria (7 variables: the average
height, relative height, slope length, length
index, inclination, surface and exposition
regularity), b) geological criteria (vari-
able: the strength coefficient of the rock
masses) and c) pedological criteria (vari-
able: the ecological depth expressed as the
average soil depth of a certain cartograp-
hic soil unit, according to Appropriated
pedological map of the Republic of Cro-
atia, 1:300 000). Geological and
pedological criteria are included in the
analysis because of a wider and more
complex insight into interdependence
among the relief, soil and geological base,
which will be important, especially in later
relief evaluation.

The size and complexity of the resear-
ched area, and need for exact defining of
the relief characteristics understand a de-
tailed quantification of every sample and
use of the corresponding mathematical-
statistical methods which will best meet
this aim. In the spatial data typology, the
results obtained by means of the classifi-
cation by the cluster analysis method,
were used as the starting point. The es-
cence of this technique is a gradual group-
ing of a larger number of samples into the
cluster groups, the complexity of which
grows proportionally with the number of
iterations. By gradual grouping, the num-
ber of clusters decreases, and their size
(number of the included members) in-
creases, as well as their mutual variabil-
ity. In that way the hierarchial grouping
simplifies the complexity of relations in
nature and sets up a large number of the
infinte spatial data into a logical system.

There are several distance measures
used in the hierarchial grouping, and the
most spread one is the Euclidean distance,
which represents a geometrical distance
in multi-dimensional space and is ex-
pressed as:

$$\text{distance} (x,y) = \left[ \sum (x_i - y_i)^2 \right]^{1/2}$$

In further phases, when more objects
are being grouped according to similarity,
new cluster groups generate towards particular grouping rules. These rules specify the moment at which two cluster groups are similar enough to be grouped into a new cluster. There are several grouping rules. Some of them are based on the principle of “the nearest neighbour” or “the furthest neighbour”, unpondered or pondered average of the group pairs, etc.

Here, we come upon the Ward’s method, which is somewhat different from the previously mentioned methods, because it is based on the variance analysis, which has enabled distance evaluation among the cluster groups. This procedure was operationalized by Ward (1963.), and the statistical test of differences among medium vectors of two cluster groups was mathematically expressed by Rao (1951., 1965, according to King, 1969):

\[
F = \frac{N_a + N_b - p - 1}{p} \times \frac{N_a N_b}{(N_a + N_b)(N_a + N_b - 2)} \times D^2
\]

where \(N_a\) and \(N_b\) are the cluster groups, \(D^2\) = generalized distance statistics, \(p\) = variates.

The sum of two squared hypothetic clusters (formed in any phase) was minimized within the framework of this method. To serve the needs of this research, we used the Euclidean distance measure and the Ward’s grouping method.

By means of the cluster technique, the researched area of North-Western Croatia, covered with 4495 samples and 9 variables, was classified into 10 cluster groups and 17 subgroups according to the common characteristics (Fig. 2). The isolated groups and subgroups (Tabl. 1.), make the basis of singling out the relief types and subtypes (Lozić, 1999, 2000).

TESTING OF VARIABLE STATISTICAL IMPORTANCE

There are two basic purposes of the multiple discriminant analysis in typology: a) determination of the relief type variability causes to find mutually most optimal linear combinations of the predictor variables formed in the way that each one takes part in the relief types discrimination to the maximum extent, and b) establishment of the spatial discriminant model (Mather, Doornkamp, 1970) of the relief type relations and dominant slope morphological processes, the indicators of which are combinations of the variables included in discriminant functions. These purposes represent the criteria on the basis of which typology is performed.

The basic step in typology is testing of the results obtained by classification, i.e. determination of the model discriminant power in entirety, which is possible by means of the Wilks' lambda test, based on the proportion between the variance determination within a group and total variance determination:

\[
\text{Wilks' } \lambda = \text{det (W) / det (T)}
\]

The values of each variable initial cluster group are tested by means of the variance analysis equality. The variance analysis is applied while testing the null-hypothesis that the cluster group centroids
Tab. 1.: Absolute values of the cluster groups and subgroups centroids

<table>
<thead>
<tr>
<th>Types of relief slopes</th>
<th>Average height</th>
<th>Relative height</th>
<th>Length of the slopes</th>
<th>Length rel. height</th>
<th>Inclination</th>
<th>Number of incl. changes</th>
<th>Exposition index</th>
<th>Ecological depth of the soil</th>
<th>Coef. of rock hardness</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>191.81</td>
<td>55.67</td>
<td>451.6</td>
<td>8.314</td>
<td>3.01</td>
<td>1.00</td>
<td>0.185</td>
<td>105.28</td>
<td>1.02</td>
</tr>
<tr>
<td>1a</td>
<td>191.35</td>
<td>53.18</td>
<td>516.7</td>
<td>9.883</td>
<td>2.99</td>
<td>1.00</td>
<td>0.186</td>
<td>106.87</td>
<td>1.00</td>
</tr>
<tr>
<td>1b</td>
<td>192.21</td>
<td>57.84</td>
<td>394.7</td>
<td>6.941</td>
<td>3.02</td>
<td>1.00</td>
<td>0.183</td>
<td>103.89</td>
<td>1.05</td>
</tr>
<tr>
<td>2</td>
<td>258.6</td>
<td>84.71</td>
<td>645.6</td>
<td>7.749</td>
<td>2.99</td>
<td>1.00</td>
<td>0.318</td>
<td>80.14</td>
<td>6.04</td>
</tr>
<tr>
<td>2a</td>
<td>316.2</td>
<td>110.25</td>
<td>885.7</td>
<td>8.121</td>
<td>2.97</td>
<td>1.01</td>
<td>0.391</td>
<td>80.25</td>
<td>4.98</td>
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<td>2b</td>
<td>225.0</td>
<td>69.81</td>
<td>505.5</td>
<td>7.531</td>
<td>3.00</td>
<td>1.00</td>
<td>0.276</td>
<td>80.07</td>
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<tr>
<td>3</td>
<td>207.39</td>
<td>62.52</td>
<td>443.1</td>
<td>7.343</td>
<td>3.05</td>
<td>1.00</td>
<td>0.637</td>
<td>97.51</td>
<td>1.96</td>
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<td>3a</td>
<td>188.03</td>
<td>55.77</td>
<td>421.5</td>
<td>7.111</td>
<td>3.01</td>
<td>1.00</td>
<td>0.623</td>
<td>104.55</td>
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<td>3b</td>
<td>214.77</td>
<td>67.92</td>
<td>462.8</td>
<td>6.987</td>
<td>3.03</td>
<td>1.00</td>
<td>0.654</td>
<td>87.47</td>
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<td>4</td>
<td>187.46</td>
<td>55.00</td>
<td>718.9</td>
<td>13.683</td>
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<td>1.01</td>
<td>0.427</td>
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</tr>
<tr>
<td>4a</td>
<td>185.02</td>
<td>56.01</td>
<td>576.0</td>
<td>10.653</td>
<td>2.79</td>
<td>1.00</td>
<td>0.547</td>
<td>109.32</td>
<td>1.07</td>
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<td>4b</td>
<td>198.29</td>
<td>60.92</td>
<td>816.3</td>
<td>13.789</td>
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<td>1.03</td>
<td>0.349</td>
<td>106.30</td>
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<td>4c</td>
<td>176.51</td>
<td>44.67</td>
<td>845.3</td>
<td>19.159</td>
<td>2.07</td>
<td>1.02</td>
<td>0.316</td>
<td>109.37</td>
<td>0.67</td>
</tr>
<tr>
<td>5</td>
<td>255.31</td>
<td>89.38</td>
<td>424.4</td>
<td>5.065</td>
<td>3.99</td>
<td>1.00</td>
<td>0.200</td>
<td>83.55</td>
<td>2.78</td>
</tr>
<tr>
<td>5a</td>
<td>216.67</td>
<td>67.75</td>
<td>357.3</td>
<td>5.393</td>
<td>4.00</td>
<td>1.00</td>
<td>0.194</td>
<td>97.96</td>
<td>0.99</td>
</tr>
<tr>
<td>5b</td>
<td>283.77</td>
<td>105.33</td>
<td>473.9</td>
<td>4.824</td>
<td>3.97</td>
<td>1.00</td>
<td>0.203</td>
<td>72.93</td>
<td>4.10</td>
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<td>6</td>
<td>230.31</td>
<td>78.62</td>
<td>408.3</td>
<td>5.303</td>
<td>3.99</td>
<td>1.00</td>
<td>0.594</td>
<td>98.18</td>
<td>2.21</td>
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<tr>
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<td>335.06</td>
<td>127.14</td>
<td>569.9</td>
<td>4.681</td>
<td>3.99</td>
<td>1.01</td>
<td>0.649</td>
<td>71.43</td>
<td>5.39</td>
</tr>
<tr>
<td>8</td>
<td>430.17</td>
<td>124.61</td>
<td>489.8</td>
<td>4.296</td>
<td>4.06</td>
<td>1.03</td>
<td>0.387</td>
<td>53.72</td>
<td>10.05</td>
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<td>353.79</td>
<td>112.24</td>
<td>426.2</td>
<td>4.116</td>
<td>4.14</td>
<td>1.02</td>
<td>0.392</td>
<td>50.40</td>
<td>8.77</td>
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<td>8b</td>
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<td>155.53</td>
<td>649.0</td>
<td>4.747</td>
<td>3.86</td>
<td>1.06</td>
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<td>9</td>
<td>249.17</td>
<td>92.32</td>
<td>556.4</td>
<td>6.517</td>
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<td>2.02</td>
<td>0.376</td>
<td>90.18</td>
<td>3.31</td>
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<td>9a</td>
<td>216.07</td>
<td>79.11</td>
<td>547.0</td>
<td>7.329</td>
<td>3.35</td>
<td>2.03</td>
<td>0.270</td>
<td>99.71</td>
<td>1.69</td>
</tr>
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<td>9b</td>
<td>289.37</td>
<td>108.36</td>
<td>567.8</td>
<td>5.530</td>
<td>3.74</td>
<td>2.01</td>
<td>0.503</td>
<td>78.60</td>
<td>5.27</td>
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<td>10</td>
<td>415.39</td>
<td>266.00</td>
<td>1176.9</td>
<td>4.963</td>
<td>3.91</td>
<td>1.34</td>
<td>0.366</td>
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<td>1062.3</td>
<td>3.978</td>
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<td>0.399</td>
<td>63.33</td>
<td>6.82</td>
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<td>10b</td>
<td>338.28</td>
<td>219.35</td>
<td>1471.7</td>
<td>7.497</td>
<td>3.43</td>
<td>1.72</td>
<td>0.280</td>
<td>81.35</td>
<td>4.65</td>
</tr>
</tbody>
</table>
Fig. 2. The dendrogram of 260 initial clusters

Sl. 2. Dendrogram 260 inicijalnih clustera
Table 2: The results of the discrimination analysis for North-Western Croatia according to the variables

**Tab. 2.: Rezultati diskriminantne analize za Sjeverozapadnu Hrvatsku prema varijablama**

<table>
<thead>
<tr>
<th>Discrimination analysis</th>
<th>Number of variables in model: 9</th>
<th>Wilks Lambda: 0.00067 approx. F (81, 1572) = 40.771 p&lt;0.0000</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>N=260</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wilks</td>
<td>Partial</td>
<td>F - remove</td>
<td>p - level</td>
</tr>
<tr>
<td>Lambda</td>
<td>Lambda</td>
<td>9,242</td>
<td></td>
</tr>
<tr>
<td>average height</td>
<td>0.0007669</td>
<td>0.8873371</td>
<td>3.414013</td>
</tr>
<tr>
<td>relative height</td>
<td>0.0010827</td>
<td>0.6284866</td>
<td>15.89467</td>
</tr>
<tr>
<td>length of slope</td>
<td>0.0008354</td>
<td>0.8145156</td>
<td>6.123235</td>
</tr>
<tr>
<td>length/rel. height</td>
<td>0.0011085</td>
<td>0.6138716</td>
<td>16.91325</td>
</tr>
<tr>
<td>inclination</td>
<td>0.0017506</td>
<td>0.3886901</td>
<td>42.28932</td>
</tr>
<tr>
<td>inclination change</td>
<td>0.0041896</td>
<td>0.1624172</td>
<td>138.6656</td>
</tr>
<tr>
<td>expositions</td>
<td>0.0017297</td>
<td>0.3933877</td>
<td>41.46325</td>
</tr>
<tr>
<td>ecological depth of soil</td>
<td>0.0008032</td>
<td>0.847137</td>
<td>4.852009</td>
</tr>
<tr>
<td>coefficient of rock hardness</td>
<td>0.0009061</td>
<td>0.7509882</td>
<td>8.915787</td>
</tr>
</tbody>
</table>

(arithmetic means) are mutually equal. If the null-hypothesis is rejected, further analyses can be done.

Generally, the values of the Wilks' lambda test range from 1.0 (there is no discrimination power) to 0.0 (absolute discrimination power).

For 10 analyzed cluster groups, the value of the Wilks' lambda test amounts to 0.007 (Tabl. 2.), which means that there is a prominent discrimination power of variables among the groups.

**RELIEF TYPE DIFERENTIATION CAUSES**

Individual variable testing with regard to the statistical significance is based on the partial Wilks' lambda test, by means of which each individual variable of discrimination within the groups is determined on the basis of the relation: the Wilks' lambda value after including a certain variable into the test and the Wilks' lambda value before that including, which is also indicated by the F-values (Tabl. 2., Fig. 3.).

On the whole model level, we can notice a dominant influence on discrimination of the following variables: surface regularity, inclination and expositions, then index of length and relative height, relative height and lithology. The influence of the average height and ecological depth is least noticeable. If particular variables are observed as indicators of geomorphological processes, we can conclude that, according to the established model, the gravitational slope processes, whose intensity directly depends on the surface regularity, slope inclination (including the index of length and relative height) and slope length, represent the most important causes of particular relief types in the area of North-Western Croatia. Since the variables of the ecological
depth and exposition are also somewhat significant, we can say that the relief type features depend, to a large extent, on the pedological structure (feedback mechanism) and climatic element activity. The variables of the average height and lithology have the least share in discrimination.

It is necessary to point out that the variable shares are expressed relatively and independently of their position in the hierarchy; statistically, all variables significantly influence differentiation (p-level).

After determination of the model and particular variable discrimination power, there followed the extraction of the discriminant function by means of the canonical correlation method. This method was mathematically worked out by Hotelling (1935, according to Fulgosi, 1978), who formulated it as looking for “the most predictive criteria”. The essence of this method is to connect simultaneously several variables -predictors with the cluster groups, with the purpose to find within a group of variables the most optimal variable combinations, which significantly discriminate the groups. In other words, the discriminant functions, obtained by canonical correlation, represent mutually orthogonal linear combinations of the predictor variables, which are, similar to the factor analysis, formed so that each of them takes part in discrimination to the maximum extent. Then, each linear function is tested by the Wilks' lambda test of significance. The share in discrimination is hierarchial, which means that the first function has the greatest discriminant power, and each next one contains the maximal variance among the groups, which remained after the removal of the variance caused by the previous linear functions. The functions whose share is not significant, are usually eliminated from further analysis.
Table 3.: Features of discriminant functions  
*Tab. 3.: Značajke diskriminantnih funkcij*  

<table>
<thead>
<tr>
<th>Roots removed</th>
<th><strong>EIGEN</strong></th>
<th><strong>CANONICAL R</strong></th>
<th><strong>Wilks Lambda</strong></th>
<th><strong>Chi-Sqr.</strong></th>
<th><strong>df</strong></th>
<th><strong>p-level</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>6.50830</td>
<td>0.93103</td>
<td>0.00068</td>
<td>1819.54</td>
<td>81</td>
<td>0.0000000</td>
</tr>
<tr>
<td>1</td>
<td>4.31517</td>
<td>0.90103</td>
<td>0.00511</td>
<td>1316.55</td>
<td>64</td>
<td>0.0000000</td>
</tr>
<tr>
<td>2</td>
<td>2.76420</td>
<td>0.85694</td>
<td>0.02716</td>
<td>899.74</td>
<td>49</td>
<td>0.0000000</td>
</tr>
<tr>
<td>3</td>
<td>1.40487</td>
<td>0.76431</td>
<td>0.10222</td>
<td>569.02</td>
<td>36</td>
<td>0.0000000</td>
</tr>
<tr>
<td>4</td>
<td>1.13134</td>
<td>0.72857</td>
<td>0.24582</td>
<td>350.08</td>
<td>25</td>
<td>0.0000000</td>
</tr>
<tr>
<td>5</td>
<td>0.73334</td>
<td>0.65044</td>
<td>0.52394</td>
<td>161.27</td>
<td>16</td>
<td>0.0000000</td>
</tr>
<tr>
<td>6</td>
<td>0.05635</td>
<td>0.23096</td>
<td>0.90816</td>
<td>24.04</td>
<td>9</td>
<td>0.004254</td>
</tr>
<tr>
<td>7</td>
<td>0.04100</td>
<td>0.19846</td>
<td>0.95933</td>
<td>10.36</td>
<td>4</td>
<td>0.034811</td>
</tr>
<tr>
<td>8</td>
<td>0.00134</td>
<td>0.03653</td>
<td>0.99867</td>
<td>0.33</td>
<td>1</td>
<td>0.563786</td>
</tr>
</tbody>
</table>

By means of the canonical analysis 9 discriminant functions were singled out. Their significance degrees were determined by the Chi-square test, which is also evident from their peculiar (Eigen) values (Tabl. 3). The first three functions (0, 1 and 2) are the most significant, because they explain the largest part of the system variance (80.33%), which can be seen from the graph of peculiar values (Fig. 4.).

The standardized coefficients of discrimination were used to interpret the relations between variables and discriminant functions, because they relate to all standardized variables included in the analysis, and use the comparable scale of values. Tabl. 4. shows that the first two discriminant functions are, to the maximum extent, burdened with the variables of the surface regularity, inclination and length. The first function is also considerably burdened with the
variables of the index of length and relative height and ecological depth, and the second one is burdened with the variables of the index of expositions and index of length and relative height. The third discriminant function is mostly burdened with the variables of the relative height and inclination, and somewhat significantly with the variables of length and average height.

Taking into consideration the discriminant function features, we can say that the variables of the surface regularity, slope inclination and length play first fiddle in differentiation of the relief types of North-Western Croatia. The variables of the average height, relative height, index of length and relative height, and of the ecological depth of the soil, are somewhat less significant. The least is the influence of the variables of the average height and lithology in discrimination within the whole three-dimensional area defined by three discriminant functions. Since the Wilks’ lambda test has stated that all variables notably take part in discrimination, the share of each variable will be taken into account on the occasion of the function interpretation.

If we connect the mentioned variable combinations in particular discriminant functions with the corresponding slope processes (Fig. 5), we can say that the discriminant function 1 on the positive side of the axis points to the mostly favourable conditions on the slopes, with the possibility of the excessive phenomena of the land-slope slope processes (on the negative side of the axis the situation is reverse).

Generally, the slopes discriminated by this function with the positive sign, are stable and aspire to increase their stability. The positive side of the axis of the discriminant function 2 points to a different condition, that means to a low balance degree, with a great probability of the gravitational processes of slope-wash and gullyng. The land-slide processes are not observable to an increased extent because of the rock strength (on the negative side of the axis the conditions are reverse). The
Fig. 5.: Scheme of the model representing relations between variables and discriminant functions

Sl. 5.: Shema modela odnosa varijabli i diskriminantnih funkcija
third discriminant function points to relatively unfavourable conditions, because, although there are the inclination decrease, increase of the index of length and relative height and exposition index, there are simultaneously the increase of the average and relative height, slope length and surface irregularity, which essentially decreases the stability of the slopes discriminated by this function to an increased degree. Considering the strength coefficient value decrease, there is a danger of intensification of the land-slide destruction processes. The balance is minor, but not to such a degree as it is on the slopes discriminated by the second function. Generally, there are not prominent differences between the positive and negative side of this discriminant function axis.

MODELS REPRESENTING RELATIONS BETWEEN TYPES AND SUBTYPES OF RELIEF AND DISCRIMINANT FUNCTIONS

One of the basic purposes of the multivariate approach in this research are the construction and application of the spatial models aiming at abstraction and synthesis of a great number of attributes into a logical system, on the basis of which one will be able to identify the spatial systems differentiated concerning the relation between the forms and morphological processes. As the models represent the relief subsystems differentiated by the interior homogeneity of the forms and processes connected with them, there is a significant possibility of their application for practical purposes.

The influence of particular variables on the whole system variability being determined, we can come up to the next phase of the analysis which deals with the determination of the influence of variables or variable combinations included in discriminant functions on variability of particular relief types and subtypes within the slope system of North-Western Croatia. For this purpose, it is necessary to perform the analysis of the canonical variable means for each cluster group (Tabl. 5.).

The arrangement of the discriminant function values according to types (Fig. 6)

<table>
<thead>
<tr>
<th>Grupe</th>
<th>Diskr. 1</th>
<th>Diskr. 2</th>
<th>Diskr. 3</th>
<th>Diskr. 4</th>
<th>Diskr. 5</th>
<th>Diskr. 6</th>
<th>Diskr. 7</th>
<th>Diskr. 8</th>
<th>Diskr. 9</th>
</tr>
</thead>
<tbody>
<tr>
<td>G.1:1</td>
<td>2.20446</td>
<td>-0.55764</td>
<td>-0.36122</td>
<td>-1.69750</td>
<td>-0.28988</td>
<td>0.74815</td>
<td>0.25493</td>
<td>0.20113</td>
<td>-0.04443</td>
</tr>
<tr>
<td>G.2:2</td>
<td>1.17000</td>
<td>0.28953</td>
<td>0.43534</td>
<td>-0.62679</td>
<td>1.92161</td>
<td>0.91746</td>
<td>-0.63258</td>
<td>0.02814</td>
<td>-0.00630</td>
</tr>
<tr>
<td>G.3:3</td>
<td>2.46879</td>
<td>-1.17127</td>
<td>0.15995</td>
<td>1.55317</td>
<td>0.12164</td>
<td>1.18766</td>
<td>0.18808</td>
<td>-0.13018</td>
<td>0.04348</td>
</tr>
<tr>
<td>G.4:4</td>
<td>3.46299</td>
<td>-1.63537</td>
<td>1.24432</td>
<td>-0.17430</td>
<td>0.05504</td>
<td>-1.75670</td>
<td>-0.03040</td>
<td>-0.05790</td>
<td>0.00499</td>
</tr>
<tr>
<td>G.5:5</td>
<td>-0.52504</td>
<td>1.81805</td>
<td>-1.72209</td>
<td>-1.32767</td>
<td>-1.03122</td>
<td>-0.05550</td>
<td>-0.07471</td>
<td>-0.28074</td>
<td>0.02618</td>
</tr>
<tr>
<td>G.6:6</td>
<td>0.18849</td>
<td>0.85615</td>
<td>-1.45052</td>
<td>1.51718</td>
<td>-1.70895</td>
<td>-0.25242</td>
<td>-0.25235</td>
<td>0.42752</td>
<td>0.01218</td>
</tr>
<tr>
<td>G.7:7</td>
<td>-0.55327</td>
<td>1.72176</td>
<td>-0.28660</td>
<td>1.93505</td>
<td>0.00332</td>
<td>-0.14519</td>
<td>0.01283</td>
<td>-0.25577</td>
<td>-0.09307</td>
</tr>
<tr>
<td>G.8:8</td>
<td>-1.62643</td>
<td>2.72797</td>
<td>-1.52604</td>
<td>0.18053</td>
<td>2.23438</td>
<td>-0.76816</td>
<td>0.29608</td>
<td>0.16796</td>
<td>0.02546</td>
</tr>
<tr>
<td>G.9:9</td>
<td>-4.54423</td>
<td>-4.03085</td>
<td>-0.59492</td>
<td>-0.07916</td>
<td>0.12416</td>
<td>-0.06936</td>
<td>-0.0379</td>
<td>-0.01179</td>
<td>-0.00321</td>
</tr>
<tr>
<td>G.10:10</td>
<td>-2.78602</td>
<td>2.02746</td>
<td>4.16190</td>
<td>-0.26471</td>
<td>-0.56136</td>
<td>0.22204</td>
<td>0.05435</td>
<td>0.05255</td>
<td>0.01221</td>
</tr>
</tbody>
</table>
Fig. 6: Values of the discrimin. funct. 1,2 and 3 according to the relief types

Sl. 6.: Vrijednost diskriminantnih funkcija 1, 2 i 3 prema tipovima reljefa

shows that the first discriminant function discriminates most intensively the type 9 (with the negative sign), the type 4 (positive sign), and, to a somewhat smaller extent, the type 10 (negative sign), 3 (positive sign) and 1 (positive sign).

The discriminant function 2 discriminates most intensively (like DF 1) the type 9 (negative sign), and, to a somewhat smaller extent, the type 8 (positive sign) and the type 10 (positive sign). The influence on the types 7 (positive sign), 4 (negative sign) and 5 (positive sign) is also significant.

The discriminant function 3 discriminates most intensively the type 10 (positive sign), and to a smaller extent the types 5 and 6 (negative sign).

The Fig. 7 presents the models of the relations between the relief types and variables from the area of North-Western Croatia. For the easy reference, the relations of the relief types with the discriminant functions 1 and 2, then 2 and 3 are presented separately.

The position of the groups 4, 3 and 1, determined by the positive sign of the discriminant function 1 and negative sign of the discriminant function 2, points to mainly favourable characteristics of the slopes belonging to these types. This is also pointed to by variable combinations and their signs characterized by these two axes. So, the positive side of the axis of the discriminant function 1 is marked by the increase of the ecological depth, length and relative height index, and the index of expositions and surface regularity. On the other hand, there is a value decrease of the average height, relative height,
Fig. 7.: Models of the relationship of the relief types and discriminant functions 1, 2 and 3

Sl. 7.: Modeli odnosa tipova reljefa i 1., 2. i 3. diskriminatorne funkcije
Fig. 8.: Models of the relationship of the relief subtypes and discriminant functions 1, 2 and 3
Sl. 8.: Modeli odnosa podtipova reljefa i 1., 2. i 3. diskriminantne funkcije
inclination, slope length and strength coefficient. The negative side of the axis of the discriminant function 2 is marked by the increase of the length and relative height index, exposition and ecological depth index, and by the value decrease of the surface regularity, relative height, inclination, length, average height and strength coefficient. In that way, the quoted types are clearly singled out by the positive characteristics of the variable combinations on both discriminant functions.

A similar trend can be noticed from the position of these groups, which is determined by the discriminant functions 2 and 3.

Contrary to the types 4, 3 and 1, the types 8, 10, 7 and 5 are determined by the variable combinations pointing to an increased instability and greater risk of the slope processes, especially of slope-wash, gully-creating and rock-fall (with regard to the higher values of the strength coefficient). The position of these groups is determined by the discriminant function 1 negative sign and by the positive sign of the discriminant function 2, which is quite opposite from the position of the types 1, 3 and 4. Expressed by the variable features, it means the increase of the average height, inclination relative height, slope length and strength coefficient, and, on the other hand, the decrease of the length and relative height index, and of the expositions and ecological depth index. The similar goes for the position in relation to the discriminant functions 2 and 3.

The remaining three types, 2, 6 and 9, according to their position, find themselves somewhere between these two extremities, i.e. they have neither markedly positive nor negative features. This is indicated by appearance of the lessening of the variable combination positive character of a certain discriminant function by variable combinations of negative character of other discriminant functions. So, in the case of the groups 2, 6 and 9, the positive character of the discriminant function 1 overlaps with the negative character of the discriminant function 2, and, partly, with the negative character of the discriminant function 3.

Besides the position of the main relief types, it is sometimes necessary to know the position of the subtypes, which will be of particular importance in the later relief evaluation. For this reason, it is necessary to make up the models of the relations between the relief subtypes and discriminant functions, on which we will be able to recognize the subtype positions in relation to the variable combinations included in discriminant functions (Fig. 8.).

**RELIEF TYPES OF NORTH-WESTERN CROATIA**

The results of the cluster and discriminant analyses, i.e. the absolute values of the centroid cluster groups and subgroups (Tabl. 1.) and centroid positions in the mathematical three-dimensional space defined by the discriminant function
Fig.9: Medvednica - relief types
Sl.9: Medvednica - типи релефа
features, have served as criteria of the spatial isolating of the relief types and subtypes.

The following relief types and subtypes were singled out:

Type 1 – a slightly dissected hilly relief of the lower height above sea-level, of more gentle slopes exposed to the humid air masses, of great ecological depth of the soil; formed on the softer sediments. This type has 2 subtypes.

Type 2 – a moderately dissected hilly relief of more gentle slopes and average ecological depth of the soil; formed in the rocks. Type has 2 subtypes.

Type 3 – a slightly dissected hilly relief of a lower height above sea-level, of more gentle slopes, mainly not exposed to the humid air masses, and of a relatively large ecological depth of the soil; formed in the softer rocks. Type has 2 subtypes.

Type 4 – a slightly dissected hilly relief of a lower height above sea-level, of gentle slopes, of a great ecological depth of the soil; formed on the markedly soft sediments. Type has 3 subtypes.

Type 5 – a moderately dissected hilly relief of more prominent inclinations, exposed to the humid air masses, with the average ecological depth of the soil; formed in the soft rocks. Type has 2 subtypes.

Type 6 – a moderately dissected hilly relief of more prominent inclinations, mainly protected from the humid air masses, with a relatively large ecological depth of the soil; formed in the soft rocks. Type has no subtypes.

Type 7 – a moderately dissected hilly relief of prominent inclinations, protected from the direct activity of the humid air masses, with the average ecological depth of the soil; formed in the harder rocks. Type has no subtypes.

Type 8 – a markedly dissected hilly and mountainous relief of a larger height above sea-level, of prominent inclinations, with a markedly small ecological depth of the soil; formed on the prominently hard rocks. Type has 2 subtypes.

Type 9 – a moderately dissected hilly relief of markedly irregular slopes, with the average ecological depth of the soil; formed on the softer or medium-strengthed rocks. Type has 2 subtypes.

Type 10 – a markedly dissected hilly and mountainous relief of a larger height above sea-level, of to a large extent irregular slopes with prominent inclination and length, with smaller ecological depth of the soil; formed on the hard rocks. Type has 2 subtypes.

On the basis of the isolated relief types and subtypes, i.e. of belonging of every single sample to a determined type or subtype, it is possible to work out the corresponding typological relief maps. An example of typological relief map based at multivariate criteria is shown at Fig. 9 (Medvednica mountain).

**CONCLUSION**

On the basis of the multivariate criteria analysis, by application of the cluster techniques and discriminant analysis, we have performed a relief classification and typology, as well as the prognostic models of the slope processes risk based on
the relations between the relief types and discriminant functions defined by the quantitative variable combinations. Such an approach enabled determination of the variability cause of the conditions on the slopes on the basis of the morphological, pedological and lithological variable combinations which indicate character, volume and intensity of the slope processes.

The approach to the relief classification and typology according to the multivariate analysis criteria, is the basis of more exact estimate of the recent condition of the relief dynamic stability, of the risk prognosis of the possible future balance disturbance, but also of the evaluation from the mentioned aspects, which is of great practical importance for almost all fields of human activity. The application of the typology based on the multivariate criteria is supported by its synthetic character, accessibility of information about individual influences of the exogenic morphological processes expressed by particular variables, and by taking into account the ecological aspect, considering the fact that, besides the quantitative geomorphological variables, the soil and lithological base characteristics are also included in the analysis.

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Sanja Lozić: Multivariate approach to relief ...


Sažetak
MULTIVARIJANTNI PRISTUP KLASIFIKACIJI I TIPOLOGIJI RELJEFA - PRIMJER SJEVEROZAPADNE HRVATSKE

SANJA LOŽIĆ

Osnovno polazište istraživanja temelji se na pretpostavci o modificirajućem utjecaju reljefa na djelovanje egzogenih geo-morfoloških procesa, koji se izražen u tolikoj mjeri da njegovi kvantitativni parametri, zajedno s temeljnim pedološkim i litološkim značajkama, mogu biti značajni procjenitelji rizika od derazijskih procesa. U skladu s navedenom pretpostavkom, kvantificirani su temeljni parametri denudacijsko-tektonskog i denudacijsko-akumulacijskog reljefa Sjeverozapadne Hrvatske. Nakon toga testirana je sposobnost navedenih kvantitativnih varijabli da zajedno s pedološkim i litološkim parametrima objasnu prostornu varijabilnost različitih tipova reljefa na istraživanom području.

Osnovno polazište analize čine tri grupe kriterija (varijabli): a) morfometrijski (variablene srednje visine, relativne visine, dužine padina, indeksa dužine i relativne visine, nagiba i regularnosti površine), b) geološki (variablan koeficijent čvrstoće stijenskih masa) i c) pedološki kriterij (variabla ekološka dubina tla izražena kao prosječna dubina tla određene kartografjske jedinice tla, prema Namjenskoj pedološkoj karni RH, 1 : 300 000). Geološki i pedološki kriterij uključeni su u analizu radi šireg i kompleksnijeg uvida u međuvisinost reljefa, tla i geološke podloge.

Primjenom multivarijantne cluster tehnike, istraživano područje Sjeverozapadne Hrvatske (4495 uzoraka) klasificirano je prema zajedničkim osobinama 9 varijabli. Hijerarhijskim grupiranjem izdvojeno je 10 temeljnih cluster grupa. Na nizem stupnju grupiranja, bližem inicijalnom studiji postupka, uččeno je da clusteri 1, 2, 3, 5, 8, 9 i 10 imaju po dvije podgrupe, cluster 4 tri podgrupe, dok su clusteri 6 i 7 homogeni, tj. nemaju podgrupa. Izdvojene grupe i podgrupe temelj su izdvajaju tipova i podtipova reljefa. Problem utvrđivanja vjerodostojnosti prethodno izdvojenih cluster grupa koje reprezentiraju tipove reljefa Sjeverozapadne Hrvatske riješen je primjenom diskriminantne analize, čije je osnovno polazište matrica od 260 inicijalnih cluster-grupa kodirana prema prikladnosti članova glavnim grupama i podgrupama.

Vrijednosti inicijalnih cluster grupa na svakoj varijabli testirane su jednadžbom analize varijance, koja je primjenjena pri testiranju nul hipoteze da su centoidi (aritmetičke sredine) cluster grupa međusobno jednaki. Analiza je pokazala da su razlike izmedu 10 glavnih clusteru veće nego razlike unutar svakog pojedinačnog clusteru čime je uspješnost cluster klasifikacije.

Diskriminacijskom analizom, na temelju Wilk’s lambda testa, potvrđeno da
postoji izrazita diskriminacijska snaga varijabli između grupa.

Pojedinačno testiranje varijabli s obzirom na statističku značajnost temeljeno je na parcijalnom Wilk’s lambda testu, po-moću kojeg je određen pojedinačni udio svake varijable na diskriminaciju unutar grupa. Na razini modela u cjelini, utvrđen je dominantni utjecaj na diskriminaciju koji imaju varijable regularnosti površine, nagiba i ekspozicija, zatim indeksa dužine i relativne visine, relativne visine i lito-logije. Ako se pojedine varijable promatraju kao indikatori geomorfoloških pro-cesa, može se ustvrditi da najvažnije uzroke diferencijacije pojedinih tipova reljefa na području Sjeverozadne Hrvatske predstavljaju derazijski gravitacijski procesi čiji intenzitet direktno ovisi o regularnosti površine, nagibu padina i dužini padina. Budući da su donekle značajne i varijable ekološka dubina i ekspozicija, može se reći da su značajke tipova reljefa u velikoj mjeri ovisne i o pedološkom sastavu (povratna veza) i djelovanju klimatskih elemenata. Najmanji udio u diskriminaciji imaju varijable srednja visina i litologija.

Nakon ove faze, izvršeno je ekstahiranje diskriminantnih funkcija. Kanoničkom korištenjem izdvojeno je 9 diskriminatnih funkcija, za koje su Hi - kvadrat testom utvrđeni stupnjevi značajnosti. Od 9 izdvojenih funkcija najznačajnije su prve tri (0, 1 i 2), jer objašnjavaju najveći dio varijance sustava (80.33 %).

Prve dvije diskriminantne funkcije su u najvećoj mjeri opterećene varijablama regularnosti površine, nagiba i dužine, s tim da je za prvu funkciju značajno i opterećenje varijablama indeksa dužine i relativne visine i ekološke dubine, a za drugu varijablama indeksa ekspozicija i indeksa dužine i relativne visine. Treća diskriminantna funkcija najviše je opte-rećena varijablama relativne visine i nagiba a donekle je značajno opterećenje varijablama dužine i srednje visine.

Na temelju analize standardiziranih koeficijenata diskriminantnih funkcija uočljivo je da najznačajniju ulogu u diferencijaciji tipova reljefa Sjeverozadne Hrvatske imaju varijable regularnosti površine, nagiba padina i dužine. Nešto manji značaj imaju varijable srednje visine, relativne visine, indeksa dužine i relativne visine i ekološke dubine tla, dok je unutar ukupnog trodimenzionalnog prostora definiranog s tri diskriminacije-re funkcije utjecaj varijabli srednja visina i litologija u diskriminaciji najmanji. Budući da je Wilk's lambda testom utvrđeno da sve varijable značajno sudjeluju u diskriminaciji, prilikom interpretacije funkcija uzet je u obzir doprinos svake varijable.

Povezivanjem kombinacija varijabli na pojedinim diskriminantnim funkcijama s odgovarajućim derazijskim procesima, utvrđeno je da diskriminantna funkcija 1 ukazuje na uglavnom povoljne uvjete na padinama, s mogućnošću ekscesivne po-jave derazijskih procesa puženja i klječenja. Generalno, padine diskriminirane ovom funkcijom u stanju su ravnoteže i teže daljnjem povećanju stabilnosti. Diskriminantna funkcija 2 ukazuje na dru-gačije uvjete, a to znači nizak stupanj
ravnoteže, uz veliku vjerojatnost pojave gravitacijskih procesa, spiranja i jaruženja. Klizenja i puženja zemljišta nisu izražena u većoj mjeri s obzirom na veću čvrstoću stijena. Treća diskriminatorna funkcija ukazuje na relativno nepovoljne uvjete, jer iako se zamjećuje pad nagiba, porast indeksa dužine i relativne visine i indeksa ekspozicija, istovremeno je prisutan porast srednje i relativne visine, dužine padina i neregularnosti površine, što bitno umanjuje stabilnost padina diskriminiranih u većoj mjeri ovom funkcijom. S obzirom na pad vrijednosti koeficijenta čvrstoće, postoji opasnost intenziviranja destrukcijskih procesa kliženja i puženja. Ravnoteža je umanjena ali ne u tolikoj mjeri kao na padinama diskriminiranim drugom funkcijom.

Radi egzaktnije identifikacije reljefnih sustava sličnih značajki konstruirani su modeli odnosa tipova i podtipova reljefa s kombinacijama varijabli izraženih diskriminacijskim funkcijama, na temelju kojih je provedena tipologija. Treba naglasiti da svaka kombinacija varijabli upućuje na različitu relativnu važnost određenih morfoloških procesa u oblikovanju pojedinih tipova reljefa i upućuje na rizik od određenih derazijskih procesa. Izdvojeno je 10 temeljnih tipova i 17 podtipova reljefa što je prikazano na odgovarajućim tipološkim kartama u mjerilu 1: 200 000.

Podaci dobiveni primijenjeno-geomorfološkom tipologijom kvantitativnih geomorfoloških, pedoloških i litoloških pokazatelja mogu biti vrlo korisni pri prostormnom i urbanističkom planiranju lokacije, razvoja i rekonstrukcije urbanih i agrarnih prostora, radi informacije o recentnom stanju dinamičke stabilnosti reljefa ali i prognoze rizika od eventualnog narušavanja ravnoteže u budućnosti.

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