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Robert Olszewski
Andrzej Żyła

Institute of Photogrammetry and Cartography
Warsaw University of Technology
(00-661 Warszawa, Plac Politechniki 1)

Utilisation of artificial neural networks for determination of morphometric features of the terrain relief

The paper discusses selected, contemporary methods of determination of the basic geomorphologic units, basing on morphometric analyses of the Digital Elevation Model. It also presents methods of multi-feature data classification and the possibility to use those methods in cartography and geomorphology. Particular attention has been paid to the possibility to use Kohonen neural networks as a tool of unsupervised classification and generalisation of spatial data.

INTRODUCTION

Rapid development of the earth sciences which occurred at the beginning of the 19th century, an in particular the development of natural sciences and geomorphology, resulted in an attempt to arrange the then existing results of observations of the terrain relief and to systematise the recognised forms. Geomorphology is a science on forms and on forming of the Earth surface; its objective is to investigate the relief of the earth surface. Investigations of the relief concerns description of forms, which occur on the Earth surface (morphology), determination of geometric features (morphometry), specification of origin (morphogenesis) and determination of age of forms (morphochronology). Both, individual forms (form types are determined basing on such investigations), as well as groups of forms (what allows to distinguish genetic relief types) are investigated [9]. In the introduction to the Encyclopaedia of Geomorphology Rhodes Fairbridge has determined this science as "The Science of Scenery". There are no doubts concerning the importance of geomorphologic investigations for physical geography and for cartography, and in particular, for construction of a reliable model of the terrain relief.

At the beginning, the descriptive approach dominated in geomorphologic investigations; therefore developed classifications were usually based on physiognomic criteria. Works performed by the German and Austrian geomorphologists, Humboldt and Ritter allowed to utilise physiometric indices (besides descriptive criteria).

The objective of geomorphologic classification is determination of spatial arrangements, which objectively exist in location of phenomena and objects in the four-dimensional sphere of the geographic environment.

Forms may be ordered based on [9]:

- appearance – morphological classification,
- dimensions – morphometric classification,
- origin – morphogenetic classification,
- age – morphochronological classification.

Between physiognomic, metric and genetic features of the Earth surface relief forms and their age, as well as geological structure, specified relations occur, so the classification of those objects should be performed in a systematic way, which considers a group of direct relations of unique features of investigated objects.

The importance of morphometric investigations grew in the seventies of the 20th century, when their importance for physical-and-geographical regionalisation was noticed. In physical-and-geographical classification of complexes two systematic approaches may be distinguished: typological and regionalisation approaches. Typology is classification performed with respect to similarities; it consists of searching for common features and regularities in structure. Regionalisation consists of distinguishing of distinctive features, i.e. on determination of their individualism [18]. On the other hand, considers that the terms of classification and typology should be separated [17]. Clasasification is performed through division ("from the top") while typology is performed through grouping ("from the bottom"). In this approach classification must lead to distinction of separable classes, which cover the entire set, and typology does not have to meet those conditions. However, in the Earth sciences th eterm of typology is widely applied, but understood as classification, which consists of grouping spatial units according to their similarity to certain patterns.

Classification of terrain forms

Forms of the Earth surface have various shapes and size, they are of various origin and age. Therefore it is necessary to classify forms and to arrange them basing on their appearance, dimensions, origin and age. In geomorphologic classification simple forms (as a valley, a terrace, a bank, an edge, a saddle) or complex forms (as a mountain chain) may be distinguished [5].

Distinguished six form categories, basing on morphometric criteria [16]:

Forms	Size of forms	Differences in heights
Planetary	> 1000000 km^2	2.5–20 km
Megaforms	10000–1000000 km^2	0.5–11 km
Macroforms	10–10000 km^2	200–2000 m
Mesoforms	100 m^2–10 km^2	200–300 m
Microforms	1–100 m^2	1–100 m
Neoforms	1 dcm^2–10 m^2	1–2 m
Roughness	1 cm^2	< 1 cm

Difficulties in classification result from the assumption that endogenic (structural) forms were created first and then they were modelled by external (destructive) forces. According to Klimaszewski the Earth surface was modelled at the same time by external and internal forces [9].

Morphometric features of the terrain relief may be determined directly, in the field, or basing on derivative works – a topographic map or a digital elevation model. Cartographic data, being the result of field surveys, may be considered as a fully reliable source of spatial analyses [1]. This data is mostly recorded as thematic layers of geographic information systems and GIS tool software is used for complex spatial analysis.

Geomorphologic objects may be classified following various criteria. Mostly physiognomic criteria are used, which allow for classification of forms with respect to their external features. The, so-called, profile criteria may be used in this group, which allow for classification of forms with respect to their shapes, reflected in a topographic profile (convex, concave and flat forms), as well as with respect to the shape of object projection on a plane (circular, oval, elongated forms etc.). Criteria, which allow for classification of entire sets of forms, also exist (plain, corrugated, hilly areas etc.).

Physiognomic criteria have descriptive nature and they allow performing qualitative classification of forms only. Quantitative classification of the terrain surface forms requires that morphometric (physiometric) criteria be applied. Those criteria include, among others: slope inclination, local differences in heights, index of form compactness, as well as hypsometric criteria [21].

Only one criterion (simple classifications) or a set of criteria (complex classifications) may be assumed as the base of typological classification of terrain relief forms. Complex classifications may be uniform (e.g. morphogenetic criteria only) or not.

The division into geomorphologic vertical classifications (when units distinguished basing on a given criterion or a group of criteria are assigned the lower/higher rank, specified by the classification level) or horizontal classifications (assigning the same rank), as well as vertical-and-horizontal classifications also exists.

Geomorphologic classification systems (models of typological classification) use taxonomic and typological units, and cartographic typological works (based on specified classification systems) use spatial typological units. In the classification system a taxonomic unit is a record of a file of objects of the same rank, which are characterised by the common feature or by a set of features, recognised as primary features for a given set. The term "typological unity" specifies a secondary set of objects, which are characterised by similarity of certain, auxiliary features. The spatial typological unit includes particular objects of the main set, which have their real reflection in the form of a specified fragment of the geographic space.

Three basic methods of distinguishing typological units exist [21]:

1. A method of division of higher order units into lower order units (which is iteratively applied until the limit of purposefulness of division is reached) (Fig. 1a),

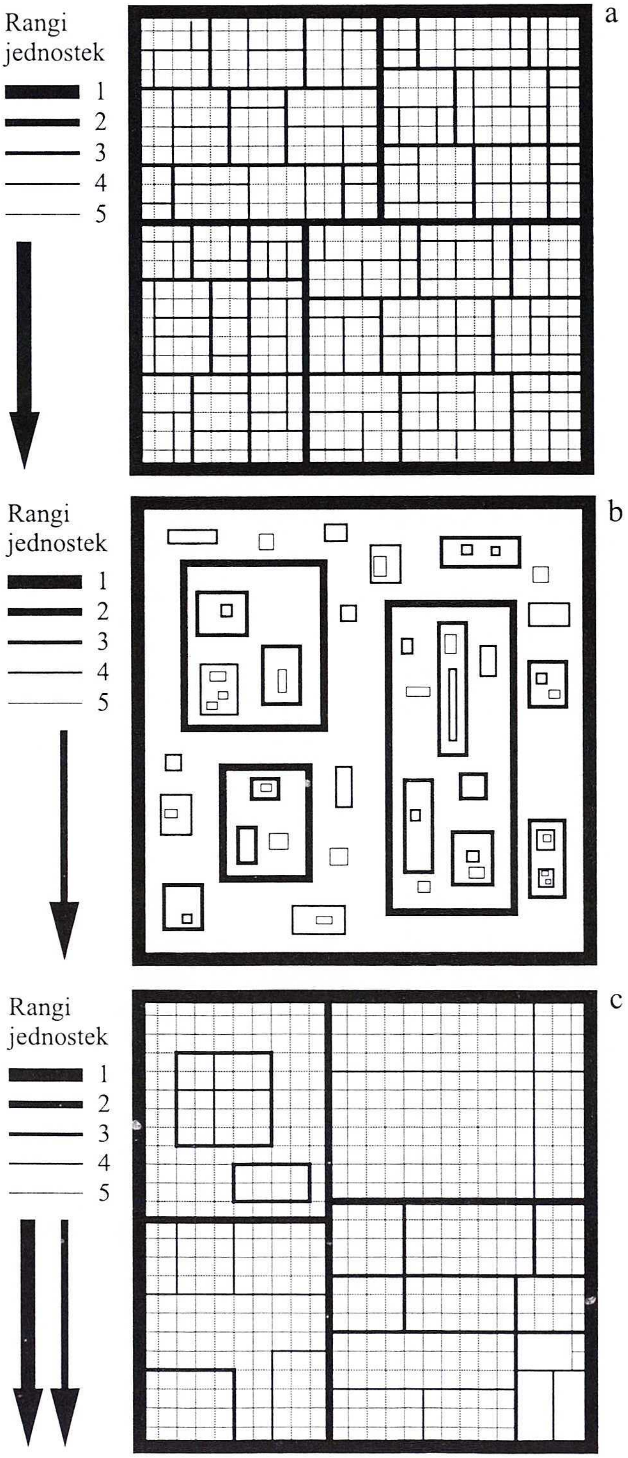

Fig. 1. Structure of the Kohonen network

2. A method of distinguishing lower order units within higher order units (Fig. 1b),
3. A combined method (division of higher order units + distinguishing lower order units). This method consists of division of a given population into the basic units of the lowest order; then those units are combined into higher order units (Fig. 1c).

Both, the first and the third methods are compliant with rules of the full (finite) classification, i.e. such classification that considers all elements included within the given population.

Distinguishing simple geomorphologic forms is based on analyses of multi-feature data. For elementary objects (e.g. geometric base field) specified morphometric coefficients are calculated. Basing on the similarity of elementary objects which are considered as the similarity of a set of investigated features, specified classes (types) of forms are distinguished. The assumed methodology allows not only to distinguish elementary terrain relief forms, but also to automate the process of generalisation of the digital elevation model, by means of selection of the basic structural lines and characteristic points of the modelled surface [20].

Investigations carried out prove, that terrain relief types, diversified with respect to their origin, have characteristic morphometric features (average inclination, local height differences etc.) [13]. In those investigations, the algorithm of *k*-means, proposed by Hartigan [7] has been used for grouping multi-feature objects. From the methodological point of view, utilisation of artificial neural networks, in particular utilisation of the Kohonen unsupervised classification is also interesting [8].

Artificial neural networks

Artificial neural networks (ANN) have been developed as a result of investigations performed in the field of artificial intelligence, and in particular, as a result of works concerning operations of the basic brain structures [19]. ANN allows for relatively simple creation of complex non-linear models, “learning” using presented examples [6].

The basic element of the ANN system is an artificial neuron, which projects the basic features of a biological system:

- a certain number of input signals reaches the neuron,
- each signal values is entered to the neuron through a connection of certain weight,
- the threshold value is specified for the neuron, which activates the neuron,
- the signal, which represents the total neuron stimulation is transformed by the specified activation function.

Particular neurons are grouped in layers, which create the SSN. The input layer allows entering source data into the network, i.e. hidden layers are used to data processing and the output layer allows outputting results from the network.

Many types of neural networks exist, which differ in structure and rules of operations. Multi-layer perceptrons – MLP, as well as radial basis functions – RBF, are mostly used. Neural networks allow for modelling of arbitrary, complex non-linear functions. The process of “learning” those networks is performed by means of the, so-called, an algorithm "with a teacher", i.e. trough multiple "presentation" of the source data network with a correct answer [15].

Utilisation of the ANN, taught in the "without a teacher" mode is also interesting from the point of view of source data classification. An example of such a structure is the, so-called, the Kohonen network. In the process of learning, this network does not receive the return information concerning the correctness of a given answer. Not knowing the required output information, the Kohonen network independently learns how to recognise the data structure [11]. Arrangement of input data is performed in this process, basing on the criterion of data mutual similarity. Kohonen networks are applied in explorative analysis of data, in the case of recognition of clusters of input data, as well as in data classification [19]. This classification is based on the internal similarity of structures of variables, without the necessity to a priori assume criteria of similarity and the number of classes to be distinguished. The most important feature, which characterises the Kohonen network, is the possibility to reflect an N-dimensional relation of similarity in the two- or even one-dimensional space.

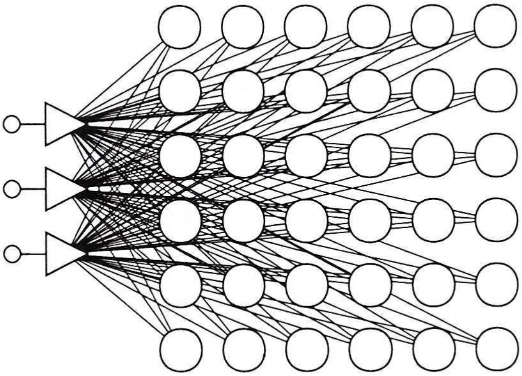

Fig. 2. Distinguishing of spatial typological units [21]

The Kohonen network is composed of two layers only: the input and the output layer. The output layer creates the, so-called, topological map (the map of Kohonen features), which presents similarities of features analysed objects in the one- or two-dimensional space [11]. The process of learning this network is performed iteratively. Initial, randomly selected values of weights of particular neurons are modified in successive stages in such a way that neighbouring neurons become specialised in recognition of similar objects.

Investigations

There are many conventional criteria and morphometric coefficients, used for typological classification of terrain relief forms, such as: slope inclination, local height differences, indices of curvature, indices of compactness etc. Contemporary works also point to purposefulness of utilisation of other indices, which characterise the terrain relief, for the needs of classification: they could be the second derivative of the terrain, the coefficient of relief energy and the local fractal dimension [10, 12, 14]. Proposes to apply several dozens of morphometric indices, grouped in several, non-correlated sets [20].

In performed investigations only several basic morphometric indices have been used. They characterised diversification in the terrain relief: slope, local differences in heights, profile curvature (determines the downhill or uphill rate of change in slope in the gradient direction (opposite of slope aspect direction) at each grid node) and tangential curvature (measures curvature in relation to a vertical plane perpendicular to the gradient direction, or tangential to the contour).

The digital elevation model (in the form of a regular grid 100 × 100 points), for a test site has been used for investigations, which covered the highest parts of the Polish Bieszczady Mountains. The DEM model in DTED 2 standard (Digital Terrain Elevation Data) was made available by the Military Geography Division, the General Staff of Polish Armed Forces. This model of 1" resolution was developed basing on the analogue map at the 1: 50 000 scale (Fig. 3a). The DTED 1 model of 3" resolution, was also used for the needs of comparing; that model was developed basing on the analogue map at the 1:200 000 scale (Fig. 3b).

For the source data, determined in that way, several Kohonen[1] networks of diversified number of parameters have been created and iteratively trained (with the use of 100 000 computational epochs):

1) x, y, z (plain co-ordinates and the absolute point elevation),
2) x, y, reverse of inclination,
3) x, y, horizontal curvature,
4) x, y, vertical curvature.

In numerical experiments two variants of the input layer of the Kohonen network were applied:

1) 225 neurons (15 × 15),
2) 625 neurons (25 × 25)

The utilised tool package allows for iterative assigning particular examples of presented networks (a set of 10 000 test points) to specified neurons of the output layer of the Kohonen network, which is also called the self-organising map of features. Networks of this type, using the model of training without a teacher, assign particular cases from the teaching file to classes, which number corresponds to the number of neurons in the output layer of that network. Organisation of neurons is given the form of a two-dimensional table. Classes, which cases are similarly represented in the structure of data, will be assigned to neurons located close to each other, which have close addresses in the matrix.

Unsupervised classification of test points, performed in the iterative process, allows to assign those points to particular classes (225 classes in the first variant and 625 classes in the second variant, respectively), represented by neurons of the output layer of the Kohonen network. Classification results should be, by definition, highly correlated with the spatial distribution of a phenomenon, i.e. with the terrain relief. The analysis of obtained results

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[1] All computations have been performed using the Statistica Neural Networks software.

allows for division of the test set into determined classes basing on the criterion of spatial location, what is ensured by plain co-ordinates (x, y), and for simultaneous consideration of the terrain relief, basing on additional variables (slope, height differences etc.).

Spatial analysis of distribution of obtained results requires that they are referenced to the source model. The above requirements are best met by visualisation of the range of impacts of particular neurons, overlaid on the hypsometric image of the source model. In order to obtain the range of impact of particular neurons, the table of overcoming neurons for particular cases has been generated. Irregular base fields, which define basic morphological structures, were created basing on the obtained set. They delineate the range of "impact" of particular neurons from the output layer of the Kohonen network.

For each set of analysed variables distribution of distinguished classes was generated on the background of the hypsometric image (Fig. 4).

Analysis of the above images allows for rejection of classification obtained with the use of the vertical curvature. This variable has the highly non-uniform distribution of values with respect to point locations, what leads to spatially incoherent classes, when applied with automatic classification performed by means of the Kohonen network. Two successive changes may be better applied in accordance to the proposed approach. Distinguished classes clearly depend on the terrain relief. Automatic distinguishing of separate classes for the main crest lines and drain lines is particularly interesting. Those classes are visualised as chains of neighbouring small fields on obtained images.

Basing on the results of classification using the analysis of three variables (x, y, z) (Fig. 4a) generalised structural lines were delineated, which describe the terrain relief. The coefficient of the terrain form curvature was used as auxiliary information (Fig. 5). The generalised model of the terrain relief was also created basing on characteristic points for particular forms.

The simple algorithm was applied for delineation of structural lines and the generalised model of the terrain relief:

- selection of a characteristic point for a given form (for convex forms – the highest point, for concave forms – the lowest point),
- determination of Delaunay's triangles (Fig. 6a),
- development fo the DEM in the form of TIN and the derivative GRID model (Fig. 6b).

CONCLUSIONS

The results obtained prove, that artificial neural networks, trained in the "without the teacher" mode, and, in particular Kohonen networks, may be used as a tool of unsupervised classification of multi-feature spatial data. Utilisation of the Kohonen algorithm for analysis of the terrain relief (represented by the DEM) allows for distinguishing basic geomorphologic structures. For the results obtained, selection of input data (morphometric indices), as well as the size of the output layer of the Kohonen network is important. Using the smaller number of neurons in that layer allows for the higher level of generalisation of results and for increasing the size of separated field units.

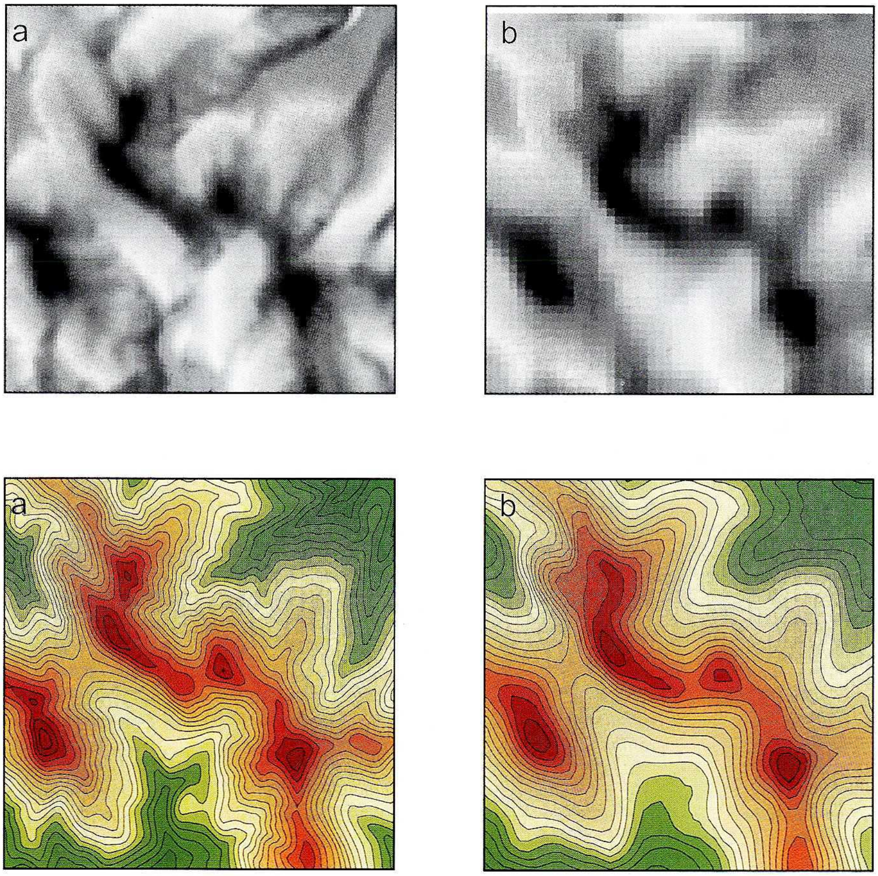

Fig. 3. Source data: raster form and a hyposometric map

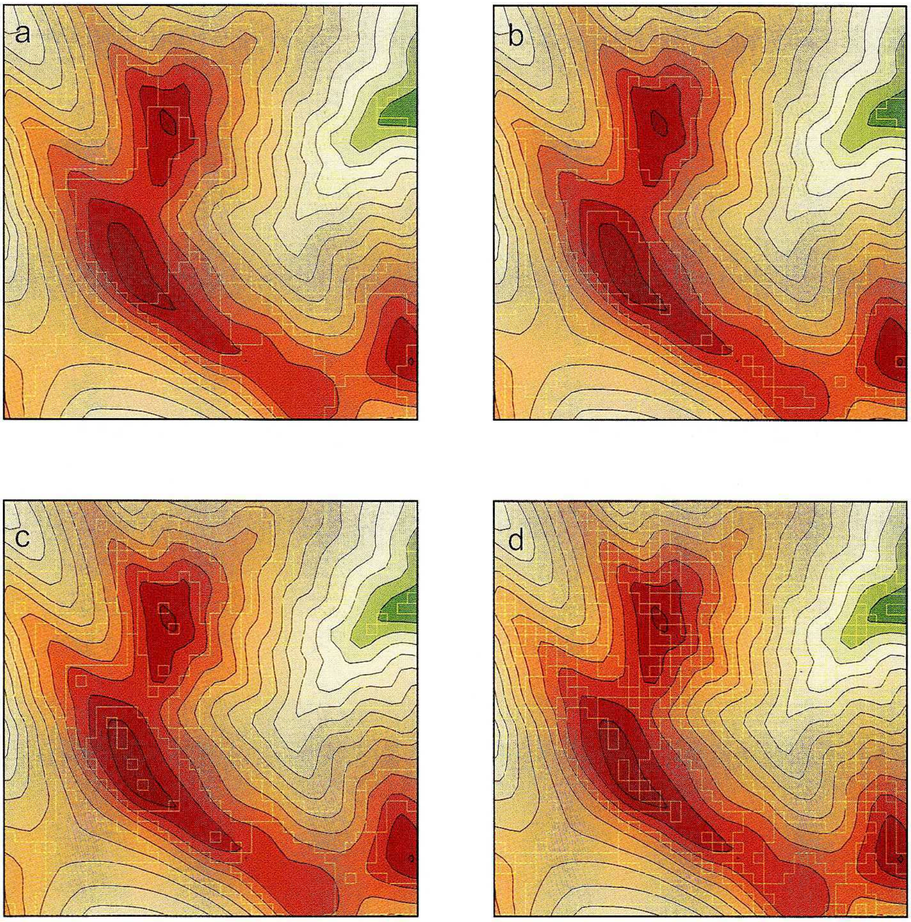

Fig. 4. Distinguishing pf the basic morphological structures – a fragment (for 225 neurons in the initial layer of the Kohonen network):

a – input variables (x, y, z)

b – input variables (x, y, reverse of a slope)

c – input variables (x, y, horizontal curvature)

d – input variables (x, y, vertical curvature)

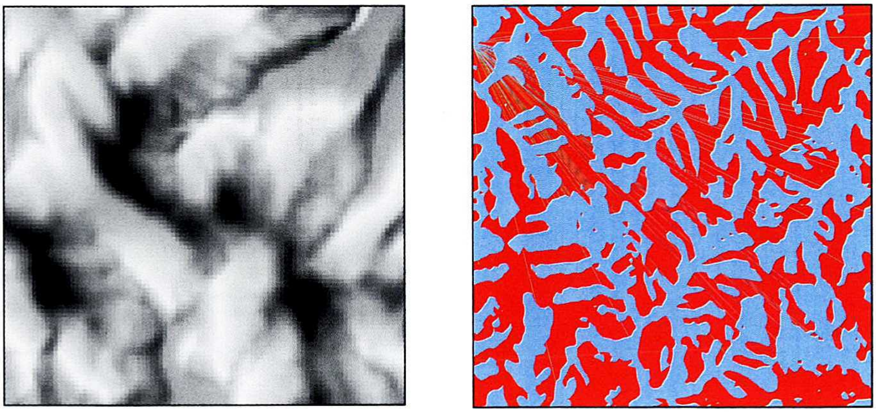

Fig. 5. Convex (red) and concave (blue) areas

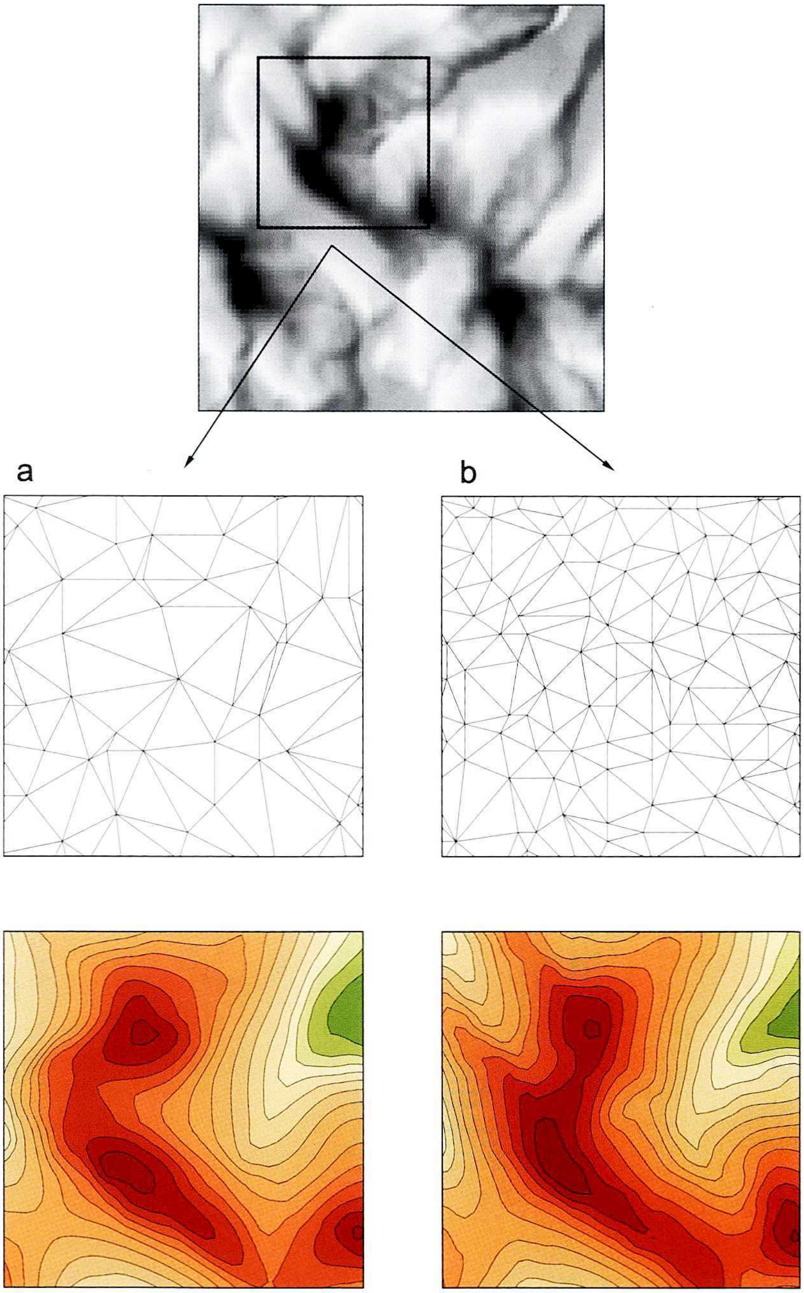

Fig. 6. Structural lines and the generalised model of the terrain relief:
a – for 225 neurons in the initial layer of the Kohonen network
b – for 625 neurons in the initial layer of the Kohonen network

An important influence on the iterative classification process has also the number of epochs of calculations. Using the too small number of iterations results in "insufficient training" of the neural network and, finally, leads to the image of structures, which are spatially incoherent.

Utilisation of proposed algorithms for generalisation of the Digital Elevation Model is also interesting. Comparing the results obtained (Fig. 6) with manual generalisation (Fig. 3b) or with trivial averaging the basic model leads to the conclusion, that the Kohonen algorithm may be applied as an alternative method of generalisation of the terrain relief.

REFERENCES

[1] Bartkowski T., *Zastosowania geografii fizycznej, (Utilising Physical Geography),* PWN, Warszawa, 1974.

[2] Burrough, P.A., *Principles of Geographical Information Systems for Land Resources Assessment.*, OUP, Ch.8, Methods of interpolation Oxford, 1986.

[3] Chojnicki Z., Czyż T., *Analiza czynnikowa w geografii. W: Metody ilościowe i modele w geografii. (Analysis of factors in geography.* In: *Quantitative methods and models in geography),* Edited by: Z. Chojnicki., PWN, Warszawa, 1977.

[4] De Floriani L., Mirra D., Puppo E., *Computer Graphics Forum,* No. 12(3), 1993.

[5] Eckes T., *Ćwiczenia z geomorfologii dla geodetów,* (*Geomorphologic tests for surveyors*) Wydawnictwa Naukowo-Dydaktyczne AGH, Kraków, 2001.

[6] Fausett, L., *Fundamentals of Neural Networks.* Prentice Hall, New York, 1994.

[7] Hartigan L., *Clustering Algorithms,* J. Wiley, New York, 1975.

[8] Kępińska M., Olszewski R., *Od Bertina i Hotellinga do Zadeha i Kohonena, czyli o zastosowaniu sztucznych sieci neuronowych w kartografii tematycznej,* (*From Bertin and Hotelling to Zadeh and Kohonen, i.e. on utilisation of artificial neural networks in thematic cartography*), Polski Przegląd Kartograficzny, vol. 34, no. 2, Warszawa, 2002.

[9] Klimaszewski M., *Geomorfologia* (*Geomorphology*), PWN, Warszawa, 1978.

[10] Klinkenberg B., *Fractals and morphometric measures: is there a relationship?,* Geomorphology 5, Elsevier Science Publishers B. V., Amsterdam, 1992.

[11] Kohonen, T., *Self–organized formation of topologically correct feature maps.* Biological Cybernetics, vol. 43 (1982).

[12] Kozieł Z., *Zmiany struktury kartograficznego obrazu energii rzeźby wywołane różnymi układami: nałożeniami sieci pól odniesienia,* (*Changes of structures of the cartographic visualisation of the energy of terrain relief, resulting from various systems: overlapping reference fields*), PPK, vol. 22, no. 3, Warszawa, 1990.

[13] Ławniczak R., *Próba zastosowania kartograficznej metody badań do określania morfometrycznych cech rzeźby terenu,* (*An attempt to utilise the cartographic method of investigations for specification of morphometric features of the terrain relief*), Polski Przegląd Kartograficzny, vol. 35, no. 1, 2003.

[14] Olszewski R., *Wymiarowanie multifraktalne jako narzędzie kwantyfikacji komponentów abiotycznych środowiska przyrodniczego w różnych skalach obserwacyjnych* (*Multifractal dimensioning as a tool of quantification of abiotic components on the natural environment at various scales of observations*), Materiały Ogólnopolskiej Szkoły Kartograficznej, Wrocław, 2001.

[15] Patterson, D., *Artificial Neural Networks.* Prentice Hall, Singapore, 1996.

[16] Piotrowski M., *Płanietarnaja gieołogija* (*Planetary geology*), 1963.

[17] Przewoźniak M., *Podstawy geografii fizycznej kompleksowej* (*Bases of complex, physical geography*), skrypt Uniwersytetu Gdańskiego, 1987.

[18] Richling A., *Kompleksowa geografia fizyczna (Complex physical geography)*, Wydawnictwo Naukowe PWN, Warszawa, 1992.

[19] Tadeusiewicz, R., *Elementarne wprowadzenie do sieci neuronowych z przykładowymi programami (Elementary introduction to neural networks with examples of programmes)*. Akademicka Oficyna Wydawnicza, Warszawa, 1998.

[20] Weibel R., *Models and Experiments for Adaptive Computer-Assisted Terrain Generalization*, Cartography and Geographic Information Systems, vol. 19, no. 3, 1992.

[21] Zgorzelski M. S., *System klasyfikacyjny form ukształtowania powierzchni niżowych obszarów polodowcowych (A classification system of the terrain relief for the lowland post-glacial areas)*, Wydawnictwa Uniwersytetu Warszawskiego, 1988.

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Robert Olszewski
Andrzej Żyła

Zastosowanie sztucznych sieci neuronowych do określania morfometrycznych cech rzeźby terenu

Streszczenie

W artykule omówiono wybrane współczesne metody wyznaczania podstawowych jednostek geomorfologicznych w oparciu o analizy morfometryczne numerycznego modelu rzeźby terenu. Przedstawiono także metody klasyfikowania danych wielocechowych oraz pokazano możliwość ich wykorzystania w kartografii i geomorfologii. Szczególną uwagę zwrócono na możliwość zastosowania sieci neuronowych, a zwłaszcza uczonych w trybie „bez nauczyciela" sieci Kohonena jako narzędzia nienadzorowanej klasyfikacji i uogólniania danych przestrzennych.

Istnieje wiele klasycznych kryteriów i wskaźników morfometrycznych stosowanych do klasyfikacji typologicznej form powierzchni terenu takich jak nachylenie zboczy, deniwelacje lokalne, wskaźnik krętości, wskaźnik zwartości/rozczłonkowania itp.

W przeprowadzonych badaniach zastosowano zestaw prostych kryteriów morfometrycznych, stosując do ich analizy sieci neuronowe Kohonena. Uzyskane wyniki wskazują, iż sztuczne sieci neuronowe uczone w trybie „bez nauczyciela" mogą być wykorzystywane jako narzędzie nienadzorowanej klasyfikacji wielocechowych danych przestrzennych. Zastosowanie algorytmu Kohonena do analizy rzeźby terenu (reprezentowanej przez NMT) umożliwia wydzielenie podstawowych struktur geomorfologicznych. Dla uzyskanych wyników istotny jest nie tylko dobór danych wejściowych (wskaźników morfometrycznych), lecz także rozmiar warstwy wyjściowej sieci Kohonena. Zastosowanie mniejszej liczby neuronów w tej warstwie pozwala na większy stopień uogólnienia wyników i zwiększenie rozmiarów wydzielonych jednostek terenowych.

Istotny wpływ na przebieg iteracyjnego procesu klasyfikacji ma także liczba epok obliczeniowych. Użycie zbyt małej liczby iteracji powoduje „niedouczenie" sieci neuronowej i w konsekwencji uzyskanie obrazu struktur niespójnych przestrzennie.

Interesujące jest także wykorzystanie zaproponowanych algorytmów do generalizacji numerycznego modelu rzeźby terenu. Porównanie uzyskanych wyników z generalizacją manualną lub uśrednieniem modelu podstawowego prowadzi do wniosku, że algorytm Kohonena może być wykorzystywany jako alternatywna metoda uogólniania modelu rzeźby.

Роберт Ольшевски
Анджей Жило

Применение искусственных нейронных сетей для определения морфометрических признаков рельефа местности

Резюме

В статье рассмотрены избранные современные методы определения основных геоморфологических единиц на основе морфометрического анализа цифровой модели рельефа местности. Представлены также методы классификации многопризнаковых данных и показаны возможности их использования в картографии и геоморфологии. Особое внимание обращено на возможность применения нейронных сетей, а, прежде всего, наученных в форме “без учителя” сетей Kohonena как орудия безконтрольной классификации и обобщения пространственных данных.

Существует много классических критериев и морфометрических показателей, применяемых к типологичесой классификации форм поверхности территории, таких как наклон скатов, локальные денивеляции, указатель извилистости, уазатель сомкнутости/расчленения и т.п.

В проведённых исследованиях применён набор простых морфометрических критериев, с использованием к их анализу нейронных сетей Kohonena. Полученные результаты показывают, что искусственные нейронные сети наученные “без учителя” могут использоваться как орудие безконтрольной классификации многопризнаковых пространственных данных. Применение алгоритма Kohonena для анализа рельефа местности (представляемого ЦММ) разрешает выделить основные геоморфологические структуры. Для получения результатов существенным является не только подбор исходных данных (морфометричесих показателей), но таже размер исходного слоя сети Kohonena. Применемие меньшего числа нейронов в этом слое даёт возможность большей степени обобщения результатов и увеличения размеров выделенных единиц местности.

Существенное влияние на ход интерпретационного процесса классификации имеет также число вычислительных эпох. Употребление слишком малого числа интерации вызывает “недоучение” нейтронной сети и в итоге получение изображения структур пространственно несвязанных.

Интересным является таже использование предложенных алгоримов для генерализации цифровой модели рельефа местности. Сравнение полученных результатов с мануальной генерализацей или усреднением данных основной модели приводит выводу, что алгоритм Kohonena может быть использован как альтернативный метод обобщения модели рельефа.