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Multi-criteria analysis on spatial data of the landscape

Paweł Jarosz, Piotr Łabędź, Paweł Ozimek

Cracow University of Technology
Institute of Computer Science
Warszawska 24, 31-155 Kraków, Poland
e-mail: pjarosz@pk.edu.pl, plabedz@pk.edu.pl, ozimek@pk.edu.pl

The method presented in this paper allows the visualization of spatial relations that could not be obtained using existing methods. Depending on the component maps that represent the analysis criteria, it is possible to indicate certain ways to develop good or bad areas. These maps may contain visibility data as well as other types of spatial impact. Thanks to this, spatial decision criteria can be broad and multi-branch.

Keywords: multiobjective optimization, spatial analysis, visibility maps.

1. Introduction

The most pleasant moments are connected with the feeling we experience when viewing beautiful landscapes. Places visited during holidays and vacations are deeply remembered. The landscape affects the comfort of our rest as well as everyday life. The impact of landscape quality on our mental health is felt by nearly everyone, and it is also confirmed by scientific research [1]. We are sensitive to the view from the window and it is so important to us that we are ready to pay a lot for it [2]. The introduction of elements unfavourable to this view results in the loss of financial benefits for enterprises not only serving tourism but also housing. These problems affect us all and are only slightly more important for people who are sensitive and actively doing tourism.

Landscapes, both urban and countryside, are analysed to determine their economic and natural value. The results of these analyses are used in spatial planning, strategic planning, nature protection, urban planning, and road and architectural design. This is particularly important in the areas covered by landscape protection, centres of historic cities, villages or tourist places. Such a type of analysis consists of a detailed verification of all the elements determining the individuality of the landscape by experts involved in landscape planning [3]. This applies to elements that both raise and lower its attractiveness. Their impact on the landscape is analysed by determining the weight, range and scope of the view as well as mutual relations. As a part of the mentioned research, guidelines for further spatial planning were defined. This results in the need for developing methods for generating graphs and maps showing these elements and allow the generation of proposals and guidelines. The results of analyses performed by experts involved in landscape planning largely depend on their preferences. Therefore there is a need to develop methods that create materials, based on which the expert's judgment could be as close as possible to the objective one.

One of the methods of landscape analysis consists of generating visibility graphs and visibility maps in the digital environment – a three-dimensional space model. Visibility graphs and maps, as thematic layers, compiled with other GIS data, support planning and decision making. They are generated due to the spatial objects having an impact on the landscape. They have weights and determine the ranges of impact in space and time [4]. The visibility graph shows the visibility of

Fig. 1. Simulation of a view with a non-existent power plant of the Tatra Mountains panorama from the vantage point on the Wdżar mountain in Gorce Mountains. Changing the view by introducing the power plant can be assessed positively and negatively by the expert, depending on the preferences.

a single point in space and the place visible from a given point because the visibility relationship is symmetrical. Maps can show the visibility of large spatial objects. They can also contain the visualization of the aggregated impact of many factors, arranged in different ways, using various modifiers depending on the requirements of the given analysis.

2. Viewsheds and visibility maps

Ozimek *et al.* [5] analysed methods for determining visibility in systems that use digital terrain models. The work presents described methods in terms of suitability for landscape analyses. It also describes an approach to generating visibility maps, exemplary creation goals and interpretations of results, illustrating them on the example of a pilot project, which was located in the Czorsztyński reservoir pool. The authors introduced an approach distinguishing between component and aggregate maps. The latter are generated to meet specific landscape analysis objectives. With the use of matrix operations, it is possible to obtain maps resulting from arithmetic and logical operations on component maps.

The visibility graph can be generated using various methods, selected accordingly to the spatial data structure that is available. In the case of landscape analyses, the integration of GIS data with projects carried out in CAD systems often takes place. For such cases, the polygon mesh is optimal for representing spatial objects and the raytracing algorithm for generating visibility graphs [6]. The rendering made by applying raytracing in a model built of polygons in an orthogonal projection shows the places visible from the point of the light source position. The obtained image contains (after thresholding) disjunctive information about visibility and can be compiled as a layer with other visibility graphs and other maps – GIS layers.

The visibility map shows visibility from many points. Depending on the needs, it is possible to obtain a visibility map of linear objects such as roads or bicycle paths, surfaces such as mountain massifs or lakes, as well as a set of objects that can be exemplified by all churches in the valley. They are obtained as a result of matrix calculation of visibility graphs. In the case of examining the visibility of a large object such as the lake surface, the map is obtained by distributing the points on its surface evenly, then the graphs are generated for each of them and the matrix arithmetic mean is calculated. The result is an image on which the brightness of the pixels is proportional to the size of the surface of the lake that can be seen from the place represented by the given pixel.

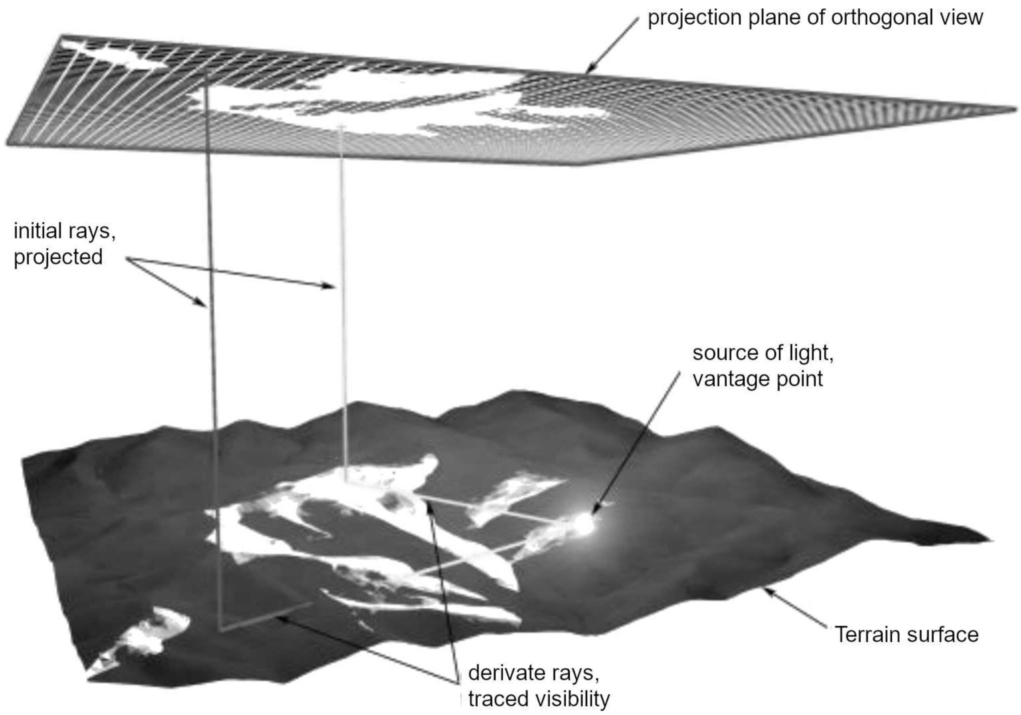


Fig. 2. Raytracing algorithm in the orthogonal projection.
The basic principle of generating graphs of visibility.

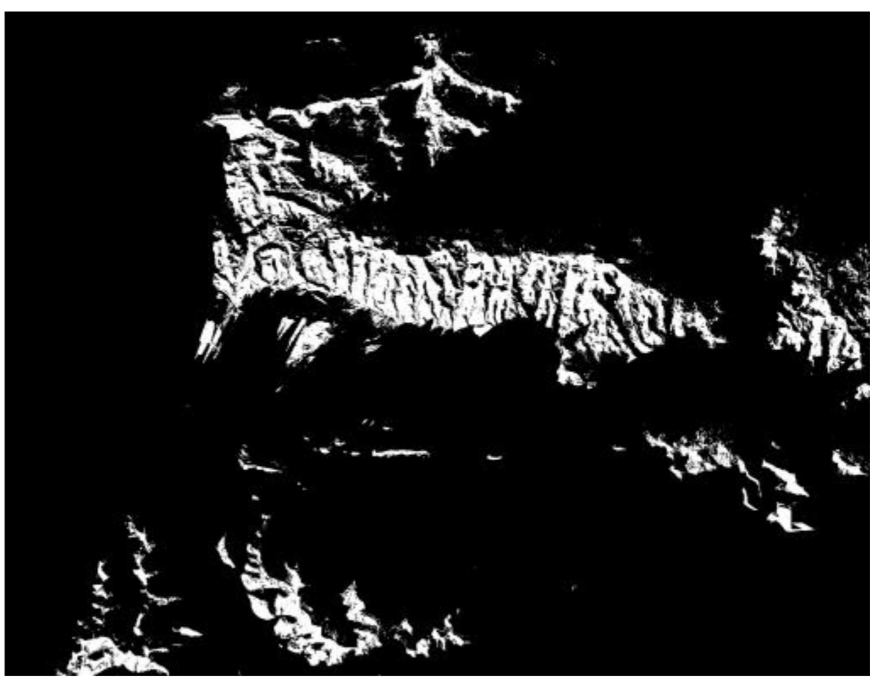


Fig. 3. The visibility graph.

By using the properties of raster graphics, it is possible to create maps on which the colours present separate phenomena. For example, the visibility of three different objects can be presented on one map with colours in an additive colour model, i.e., red, green and blue (Figs 4 and 5). Component maps showing the visibility of individual elements can be assigned to separate channels. The colour model allows mixing of channels, resulting in colours that indicate the places of visibility of more than one object at different intensities. In the additive colour model (RGB), three channels

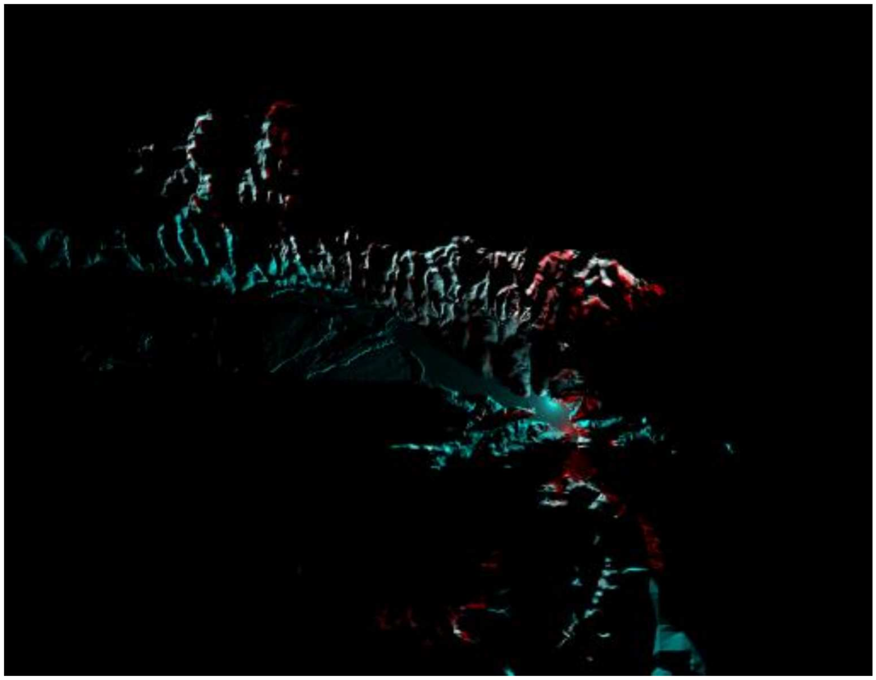


Fig. 4. The visibility map of two castles standing on two sides of the lake. The visibility graph of one of them is in the red channel and the other in both green and blue. Thanks to this, the places from which it can be seen are represented by the cyan colour and those from which both castles can be seen by the white.

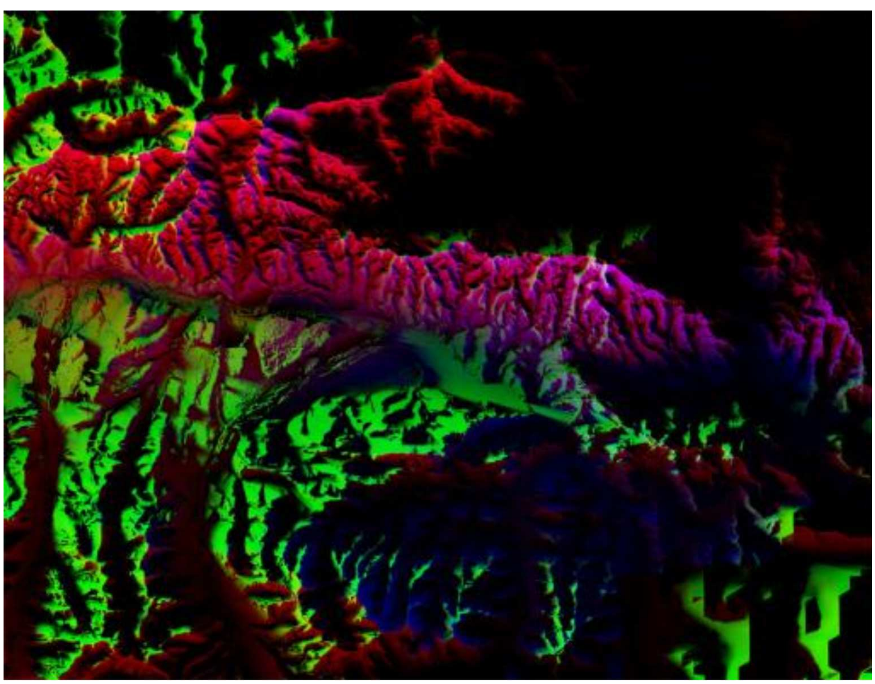


Fig. 5. The visibility map presenting the sum of the visibility of the Tatra Mountains (red), the Babia Góra mountain (green) and the Pieniny Mountains (blue).

are available, which, when mixed, give different intermediate colours with white at full intensity (Fig. 5). In the case of two objects, the visibility map of one of them can be inserted simultaneously into two channels. The presentation of such a case is shown in Fig. 4.

Modelling the impact on the landscape of certain factors requires many visibility maps, the number of which often exceeds the number of channels available in a single image. A different approach is needed to model more complex factors, especially mutual relations of elements. P. Ozimek in [7] proposes matrix arithmetic with operators in the form of component maps for obtaining maps of the spatial distribution of visibility factors such as remarkability, sublimity, the durability of motifs, the richness of plans and scenes, etc. Analysis of the impact of these factors distinguished by an expert took place in the pilot area [8]. In other cases, experts can define other factors determining the individuality of the landscape or distinguishing marks of landscape and architecture [3], giving them definitions and weights that are important in the synthesis of analysis results and conclusions for spatial planning.

For example, "sublimity", adapting the concept promoted by Jean-François Lyotard [9] after Immanuel Kant [10] to the needs of landscape analysis can be approximated as "captivating, awe-inspiring power of observation that does not cause fear". Formalizing this statement for computer modelling – in places shown on the map of sublime views, the objects of nature defining the individuality of the landscape should be visible. Their reception increases with height. However, the visibility of the buildings affects them adversely. This map (Fig. 6) was generated as a result of calculations on matrices that are maps of individual components:

$$\mathrm{mww} = ((\mathrm{mswt} + \mathrm{mswp} + \mathrm{mswb} + \mathrm{mswzc}) - \mathrm{mswzg}) \times \mathrm{hip} \times \mathrm{ml},$$

where × – element-wise multiplication of the matrix, mww – map of sublime views, mswt – component map of the visibility of the Tatra Mountains, mswp – component map of the visibility of the Pieniny Mountains, mswb – component map of the visibility of the Branisko massif, mswzc – component map of visibility of the Czorsztyn Reservoir, mswzg – component map of visibility of distributed urbanization, hip – hypsometric map in grayscale with increasing brightness in proportion to the height of the area, ml – binary mask of the forest.

Similarly, maps of the other factors were drawn up and the weights were assigned to them. Then these maps were multiplied by the weights, summed up, and the resulting matrix was normalized to the grayscale levels. In this way, a map of passive exposure of factors enhancing the attractiveness of the landscape (MEB_PK) was obtained. A similar procedure was performed with the use of factors that decrease the attractiveness of the landscape (MEB_NK). These maps can be presented together by assigning them into two different channels of the image represented in the additive

Fig. 6. The map of the sublimity.

colour model. Figure 7 presents an example where MEB_PK is assigned to the green channel and MEB_NK to the red one. The selection is not accidental due to the common associations related to these colours. This image could be described as “the map of the attractiveness of the landscape”.

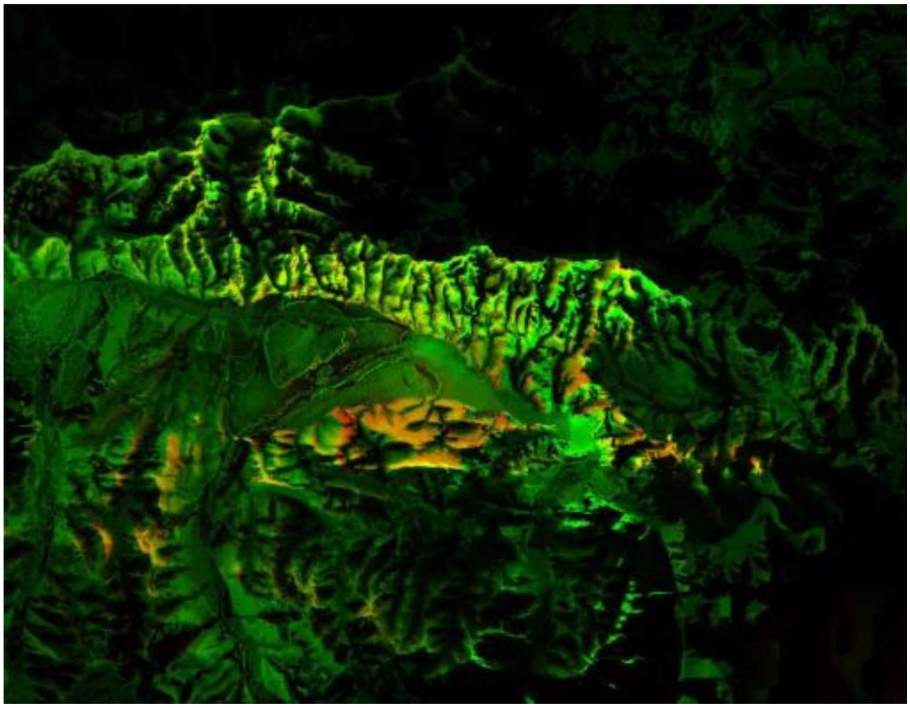


Fig. 7. The map of the landscape attractiveness (MEB_PK + MEB_NK).

The map of the landscape attractiveness presented in Fig. 7 allows the formulation of guidelines for spatial planning, it contains however very general information. This results in continuous use of the component maps by experts that perform analyses, due to misgiving of omitting particular states contained in component maps. For this reason, the research was performed to find a better presentation of detailed data on one map. In this paper, the authors propose a method for obtaining maps generated based on the multi-objective analysis. It can be used to obtain maps containing data, depending on the given component maps and the weights assigned to them.

3. Multi-objective analysis

Multi-criteria decision making is a sophisticated process of finding a solution in an environment with several objectives. Most of the problems, which occur in real life, consist of several objectives which should be taken into consideration. Solving such problems is a challenging task that has been extensively investigated. However, in real applications, simpler methods are often used. The multi-criteria decision making, which is a part of the presented research, is one of the most interesting kinds of optimization, while also being the most difficult one. The most important elements defining the multi-objective problem are the goals, criteria or just objective functions.

Objectives are written as $f_1(x);\ f_2(x);\ \ldots;\ f_k(x)$, where k is the number of criteria in the problem. Space, where the values of objectives are analysed, is called the fitness space or the objective space.

The vector of decision variables can be stated as $\mathbf{x}$:

$$\mathbf{x} = [x_1;\ x_2;\ x_3;\ \ldots;\ x_n],$$

where n is the number of decision variables that are sought.

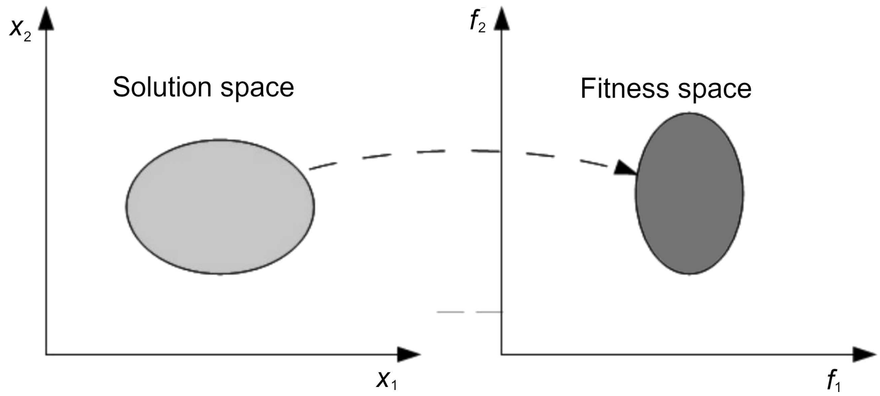


Fig. 8. The relation between solutions space and fitness space.

Two spaces are defined for such a problem:

- n-dimensional space of solutions, where each dimension is assigned to each element of the x vector;
- k-dimensional space of fitness values, where each dimension is assigned to one of the objectives. Each point in the solution space has one corresponding point in the objective space.

"**Definition 1.** *The solution x which belongs to Ω is the optimal solution in the Pareto sense, if and only if, there does not exist x' belonging to Ω, for which vector $v = F(x')$ dominates vector $u = F(x)$. The concept of Pareto optimality is considered to be the whole solution space for the problem. In other words, vector x is the optimal Pareto solution when there does not exist any other feasible vector x', for which one of the functions has lower value at the same time not increasing values of other criteria (for minimalisation problem).*

A very important concept while investigating the multi-objective optimisation is domination, which appeared in the previous definition.

Definition 2. *Vector $u = (u_1; \ldots; u_k)$ dominates another vector $v = (v_1; \ldots; v_k)$ if and only if when u is partly lower than v, i.e., for each i $u_i \leq v_i$ and there exists i for which $u_i < v_i$."* [11, 12].

The very important issue considering multi-objective analysis is the evaluation and comparison of solutions. The matter to be solved is how it can be decided if one solution is better than another. In traditional approaches, a virtual function is created where all criteria are put in. In several evolutionary approaches, another method was introduced. This method is based on the definition of domination. Let us assume that the population of results is considered. For each solution, the

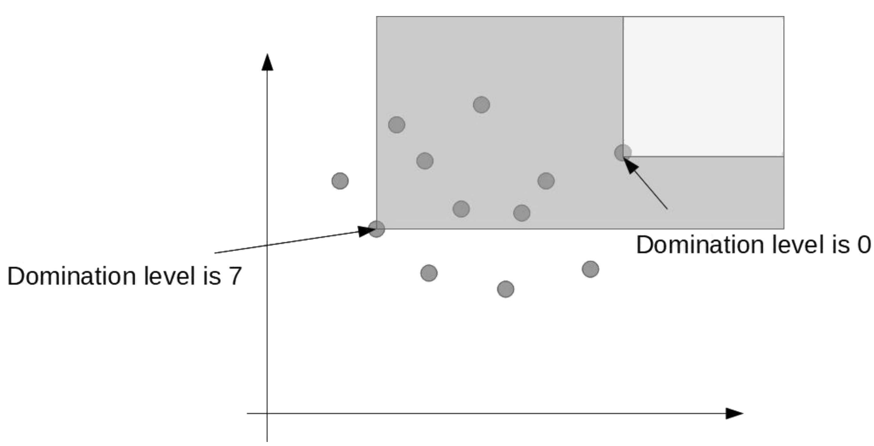


Fig. 9. Example of the domination level calculations.

number of solutions that are dominated by this one is calculated. It is called a domination level. If this value is 0, it means that there does not exist a solution for which this one is better. Thus the group of such solutions is the worst from the whole set. Solutions with the highest value of domination level are the best [13].

4. Multi-criteria analysis in landscape analysis

To analyse landscape with the use of a multi-criteria approach, we treat each factor introduced earlier as the criterion. Each point with its coordinates in analysed area is one solution in solutions space. For each solution, the values for all factors are calculated. Based on that, for each point, it could be found how many other points in the analysed area dominate this one – how many points have higher values of all factors. Dominated points have low values on the visibility map and are therefore dark. Bright points have the highest values of all factors. In the analysed space of the pilot project, there are not many non-dominated and low-dominated points. They appear on the map near the peak of Turbacz mountain, Czorsztyn village and the Stylchyn peninsula.

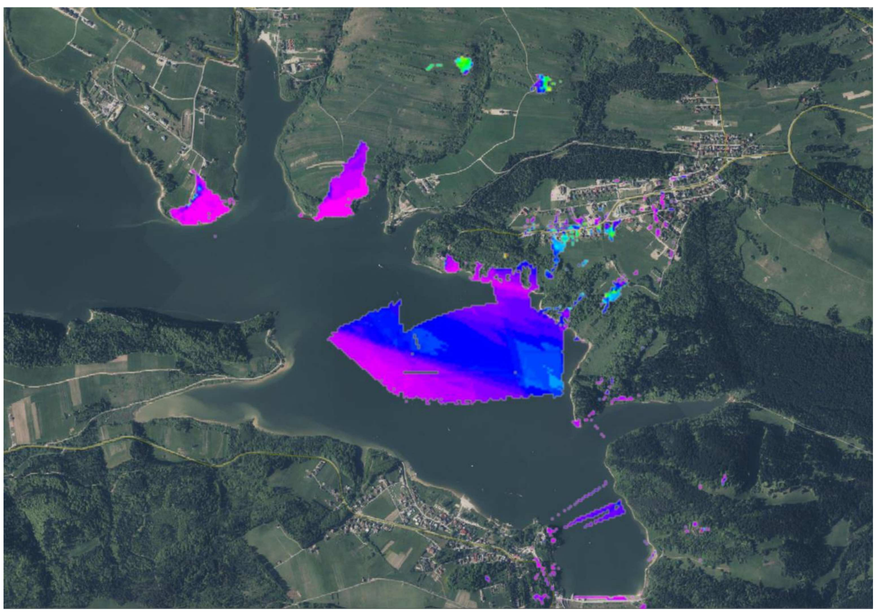
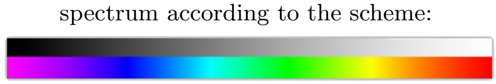


Fig. 10. Fragment of the map of multi-criteria analysis introduced to the orthophotomap. Magnification of the area with the presence of non-dominated points. The grayscale colour scheme was replaced with the spectrum according to the scheme:



5. Conclusions

The results of the presented calculations, properly normalized, are visualized in the form of maps, on which particular levels of domination are assigned to the colours in accordance with the legend. In contrast to maps obtained with the use of matrix operations, high levels of domination have a focused distribution, are easier to distinguish and identify. Thanks to that, they give clear premises for making decisions in the area of indicating guidelines for spatial planning.

The presented method allows the visualization of spatial relations that could not be obtained using the existing methods. Depending on the component maps that represent the analysis criteria, it is possible to indicate for certain ways of developing good or bad areas. These maps may contain visibility data as well as other types of spatial impact. Thanks to this, spatial decision criteria can be broad and multi-branch.

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