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THE CHOICE OF GEOSTATISTICAL METHOD IN SUBSURFACE MAPPING: CASE STUDY OF LAKE PANNON SEDIMENTS IN CENTRAL BELGRADE (SERBIA)

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ABSTRACT

Subsurface mapping includes various types of data, and thickness maps are one of the essential tools for the subsurface exploration geoscientist. Vertical thickness (isochore) maps are compiled in using different geostatistical methods for interpolation between input data points, which are in this case based on irregularly-spaced boreholes which have drilled the Lake Pannon sediments. Of the four used methods, Kriging produces the most sound map, whereas Triangulation with linear interpolation is practically useless when plotting irregular spatial data. Additional visualization tools were derived from the kriging map for cross-correlation, and supported the interpretation that the highest-thickness area is the depocenter in the north of the map, while the low-thickness zone is a basement ridge where older sediments can be found on the surface.

Keywords: *subsurface visualization, isochore maps, Pannonian Basin, geostatistics*

INTRODUCTION

The compilation of several types of contour maps is a necessary step in the process of subsurface visualization. They can be based on different input data, such as geophysical surveys, field mapping, and exploratory drilling. The borehole data gained from drilling campaigns will be considered in this study. Several kinds of contour subsurface maps exist. Three basic categories can be discerned: structure maps, thickness maps, which are subivided into isochore and isopach maps, and quantitative lithofacial maps (e.g. in Grubić, et al., 1996, Miall, 2000, Đoković, Toljić, 2009). Structure maps show the depth to a defined horizon, such as a stratigraphic boundary. Miall (2000) remarks that in post-depositionally deformed thickness maps can show the original sedimentary fill geometry better than structure maps. Isochore maps display vertical (drilled) thickness of sedimentary units, while isopach contours display true (stratigraphic) thickness, which must be calculated from vertical thickness before compiling. In the case of quantitative lithofacial maps, contour lines are boundaries between areas populated by calculated lithofacial ratios, such as sand to mud ratio or enthropy. This study is concerned with isochore, or vertical thickness maps, which are easier to construct and read, given that the formation's vertical boundaries are not highly deformed.

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STUDY AREA

The vast Lake Pannon occupied the Pannonian realm during the Late Miocene and Early Pliocene (Magyar, et al., 1999, Magyar, et al., 2013), represented by the local Pannonian Stage devised for the Paratethyan basins (Raffi, et al., 2020). Nested between moutain areas of the Alps, Carpathians and Dinarides, it exhibited traits similar to the modern Caspian Sea, having a brackish character, and great depth and geographical extent. Such paleoenviornmental conditions have thus been called „caspibrackish“. The territories of 10 countries are represented by the area which once was Lake Pannon: Austria, Bosnia and Herzegovina, Croatia, Czech Republic, Hungary, Romania, Serbia, Slovakia, Slovenia and Ukraine (Anđelković, Radivojević 2021, Tari, et al., 2023).

A large part of the Lake's southerm rim is located in what is now Serbia, strecthing from Srem and Mačva on the west to Southern Banat and Kostolac Basin on the east, with different sediments representing the different stages in the Lake's evolution. The Belgrade City Region occupies a central position in this outline. This study is focused on the downtown area of the city, where all of the boreholes were located. In this area, sediments left behind by the Lake Pannon are located at shallow depths, but never on the surface, and are represented by the hemipelagic marls deposited in calm and moderately deep waters of the ancient lake's offshore area.

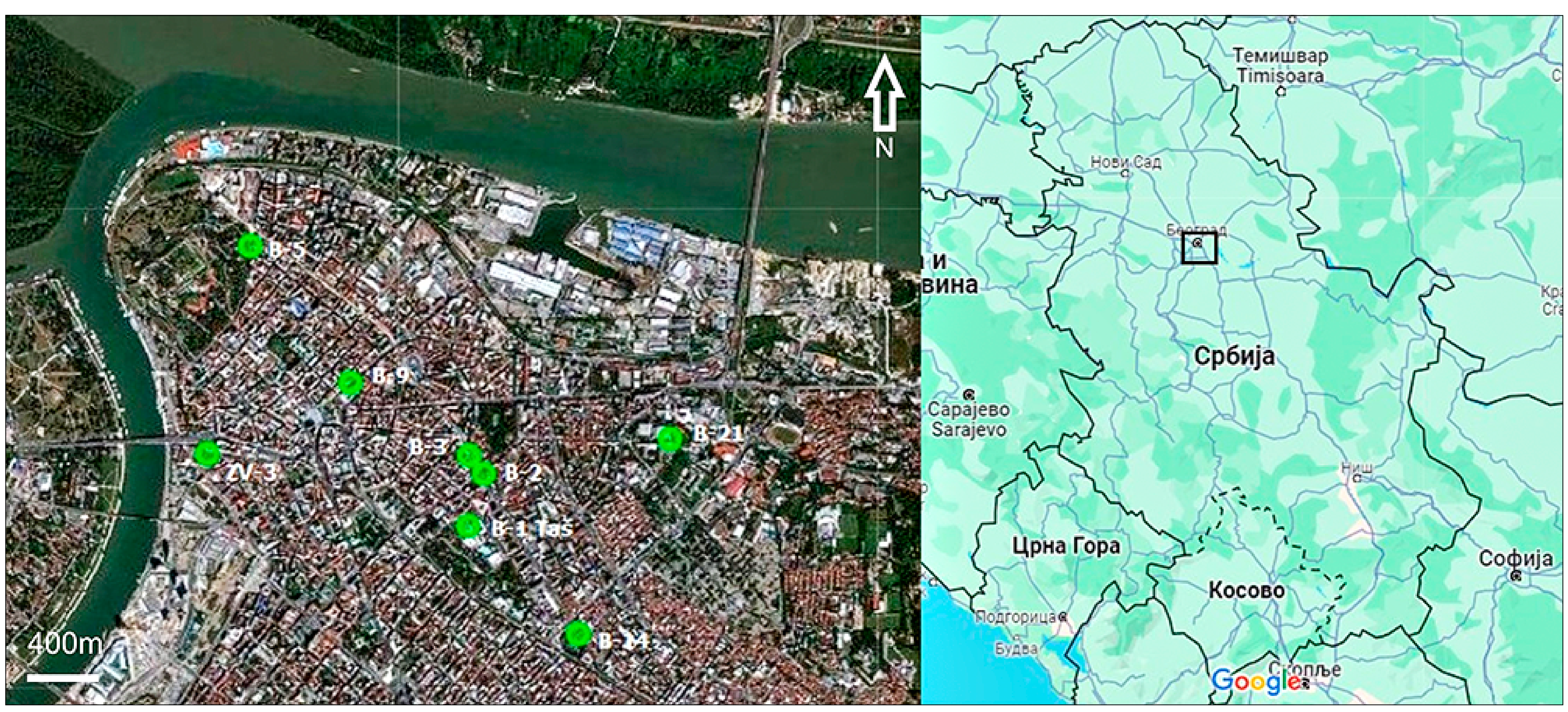

Figure 1. *Left:* Satellite image of the study area with borehole positions (https://a3.geosrbija.rs – modified); *Right:* Geographical map of Serbia, black polygon marks the study area (Google Maps – modified)

DATA

The borehole data used here is sourced from the Belgrade Detailed Town Plan project, done for the Palilula, Stari Grad, Savski Venac and Rakovica municipalities by the Highway Institute in Belgrade. The borehole material was stratigraphically studied and published by Knežević & Šumar in 1993. The total of 8 boreholes were studied by the aforementied authors, and used to visualize the subsurface in this study. The designations, coordinates and the vertical thickness of the Pannonian sediments (Z) is shown in the Table 1. The coordinates show are approximate, since the position of the boreholes was shown only descriptively in the source paper.

Table 1. Designations, location and Pannonian thickness values (Z) of the studied boreholes

Designation	Lon	Lat	Z (m)
ZV-3	44° 48' 51''	20° 27' 09''	9
B-1 Tašmajdan	44° 48' 38''	20° 28' 17''	0
B-14	44° 48' 18''	20° 28' 45''	12
B-3	44° 48' 51''	20° 28' 16''	40
B-2	44° 48' 47''	20° 28' 20''	6
B-21	44° 48' 54''	20° 29' 08''	12
B-9	44° 49' 04''	20° 27' 46''	55
B-5	44° 49' 29''	20° 27' 20''	15

Source of data: Knežević, Šumar (1993)

GEOSTATISTICAL METHODOLOGY

Geostatistical analysis provides a way of predicting valuables which are not covered by our direct measurements, in this case exploratory drilling. There are various methods for performing interpolation. Three frequently used methods are chosen, based on the marked difference in the resulting contour maps, which reflects different interpolation strategies with irregularly-spaced data. The spatial distribution of the thickness data is generally aranged to include two highs and a transitional low-thickness zone between them, so the different algorithms can be tested and compared.

There are many software solutions which are able to perform geostatistical analyses, most of them falling into the broader GIS family. Golden Software Surfer version 12 is the software of choice here. The geostatistical methods are elaborated on in further text.

Inverse distance to a power

This method provides exact or smoothing interpolation, depending on settings chosen. It functions in a way that data are weighted, so that points far from the grid node carry less influence (Davis, 1986). It's shortcoming is the creation of so called „bull's-eye" effect, where contours are unnaturally rounded-off around peaks. This can be mitigated by using the smoothing option (Golden Software, 2015).

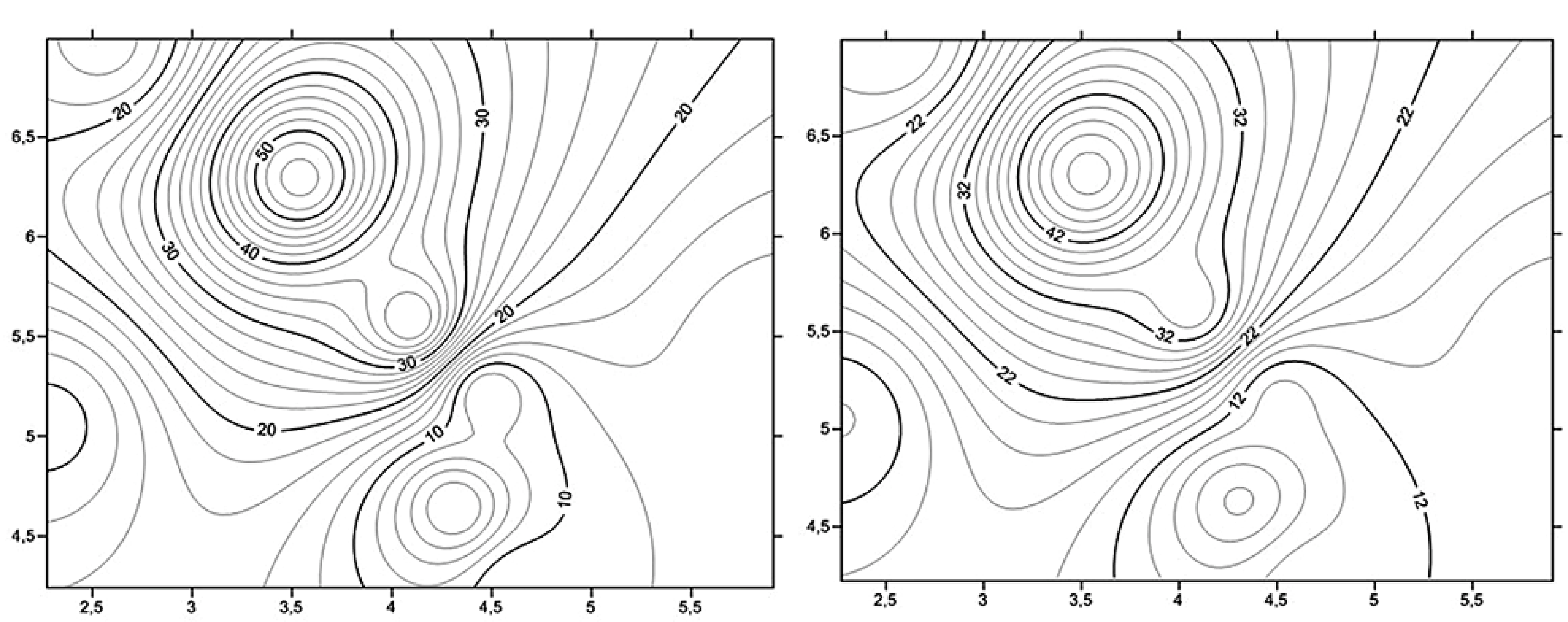

Figure 2. Isopach maps constructed with the Inverse distance method.
Left: without smoothing; *Right:* with smoothing factor 1

In this study, the method is applied to the dataset with a smoothing factor of 1, as well as without smoothing. The first algorithm produced a solid-looking contour map, with smooth transitions, but with unrealistic transition zone and the existence of the third high. The second algorithm showed problems characteristic of the non-smoothing variant of the method. The transitional low-thickness zone was appropriately displayed, but the highs were separated into „bull's-eye“ zones.

Kriging

This method is perhaps the most popular one in geostatistical mapping. It corrects problems associated with the inverse distance to a power method by connecting high points. It works well with highly-irregular data points and is fast, which means that is the method of choice for very large datasets. It can also be modified to be either exact or smoothing. The algorithm can be additionally adapted by modified variogram properties. The method is described in detail by Cressy (1991) and in the Surfer user guide (Golden Software, 2015).

Kriging was done with default parameters in this study. It produced a very smooth and sound map, with well-displayed, elongated highs. It also features a gradual transition to lower thicknesses both between high, and to the western portion of the map. Its shortcoming is the unnatural sharp boundary of the northern high.

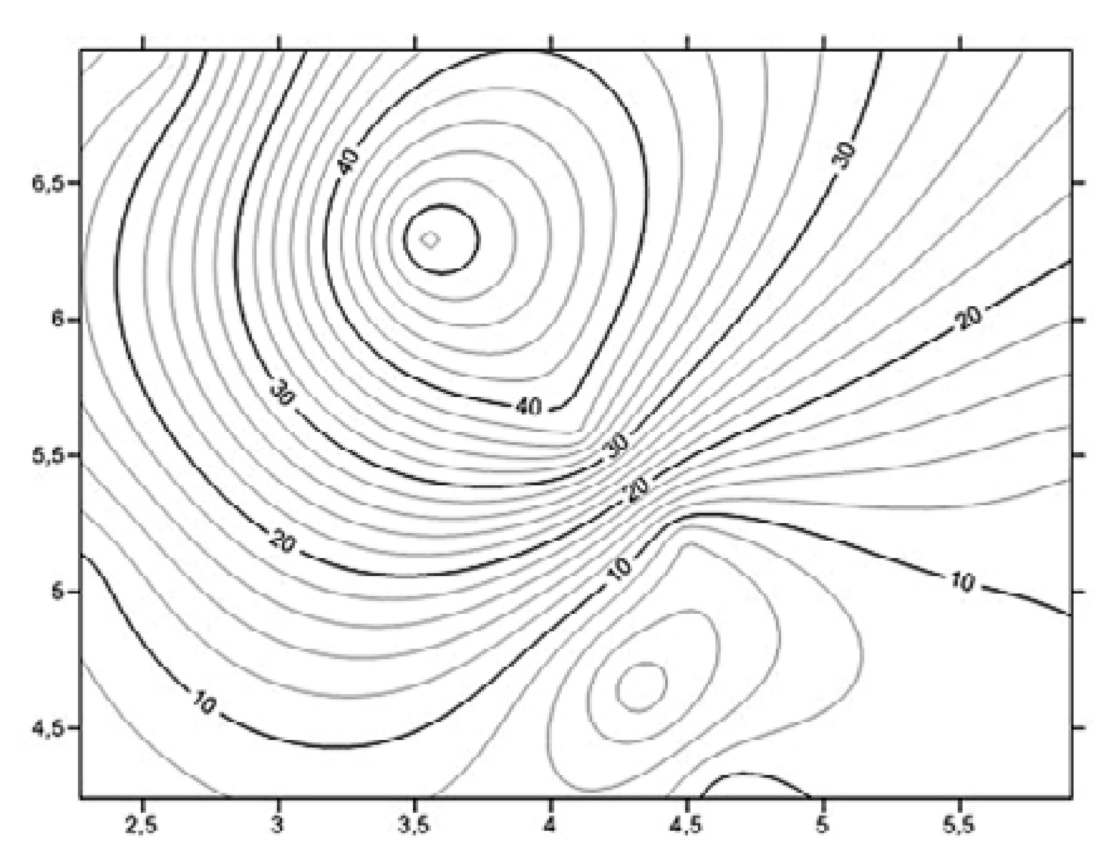

Figure 3. Isopach map constructed with Kriging

Triangulation with linear interpolation

The triangulation with linear interpolation method employs the Delaney triangulation. Triangles are created between data points, with none of them intersecting others. The grid nodes are then determined by the tilt and elevation of the triangular surface. This method only works when the data is regularly spaced and the original points are honored closely. If used on irregularly-spaced data points, it gives a highly distorted contour map, with characteristic triangular facets (Lee, Schachter, 1980, Golden Software, 2015).

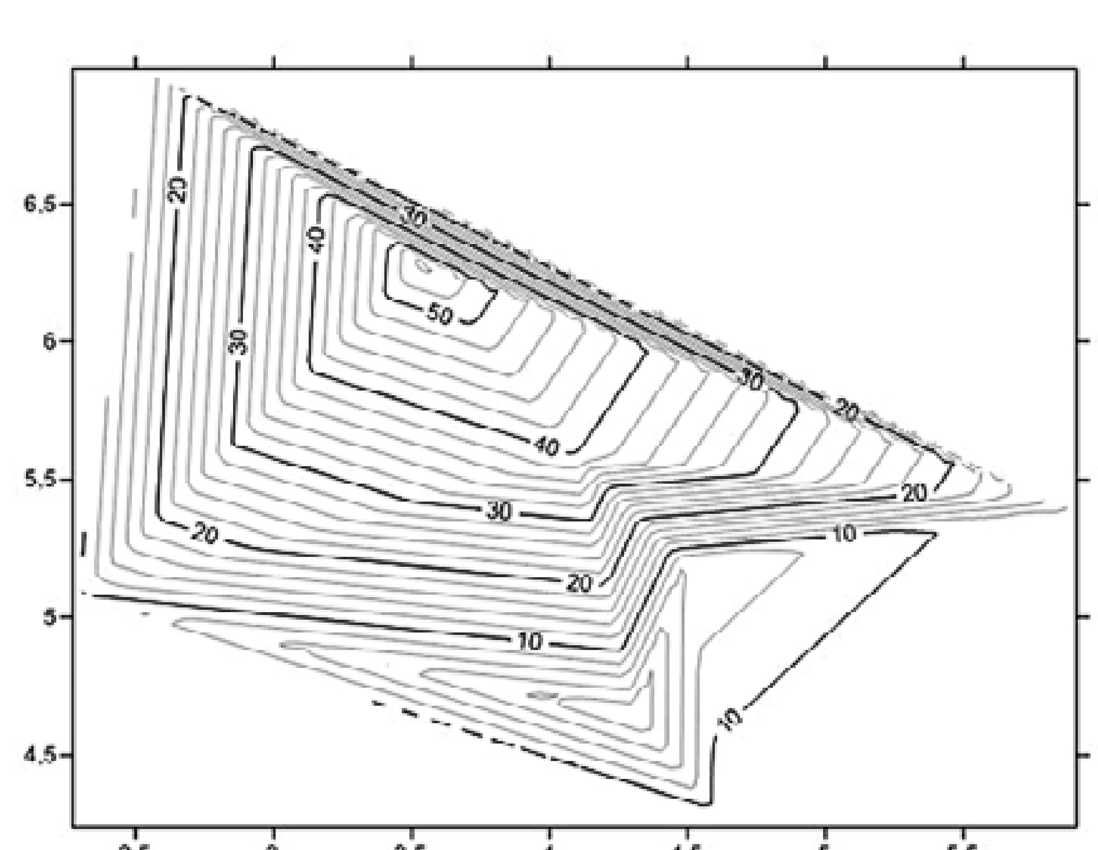

Figure 4. Isopach map constructed with Triangulation

RESULTS AND DISCUSSION

The tested geostatistical methods give slightly different results in the case of Inverse distance and Kriging methods, but a drastically differing map when using Triangulation. These slight variations can still have great significance when describing real-world imperfect data, such as underground surface thickness.

Kriging gives the most appropriate isopach map. It is very smooth, but not too generalized. It honours the imput data very well. The Inverse distance with smoothing factor 1 gives a map with satisfactorily rounded-out boundary zones, but displays a third high in the western corner of the map, which is not certainly true. The Inverse distance without smoothing shows the „bull's-eye" error when mapping the highs and is not very useful as such. Triangulation gives a map with extreme distortion and the method is dissmised for irregularly-spaced data.

Additional graphics have been produced by using Surfer's visualization tools in order to more accurately constrain the dataset and provide cross-correlation. The cross-section and the 3D wireframe clearly show that the northern part of the study area has the highest thickness, which is constrained as a depocenter in that location. The low-thickness zone is the one where Pannonian sediments almost pinch-out and where older Badenian sediments are found at the surface (Knežević, Šumar, 1993, Rundić, 2010). The basement starts dipping again southward and the thickness of the Pannonian increases.

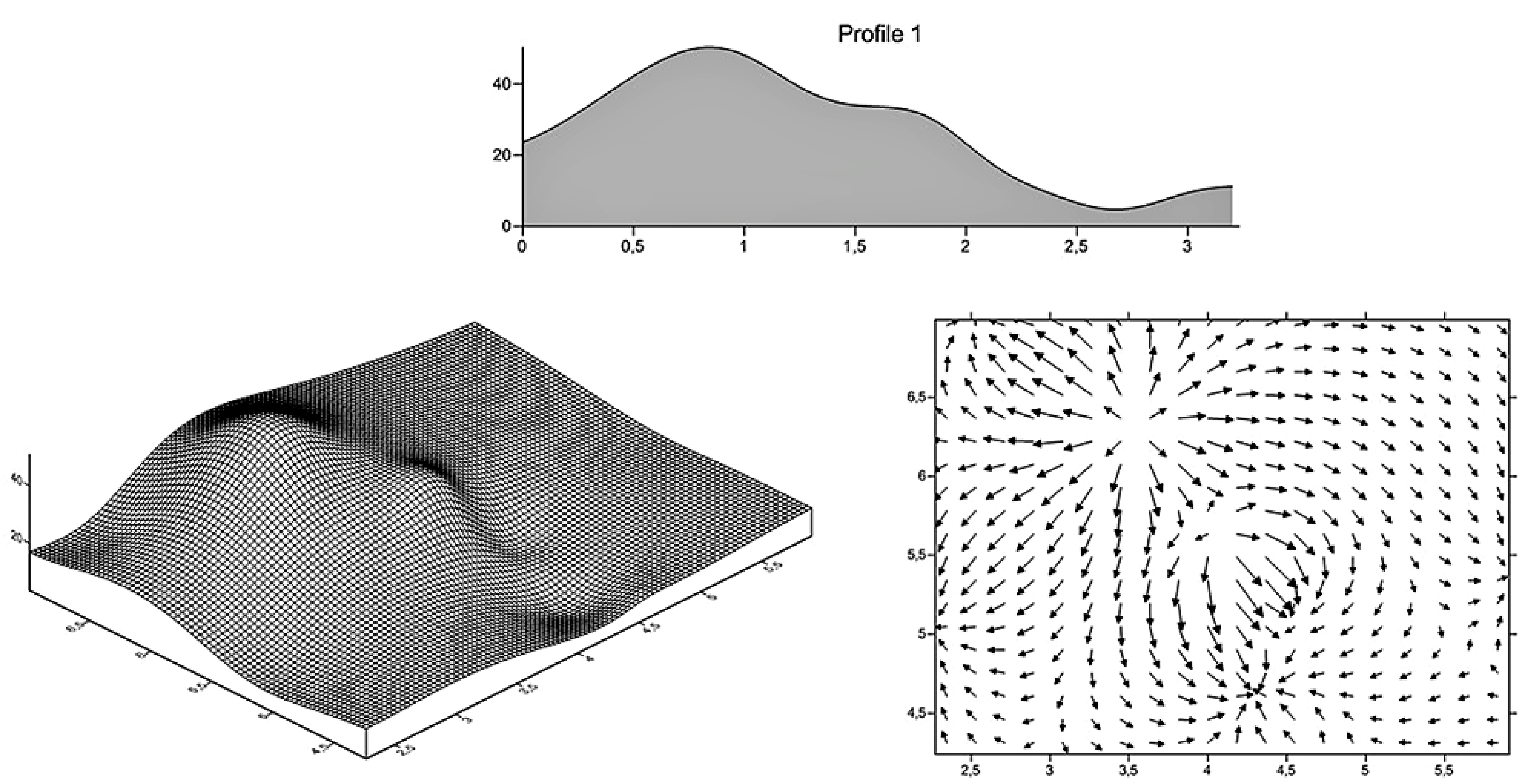

Figure 5. Cross-section, 3D wireframe and vector map derived from the kriging isopach map

CONCLUSION

The following conclusions can be drawn from this study:

- The subsurface needs to be characterized using some form of geostatistics
- Four geostatistical methods were tested on a dataset consisting of 9 irregulary-spaced points
- The dataset itself is represented by the thickness of drilled Lake Pannon sediments in the central Belgrade area
- Kriging method provided the most satisfactory map, with adequately represented highs
- Inverse distance to a power method can be applied with or without smoothing
- Without smoothing, the map is unrealistic, with the „bull's-eye" effect
- With smoothing factor 1, the problem is solved, but the map is still not very smooth and displays an uncertain third high

– Triangulation with linear interpolation method cannot be used when plotting irregular data and the resulting contours are meaningless
– Computed cross-sections, 3D wireframes and vector maps can be added for additional visualization

When all data are combined, one can conclude that the Pannonian is thickest in the northern part of the map, where its upper bounday is shallow, almost pinches-out in the transitional zone, where the older sediments are outcropping, and then increases in thickness again to the south.

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