*Article*

# Application of Modified Shepard's Method (MSM) case study with interpolation of Neogene reservoirs variables in the Northern Croatia

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**Abstract:** Interpolation is procedure that depends on spatial and/or statistical properties of analysed variable(s). It is special challenging task for data that included low number of samples, like dataset with less than 20 data. This problem is especially emphasized in the subsurface geological mapping, i.e. in the cases where data are taken solely from wells. Successful solutions of such mapping problems ask for knowledge about interpolation methods designed primarily for small datasets and dataset itself. Here are compared two methods, namely Inverse Distance Weighting and Modified Shepard's Method, applied for three variables (porosity, permeability, thickness) measured in the Neogene sandstone hydrocarbon reservoirs (Northern Croatia). The results showed that pure cross-validation is not enough condition for appropriate map selection, but also geometrical features need to be considered, for datasets with less than 20 points.

**Keywords:** Modified Shepard's Method (MSM); Inverse Distance Weighting (IDW); sandstone; neogene; Northern Croatia

## 1. Introduction

Geostatistics is a branch of applied statistics that applies theories of deterministic estimation, then stochastic processes, that is, statistical inference to different spatial phenomena in numerous sciences. The most important geostatistical term applied in geology and petroleum geology is the regionalized variable [1]. It means a measured or estimated magnitude whose behaviour is described in part by a random and partly by a deterministic variable. Each such variable shows the property of spatial continuity and as such is modelled in space. A qualitative description of the property of a regionalized variable leads to a more accurate assessment of the regionalized variable.

The interpolation methods used in the Croatian part of the Pannonian Basin System (CPBS) are described in [2], while the last applied specific interpolation method is presented in [3]. The IDW method is widely used in the CPBS for mapping geological variables, and its application is described in [4-8].

The SMS method has been applied all over the world, and the following papers are selected as appropriate examples. In [9] authors have applied the MSM method to the digital terrain model region of the Chen-Yu-Lan River (Taiwan). Authors in [10] have applied MSM for multicomponent aerosol-cloud parameterization (global climate modelling), and the same method was used for modelling of geological reserve of hydrocarbons calculation [11]. The authors in [12] applied the MSM method on selected parameters of subsurface waters in the area of approximately 10 ha, located in the Ciemięga Valley (Poland). The MSM was used by the authors [13] to determine the boundary of the smooth particle hydrodynamics (SPH) method. In selected area, the IDW and SMS methods were applied in the field "B", Late Miocene (Lower Pontian) reservoir "K" on three r geological variables: porosity, permeability and thickness.

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## 2. Geological settings of the analysed field “B” (Sava Depression, Northern Croatia)

The oil and gas field “B” is located in the CPBS, i.e. in the western part of the Sava Depression. The location of the field “B” in the depression is shown in Figure 1.


**Figure 1.** Location of field “B” in Sava Depression (from [3]).

Most of the wells drilled only sediments to the base of the Kloštar Ivanic Formation, since hydrocarbon reservoirs were proven within it. The formation is described as the alteration of marls and well-sorted sandstones. In the oldest part sandstones are hard, which according to younger part become fine-grained, even weakly consolidated sands. Marls are grey to greyish-brown, with medium hardness, whose compaction decreases upwards as well as the proportion of clay component increases. Marls represent impermeable rocks on a top of each sandstone reservoir. Inside the formation marl’s thickness is 30-150 m, while sandstone’s thickness is 20-150 m.

Structurally, tectonic blocks are considered to represent in most cases separate structural traps, where hydrocarbon accumulated in the highest parts. Therefore, these tectonic blocks represent separate hydrodynamic units with their reservoir characteristics. The structural map of the analysed Lower Pontian reservoir "K" is shown Figure 2.

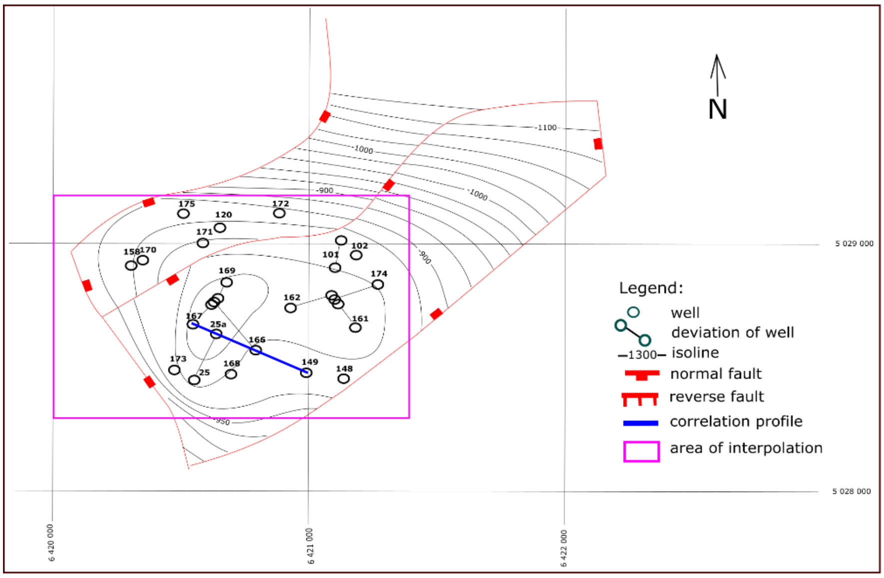


**Figure 2.** Structural map of the Lower Pontian reservoir "K".

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A typical geologic section is derived from the well data, and clearly outline the sandstone member (blue borders) where are discovered hydrocarbon reservoirs (Figure 3). The section also reveals partial structural inversion within the formation, where monocline of deeper members is changed in the syncline in upper part.

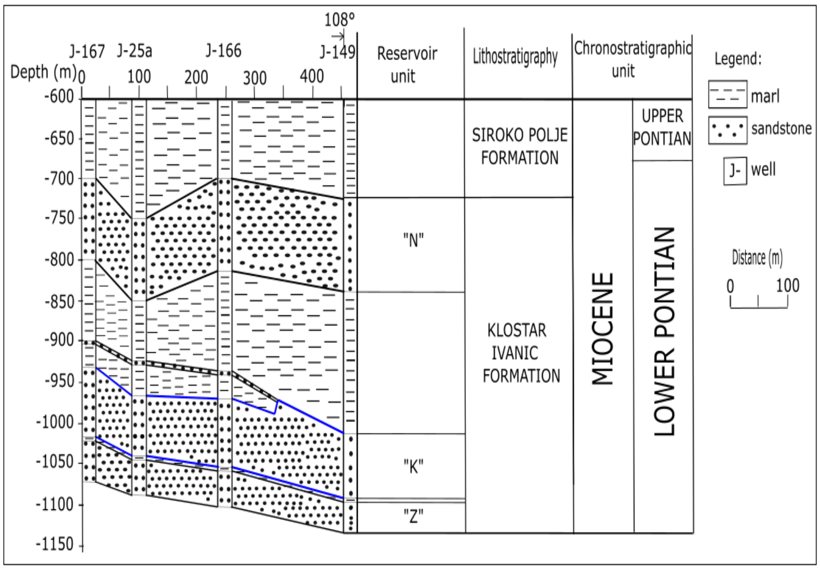


**Figure 3.** Correlation section through wells J-167 – J-25alfa – J-166 – J-149 shown on Figure 2 with blue line (from [14]).

The mapped sandstone “K” could be described as one of two typical sandstone types in the Northern Croatian Neogene. The younger are well-sorted, medium-grained, quartz-mica dominated sandstones, deposited in the lacustric environment of the Pannonian Lake, mostly brackish. The detritus had been transported with sequential turbidites during Upper Pannonian and, especially, Lower Pontian (e.g., [15]). The dominant, primary porosity is intra-granular. The second one type are poorly sorted and coarse-grained sandstones, containing some larger (ruditic) clasts, are bound together with sparritic calcite cement. They contain various lithoclasts derived from older sedimentary and metamorphic rocks: dolomites, quartzites, gneisses and various schists, as well as individual quartz grains originated from metamorphic rocks. Such calcarenaceou sandstones (e.g., [16-17]) are deposited during Middle Badenian, in the in the shallow marine back-reef environments of the Paratethys Sea, with a significant input of siliciclastic material from the nearby land (Figure 4). The dominant, primary porosity is intra-skeletal (Figure 5).

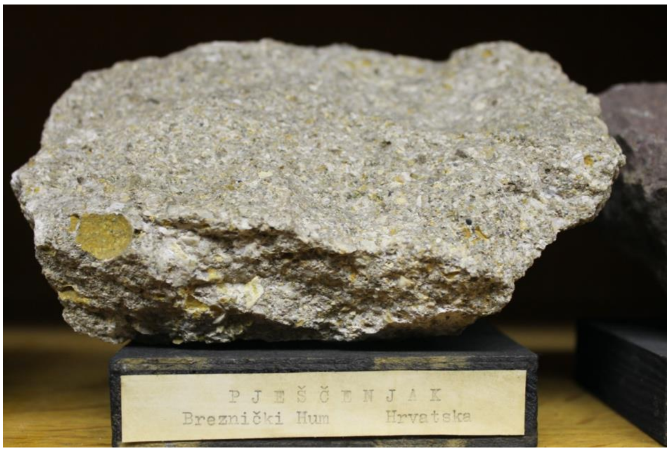


**Figure 4.** Macro sample of typical Badenian sandstone in the Northern Croatia (Breznički Hum locality).

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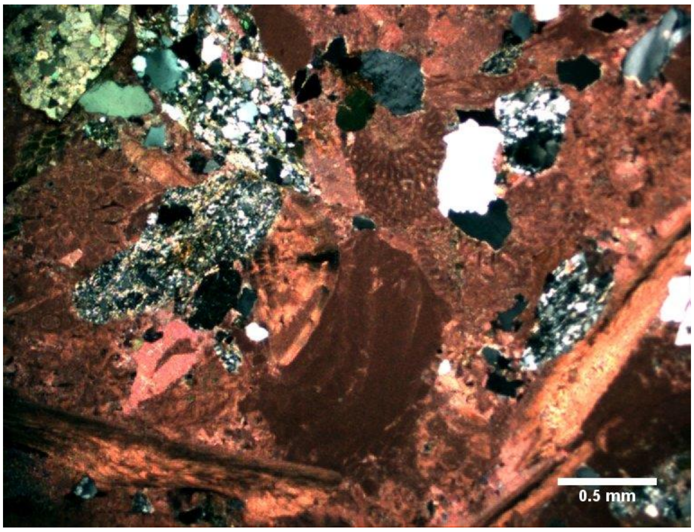


**Figure 5.** Micro sample of clasts in typical Badenian sandstone in the Northern Croatia (Breznički Hum locality).

The analysis presented in this paper, i.e. interpolation od porosity, permeability and thickness of sandstone units in the Neogene deposits in the Northern Croatia, is valid for both cases. The applied methods, interpretations and conclusion could be applied both in the Badenian as well as Pannonian/Pontian sandstone, although their origin is partially different.

## 3. Basics of the applied interpolation methods

The interpolation means the estimation among the values of variables in places where no values have been measured. When interpolating, one (primary) or multiple (primary + secondary) variables can be used. The interpolation methods applied in the reservoir "K" are Inverse Distance Weighting (IDW) and Modified Shepard's Method (MSM). Only primary variables (porosity, permeability, thickness) had been used.

### *3.1. Inverse Distance Weighting (IDW)*

The Inverse Distance Weighting method is a mathematically simple interpolation method, where the unknown value of a variable is estimated according to the known values inside the searching radius. Generally, each of them is weighted by distance (Figure 6). Single data are inversely proportional dependent on the distance between the unknown and measured values of variable.

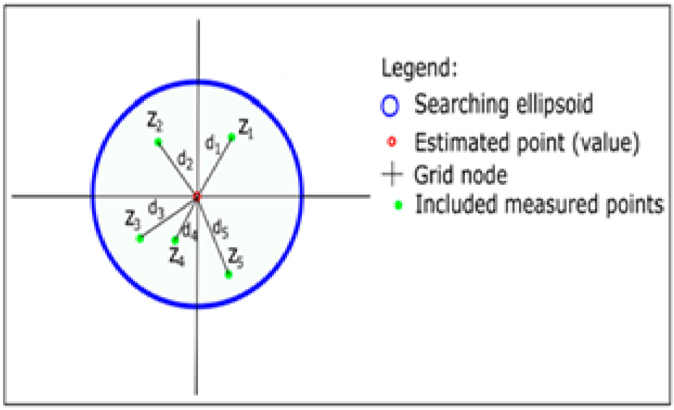


**Figure 6.** Points included within the IDW interpolation area (from [3]).

The estimation (e.g., [18-19]) in IDW is done using (Equation 1):

$$z_{IU} = \frac{\frac{z_1}{d_1^p} + \frac{z_2}{d_2^p} + \ldots \frac{z_n}{d_n^p}}{\frac{1}{d_1^p} + \frac{1}{d_2^p} + \ldots \frac{1}{d_n^p}} \tag{1}$$

where:
$z_{iu}$ —*interpolated (unknown) value;*
$d_i$ —*distance to "i-th" location;*
$z_i$ — *interpolating (known) value at "i-th" location;*
$p$ —*power of distance.*

*3.2. Modified Shepard's Method (MSM)*

The MSM interpolation is modification of the IDW method, with the aim of reducing the expressive local values (outliers, extremes) that could cause "bull-eyeing" or "butterfly shapes" effects. The method was developed by [20], sometimes named as Shepard's method, and modification of the method was carried out in the works of, for example, [21] and [22]. The estimation (e.g., [22]) using MSM function is done by (Equation 2):

$$F(x,y) = \frac{\sum_{k=1}^{n} W_k(\mathrm{x},\mathrm{y}) \cdot \mathrm{Q}_k(x,y)}{\sum_{i=1}^{n} W_i(x,y)} \tag{2}$$

where:
$F$ - *MSM function;*
$W$ - *relative weights;*
$Q_k$ - *bivariate quadratic function;*
$x, y$ -*data coordinates;*
$n$ - *number of data.*

MSM used so called relative weights determined (e.g., [22]) with (Equation 3):

$$W_k(x,y) = \left[\frac{(R_\omega - d_k)_+}{R_\omega \cdot d_k}\right]^2 \tag{3}$$

where:
$W$- *relative weights;*
$d_k$- *Euclidean distance between points at locations* $(x, y)$ *and* $(x_k, y_k)$*;*
$R_\omega$- *radius of influence about node* $(x_k, y_k)$*.*

The Figure 7 shows the searching radius of the MSM within the measured and estimated values (grid). Here could be note each unknown point is surrounded with local searching radius, instead of global like in the IDW.

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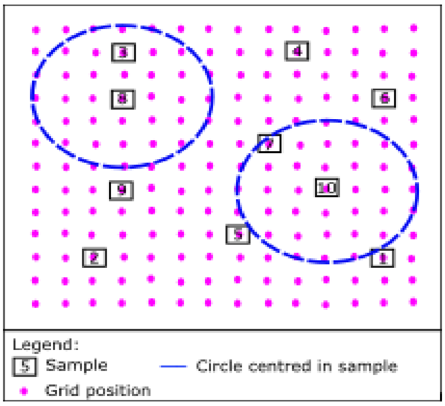


**Figure 7.** Radii of coverage of the MSM (modified from [23]).

## 4. Interpolation results in reservoir "K" for variables porosity, thickness and permeability

Here are interpolated three geological variables, measured in the reservoir "K", namely: porosity, permeability and thickness. Table 1 shows part of their descriptive statistics, calculated from values measured from the laboratory measurement and/or interpretation of the logging curves (resistivity, density and neutron).

**Table 1.** Geological variables porosity, permeability and thickness data in the "K" reservoir

| Description | No data | Min | Max | Mean |
|---|---|---|---|---|
| Porosity | 19 | 0.217 | 0.315 | 0.232 |
| Permeability ($10^{-9}$ m$^2$) | 18 | 29.6 | 121.2 | 85.7 |
| Thickness (m) | 14 | 1 | 24 | 7.7 |

According to Table 1, analysed sets belong to a small geological input data set [24; 8]. So, the interpolation has been done with mathematically simpler methods. The porosity maps obtained by the IDW and SMS methods are given in Figure 8. The value cross-validation (porosity) for IDW is 0.00119 and SMS is 0.00345.

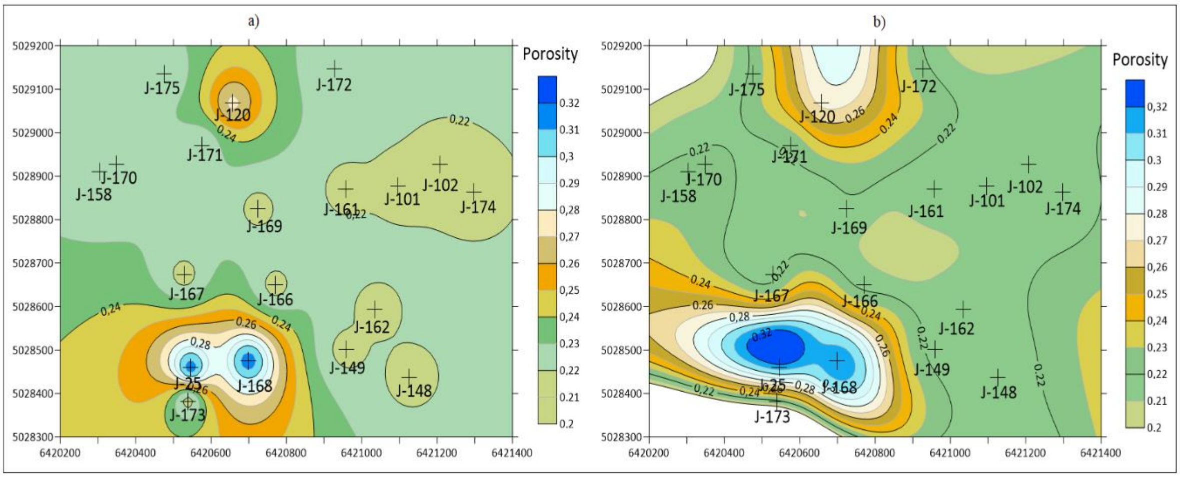


**Figure 8.** Porosity of the reservoirs "K": a) IDW b) SMS.

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A permeability maps obtained by the IDW and SMS methods are shown in Figure 9. The accompanied cross-validation (permeability) for IDW is 480.8 and SMS 516.1.

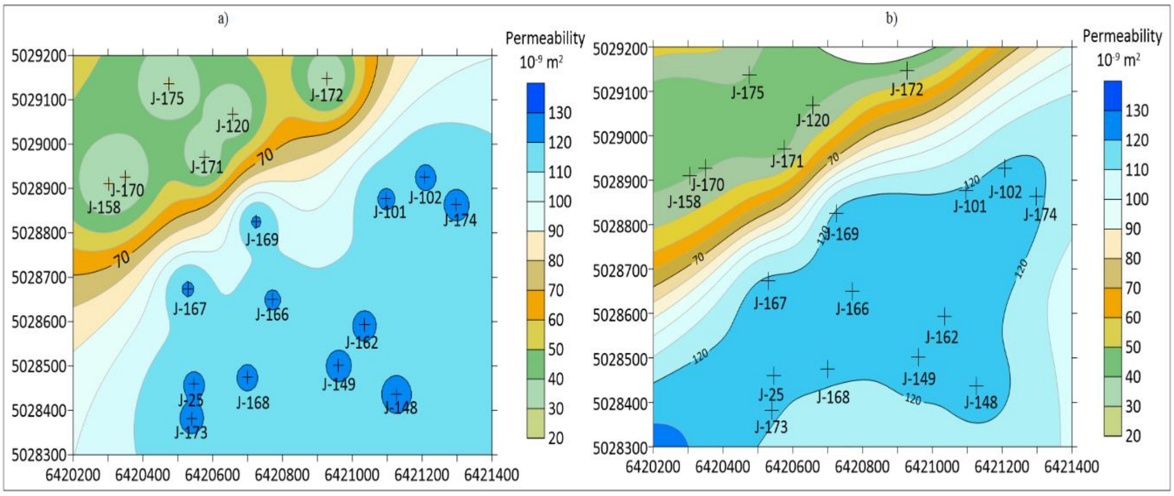


**Figure 9.** Permeability of the reservoirs "K": a) IDW b) SMS.

A thickness maps has been interpolated by the IDW and SMS methods are shown in Figure 10. The value cross-validation (thickness) for IDW is 40.7 and SMS is 60.5.

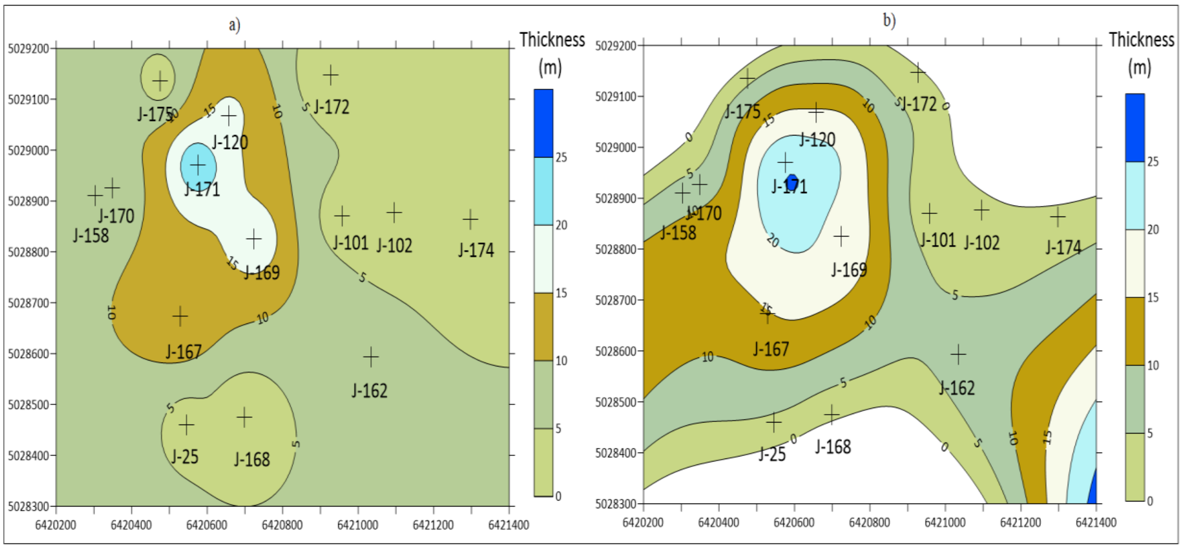


**Figure 10.** Thickness reservoirs "K": a) IDW b) SMS.

The maps obtained by the IDW and SMS methods are evaluated in quick-look, according the most observable feature of highly expressed local value, i.e. bull-eye or butterfly shape effects. The SMS is clearly advantageous because it mitigates the mentioned effects, however the numerical check using the cross-validation value strongly favours the IDW method.

## 5. Discussion and conclusion

To consider the differences between results obtained with IDW and MSM methods it is necessary to describe the main differences in their equations. The IDW does not use weighting coefficient, i.e.

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each value is "weighted" by simple (powered) inversely proportional distance from the measured point. General form of the IDW is (Equation 4):

$$u(x) = \frac{\sum_{i=1}^{N} w_i(x) \cdot u_i}{\sum_{i=1}^{N} w_i(x)}, d(x, x_i) \neq 0 \tag{4}$$

Where:

*u(x) - interpolated value in the location "x";*

*$u_i$ - i-th known value inside searching radius centred in the location "x";*

*i - no. of samples (known/measured value);*

*$w_i$ - weight for the "i-th" sample with known value;*

*N - number of samples with known value.*

So, the weighting coefficients for location "x" could be generally defined as (Equation 5):

$$w_i(x) = \frac{1}{d(x, x_i)^p} \tag{5}$$

Where are:

*$w_i$ - weight for location "x";*

*$d(x,x_i)$- is a given distance (metric operator) from the known point $x_i$ to the unknown point x,*

*p - power factor (positive real number).*

This is basic IDW function as defined by Shepard ([20], where weights decrease as distances to known values increase. Oppositely, greater values of power ("p") favour larger influence of measured points closer to interpolated point, eventually finished in zonal interpolation (like Voronoi diagram), where inside zone is used constant value of single known point centred into such polygon and no isolines are constructed. On contrary, for 2D interpolation, if power is 2 or less, more distanced measured points will have greater influence. In the "M" dimensions this statement is valid for p<=M. In all cases the IDW minimize function that measure deviation between unknown and known points using condition (Equation 6):

$$\frac{\delta(x,u)}{\delta u} = 0 \tag{6}$$

On contrary, the MSM is more advanced technique of the IDW, including weighting coefficient (**Equation 8**), and calculating interpolated value using only nearest known points within R-sphere (instead of using full set of measured samples). Weights are modified in (Equation 7):

$$w_k(x) = \left(\frac{max\left(0, R - d(x, x_k)\right)}{Rd(x, x_k)}\right)^2 \tag{7}$$

Where:

*$Rd(x,x_k)$ - is local searching radius, so called "R sphere", centred in point "x" and including "k" measured points;*

*$W_k(x)$ - weighting coefficient for known point "k", at distance "x" from interpolated point.*

By default, the IDW takes into account all measured points or work with general searching radius (or radii for ellipsoid). However, the MSM, by default, works with local searching (both can

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be changed in the most software, but those are theoretical defaults). So, "R sphere" modification would need to reduce anomalous local values, i.e. outliers or extremes. The maps on **Figures 7-9** showed that it is really so.

However, there is problem of calculated cross-validation values. They were significantly lower for the IDW then MSM (Table 2). The differences are not negligible. For porosity MSM cross-validation is 289 % larger, permeability 7 %, and thickness 49 %.

**Table 2.** Summary results of application of the IDW and SMS methods in reservoir "K"

| Description | No data | Cross-validation | |
|---|---|---|---|
| | | Inverse Distance (IDW) | Modified Shepard's Method (MSM) |
| Porosity | 19 | 0.00119 | 0.00345 |
| Permeability | 18 | 480.8 | 516.1 |
| Thickness | 14 | 40.7 | 60.5 |

So, let once more time analyse the **Equations 2** (MSM function), **3** (weighting coefficient in the MSM searching radius) or **8** (the more general form of Eq. 3). It is not surprisingly that the MSM will mostly give larger cross-validation values, because it works by default with local search and, consequently, smaller number of known values in each cross-validation iteration. If "one point out" method is applied with small number of remaining known values, the difference between real and estimated value in such point will be mostly higher than if all known measurements had been used. So, generally the MSM will tend to give larger cross-validation value for the same dataset, compared with the IDW.

Secondly, the MSM approximate the unknown value with quadratic function, i.e. polynomial of degree 2, for one or more variables in which is the 2nd degree the highest one. Any quadratic polynomial with two variables may be given as (Equation 8):

$$f(x,y) = ax^2 + by^2 + cxy + dx + ey + f \qquad (8)$$

Where:

*x,y* - *variables;*

*a, b, c, d, e, f* - *coefficients.*

Consequently, the MSM will harder force gradual interpolation for outliers (extremes), i.e. in such ways it will done smoothing instead of bull-eyeing. At the end, let's look the selection criterium of interpolation algorithm for the small datasets in the same spatial area as it was selected for this work (the Sava Depression, Northern Croatia; [3]):

**Table 3.** Recommended interpolation methods for small input data set [3].

| Number of data | Applicability of interpolation method | | |
|---|---|---|---|
| | Inverse Distance Weighting | Nearest Neighbourhood | Natural Neighbour |
| 1-5 | Yes | Yes | No |
| 6-10 | Yes | Yes | Yes |
| 11-19 | Yes | Yes | Yes |

Authors in [3] the small datasets divided into three classes regarding included points: (a) 1-5, (b) 6-10 and (c) 11-19 points. It is concluded, if the main selection criteria could be cross-validation, the

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IDW would be the best choice for interpolation. However, they also warned that this method sometimes created numerous "bull's-eyes" or "half-butterfly" features. So, we can summarize our results in conclusion and recommendation given in the following statements and Table 4:

1. The MSM could be recommended for geological subsurface mapping of Neogene in the Northern Croatia;
2. That is valid for datasets smaller than 20 measured values;
3. The selected variables could be porosity, permeability and thickness measured in Neogene lithostratigraphic units by laboratory analysed well data (cores) or interpreted logs;
4. The interpreter need to be aware of: (a) the IDW resulted with the lowest cross-validation of all applied methods without spatial model (variogram), i.e. namely Nearest neighbourhood and Natural neighbour, (b) the MSM interpolation eliminated all unwanted geological features and did not result in the cross-validation 250 % higher than in the IDW, for the same variable.
5. Based on visual (geometric) criteria, the sets with less than 5 measured points need to be consider as too small for interpolation (the IDW or MSM), and they are appropriate only for zonal estimation.

**Table 4.** Recommended choice between the IDW and MSM for small input data set (less than 20 data.

| Number of data | Applicability of interpolation method | |
|---|---|---|
| | Inverse Distance Weighting | Modified Shepard's Method |
| Criterium | (1) If Nearest Neighbourhood, Natural Neighbour or any available zonal method is tested and the IDW has the smallest cross-validation.<br>(2) If the cross-validation is single criteria for quick-look. | (1) If the IDW has the smallest cross-validation.<br>(2) If the outliers are strongly and unnaturally emphasised on the map ("bull-eye", "butterfly" features).<br>(3) If expert geologist, with knowledge about regional geology of mapped volume, can evaluate map(s). |
| 5-20 | Yes | Yes |

**Author Contributions:** **Tomislav Malvić** led the research and selected the fields for analyses. **Josip Ivšinović** collected data, selected Sheppard method and interpolated maps. **Josipa Velić** and **Jasenka Sremac** prepared regional geology presentation and **Uroš Barudžija** visualised samples and connect with regional geology.

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