

Supplementary file for:

## Approaching Prehistoric Demography: Proxies, Scales and Scope of the Cologne Protocol in European contexts

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### Manual and example application to model ‘Core-Areas’ (Optimally Describing Isolines) using ArcGIS

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#### Notation conventions:

Name of file, folder or directory

*Colum- or row heading*

/Menu / 1st submenu / 2. submenu / etc.; button

Option, value entries

[exemplification]

<default value>

## Introduction

This tutorial describes the first two parts of the Cologne Protocol, GIS-analyses of site distribution and the identification of the so-called Core Areas. For a discussion of the theoretical background and the assessment of population densities please refer to the main text and the related suppl. Material. See also <https://github.com/C-C-A-A/CologneProtocol-ArcGIS>.

The goal of the manual is to compute the first two parts of the Cologne Protocol in ArcGIS Desktop 10.X (using the extensions Spatial Analyst and Geostatistical Analyst). The necessary steps are (after. *Schmidt et al. 2020, table S2*):

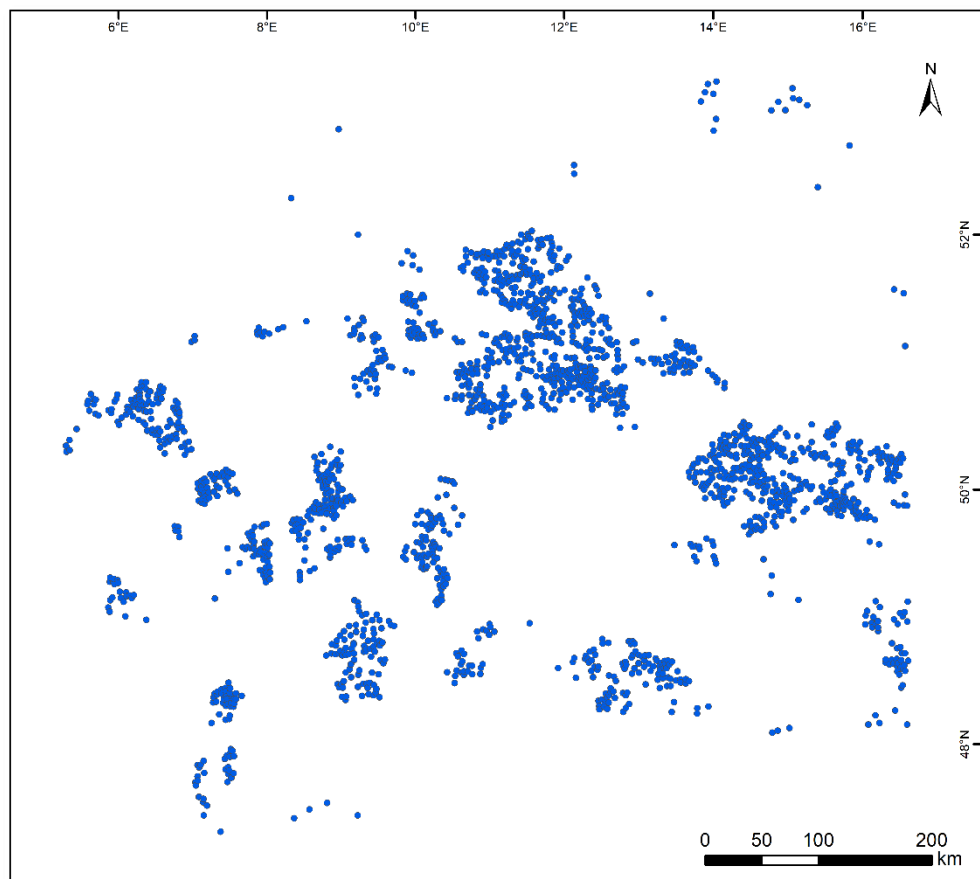
#### Steps:

1. Loading data (Shape-layer with sites as points)
2. Creating of Voronoi Diagram
3. Extraction of Vertices
4. Aggregation of Vertices
5. Defining the Radius of the “Largest Empty Circle”
6. Kriging - Preparation and Grid
7. Kriging - Semivariogram

8. Kriging - inspect and export raster output
9. Creating Contour Lines (Isolines)
10. Calculating the Area and Number of Sites per isoline
11. Data export
12. Selecting the “Optimally Describing Isoline”

### Archaeological sites (Shapefile with sites as points)

In this tutorial, we use archaeological sites derived from map of the Early Neolithic Linear Pottery Culture (LBK) in Central Europe. The map is based on *Preuss (1998, Karte 1)* and available at CRC 806 database ([crc806db.uni-koeln.de](http://crc806db.uni-koeln.de)). The original map included symbols for an agglomeration of five sites. The digital data set has been processed to resolve this issue by aggregating corresponding sites. Another prerequisite of the workflow of the Cologne Protocol is that distances can be computed in metres, kilometres etc., which is impossible in case the data set (sites) are projected in a geographic coordinate system. In the latter case it is necessary to project the data set to a projected coordinate system. Here, the data set 13\_EARLYNEOLITHIC\_CE\_SITES\_GK3 in coordinate system DHDN Gauss Krüger Zone 3 (EPSG: 31467) will be used.

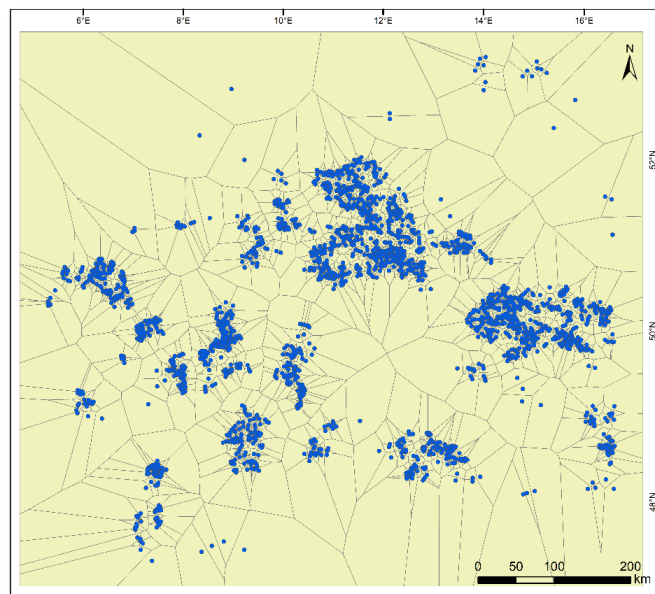
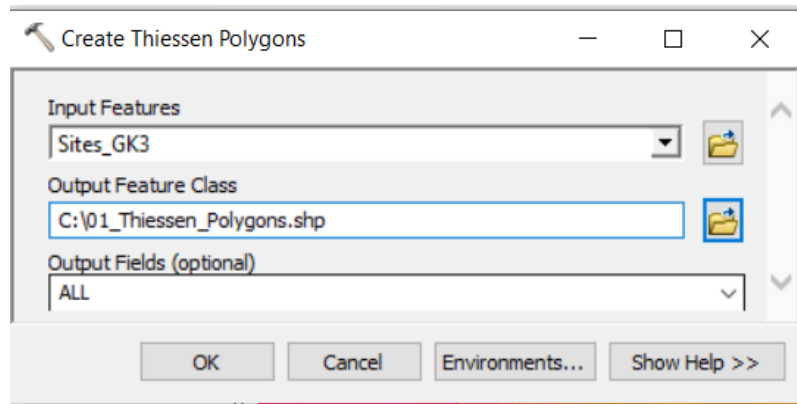


## Largest Empty Circle

The “Largest Empty Circle” (LEC), or more precisely, the radius of a LEC is a measure of site distance. Every LEC has its centre at a vertex of a Thiessen polygon (e.g. Voronoi diagram) and exactly three sites are located on every circumference of a LEC. An illustration can be found at *Zimmermann et al. (2004, fig. 5)*. In conclusion, areas with larger site distances will be characterized by larger radii of LECs and, logically, areas with smaller site distances will be characterized by smaller radii of LECs.

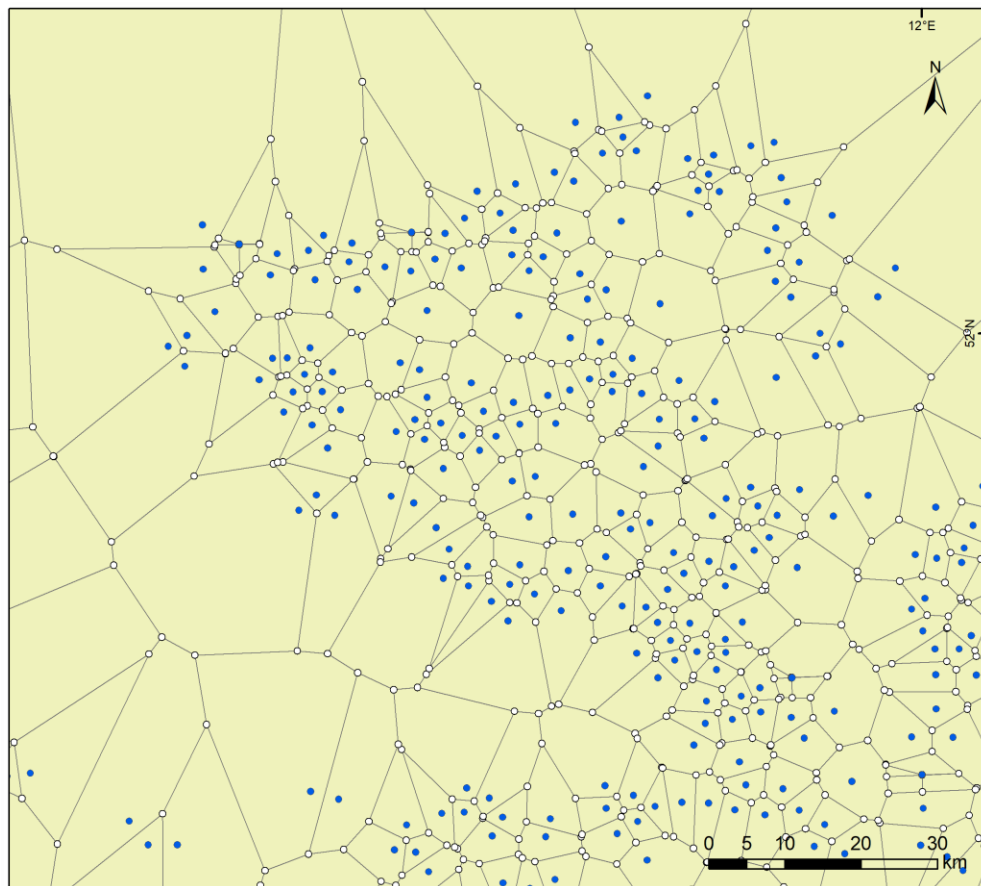
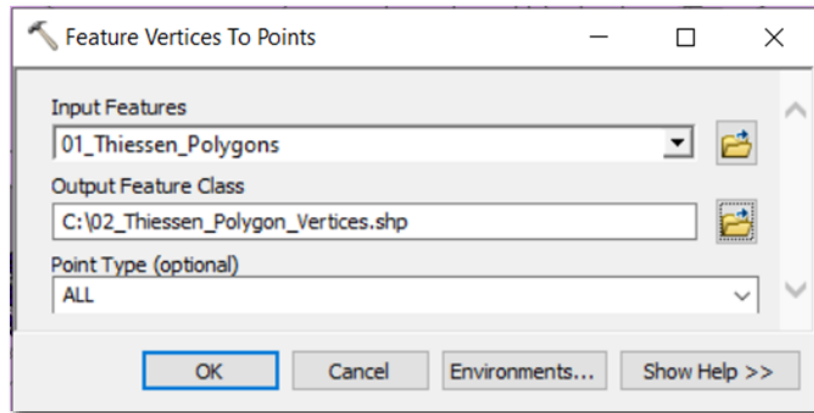
## Step 2: Creating Thiessen (Voronoi) Polygons

In the first computational step Thiessen-Polygons will be created (select the file, here Sites\_GK3) using the tool [\*/Analysis /Create Thiessen Polygons\*](#). Define output directory and file name. Choose either all or only the Field ID in [\*Output Fields\*](#). Press OK to proceed:

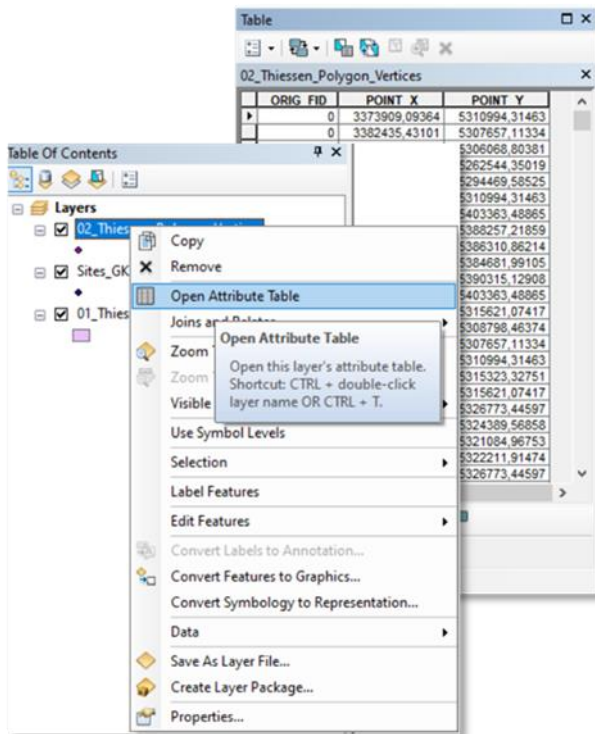


### Step 3: Extraction of TP-node points (vertices)

To extract the nodes of the Thiessen-Polygons („vertices“) from the Thiessen-Polygon-Layer (here [01\\_Thiessen\\_Polygons](#)) use */Data Management /Feature Vertices to Points*. In Dropdown *Point Type* choose ALL.



## Step 4: Aggregation of vertices



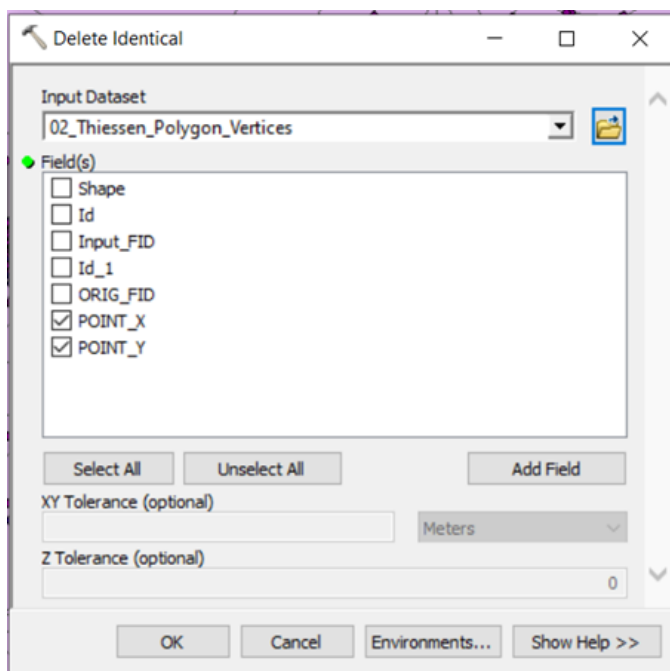
During step 3 we didn't take care of duplicate vertices. Furthermore, some of the vertices are located at the outer border of the working areas, so-called border points. These points create artificial site distances and it must be decided on a case-by-case basis whether the border points should be deleted. Here only the duplicates will be removed, not the border points.

This is accomplished by deleting vertex doublets with identical coordinates. First, coordinates need to be extracted. This is done using [/Data Management /Add Geometry Attributes](#). Select the file [02\\_Thiessen-Polygon\\_Vertices](#) as Input Feature and chose [Point X Y Z M](#) at [Geometry-Properties](#). Since no further calculations are required, other fields can remain empty.

A look at the attribute table (right-click on the vertex layer -> open attribute table in the table of contents) shows whether two columns with the values [POINT X](#) and [POINT Y](#) have been entered in

the table and whether this also contains data (not selected on screenshot).

Now we proceed with Layer [02\\_Thiessen-Polygons\\_Vertices](#) by using the tool [/Data Management /Delete Identical](#) to delete double vertices. In the tool window check marks at "Point X" and "Point Y" are to be selected. Press OK to proceed.



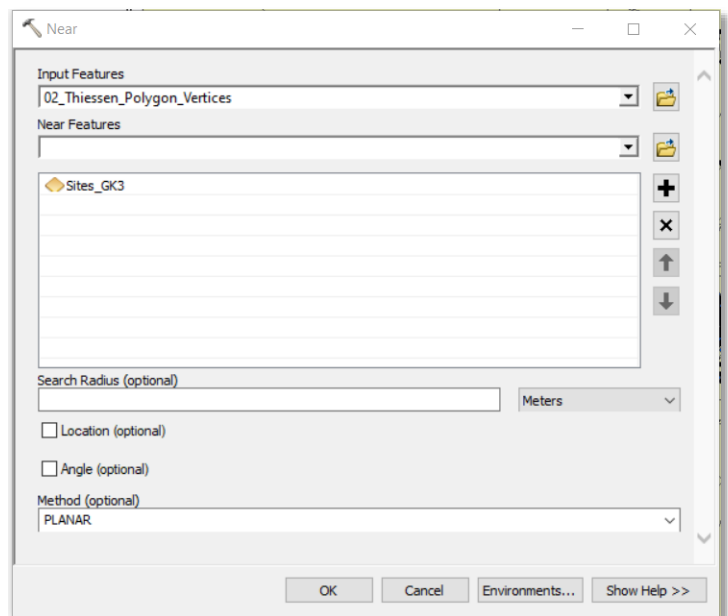
## Step 5: Defining the radius of the “Largest Empty Circle”

Each of the vertices is by definition the centre point of a circle that passes through the three most proximate sites. Since the distance to each of the three sites is identical, the distance can be measured as the nearest neighbour, or as the radius of the „Largest Empty Circle“ (LEC).

Now the LEC radius using can be determined using the tool [/Analysis /Near](#). Select the aggregated layer of Vertices as "Input Feature" (e.g. [02\\_Thiessen-Polygons-Vertices](#)) and the original layer of archaeological sites ([Sites\\_GK3](#)) as Near Feature. Search radius may remain empty, as Method we recommend Planar.

A look into the layer table of [02\\_Thiessen-Polygons-Vertices](#) reveals two new columns: [Near FID](#) contains the ID of the next nearest site (from table [Sites\\_GK3](#)). [Near Dist](#) contains the distance to the next site (given in the distance measure defined in the data frame properties, usually metres). i.e. the radius of the LEC.

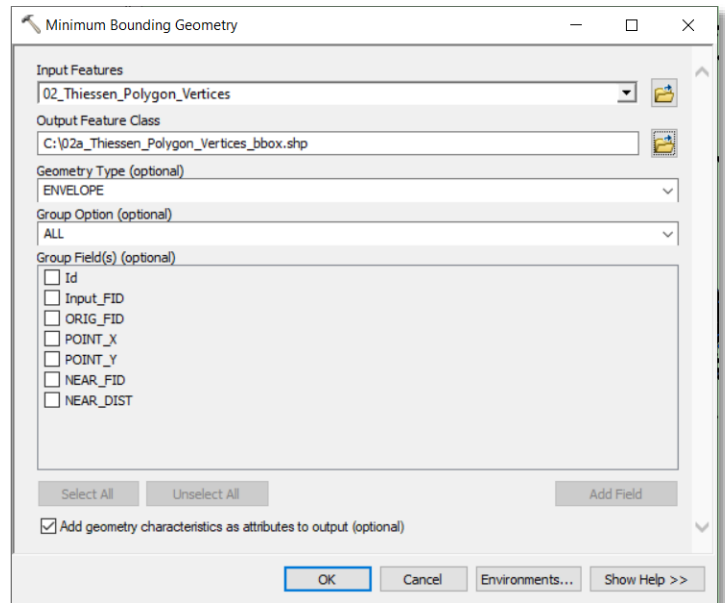
Excursion: The largest empty circles can be produced with the tool [/Analysis /Buffer](#): using the file [02\\_Thiessen-Polygons-Vertices](#) as Input Features, and the Field [Near\\_Dist](#) as Buffer Distance.



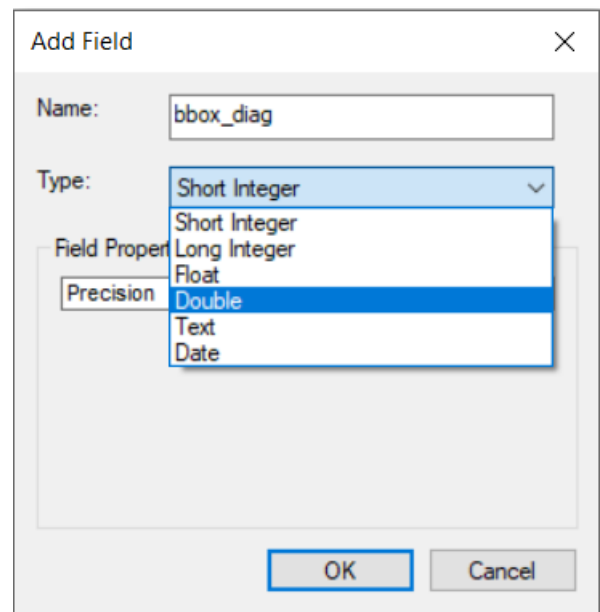
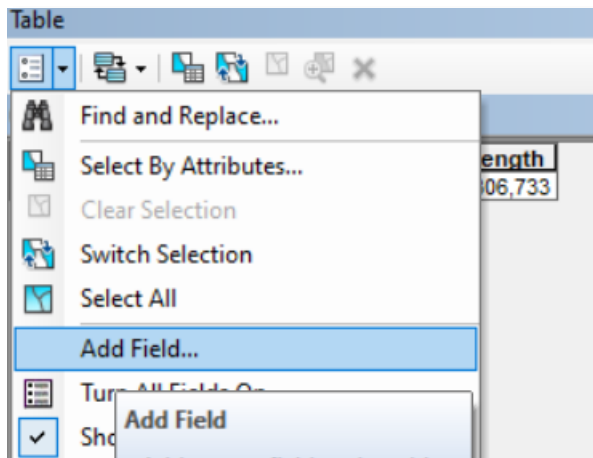
## Kriging

### Step 6: Preparation

In the next step, clustering of sites will be interpolated using kriging. The method has a variety of **parameters** which need to be estimated to fit the data (SuppMat Tab. S2). One of the parameters that needs to be given is the distance between each pair of locations, the so-called “lag-distance”. Usually, ArcGIS estimates the lag-distance from the size of a given grid, i.e. a raster file or map. But since our initial input layer is a vector layer of site locations it does not contain a grid size. Following the Cologne Protocol, lag distance is derived following a standard procedure in MapInfo, which is the diagonal of the bounding box of the data set divided by 250. A bounding box is a rectangular that includes any point feature in a given layer. First, the width and length of the layer **02\_Thiessen-Polygons-Vertices** must be computed using the tool */Data Management /Minimum Bounding Geometry*.



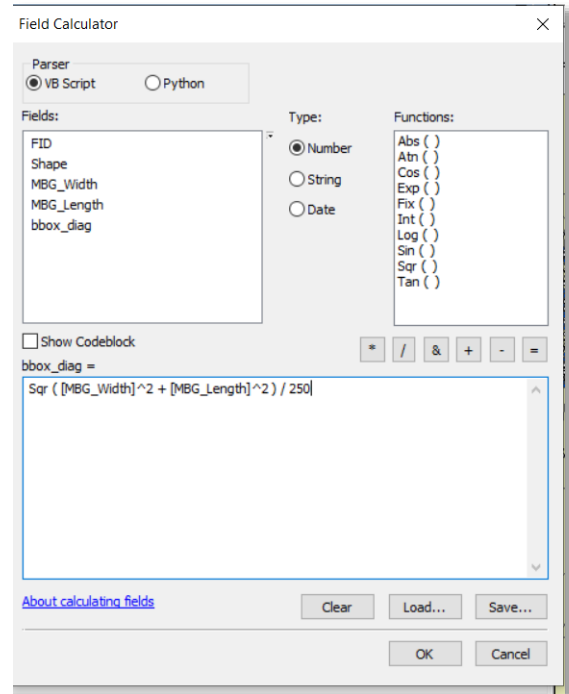
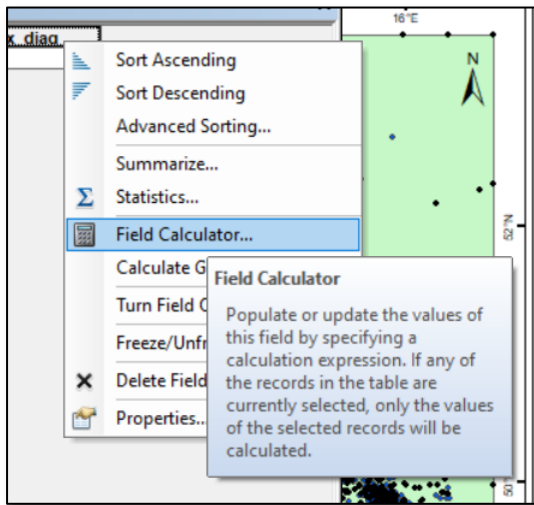
In a second step, a new column must be created in the attribute table of the new layer (e.g. **02a\_Thiessen\_Polygon\_bbox**). Open the attribute table (right-mouse click on the layer in the table of contents -> *Open Attribute Table*). In the attribute table, open the menu in the top left corner and choose *Add Field*. Choose a name (e.g. **bbox\_diag**) and choose **Double** as **Type**. Hit *OK* to create the new column.



When the new column **bbox\_diag** has been created hit the column header with a right-mouse click and choose *Field Calculator*. At the top, choose *VB Script as Parser*. The following line of code calculates the diagonal of the bounding box from its width and length:



```
Sqr ( [MBG_Width]^2 + [MBG_Length]^2 )
/ 250
```



Here, the resulting lag distance (bounding box diagonal /250) is “4376.84” metres (ca. 4.3 km). In case the value is given in kilometres it might be worth checking the current main layer properties (right mouse button click on the top layer in the table of contents -> Properties). On the tab General map units can be verified.

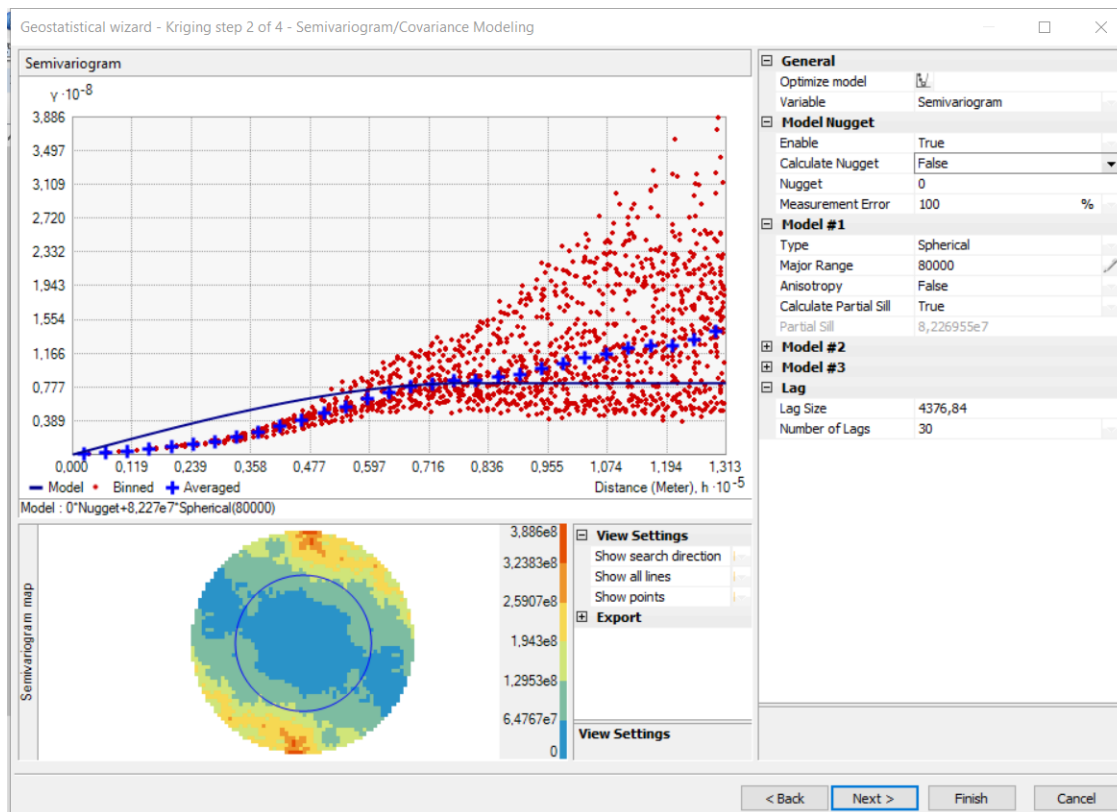
## Step 7: Semivariogram

Once the distance of the diagonal of the bounding box has been defined, kriging can be computed. In ArcGIS several Kriging tools exist: in case all statistical parameters (nugget, sill, major range, lag distance, search distance etc.) are known the tool /Spatial Analyst /Kriging can be used. Recalculating the parameters automatically can be done by the tool /Geostatistical Analyst / Moving Window Kriging. If none of the values is known, the kriging model can be fitted automatically, using the /Geostatistical Analyst /Empirical Bayesian Kriging. Finally, a semivariogram can be fitted manually, using the Geostatistical Wizard. Following the procedure of the Cologne Protocol, we will fit the model manually. Fortunately, in ArcMap the semivariogram is applied via a wizard that guides through several consecutive steps. The wizard can be started from the Geostatistical Analyst toolbar (Customize -> Toolbars -> Geostatistical Analyst). At the toolbar, the Geostatistical Wizard can be started either via a button or from a dropdown (a very interesting feature in ArcGIS is that any parameter can be changed even once the final interpolation map has been computed).

- In the first window, choose Kriging/CoKriging in the left pane, make sure that 02\_Thiessen-Polygons\_Vertices is selected as the Source Dataset in the right pane and NEAR\_DIST (the LEC radii) in the dropdown Data Field.



- In the second window, choose Ordinary as the Kriging Type and Prediction as the Output Surface Type in the left pane and none as Transformation Type as well as Order of trend removal in the right pane.
- The third window is made of three parts, a graphical representation of the covariance (model fit) at top left, a covariance map at bottom left. Here, points that are closer together are less distant than points that are further apart. The semivariogram allows you to explore this distribution in your data set. The process of fitting a semivariogram model to capture the spatial relationships in the data is known as variography. The model can be changed by editing parameters in the right pane. Four values need to be edited here. First, change the model type to Spherical. Second, set Calculate nugget to False and enter a Nugget of “0” manually. Now it is worth optimizing the fit by hitting the button next to Optimize model. Finally, Lag Size should be set to the diagonal of the bounding box divided by 250 (here:  $1094210.62681 / 250 = 4376.84$ ; cf. [step 6](#); This method for estimating the lag distance is derived from MapInfo). Finally, the Number of Lags (pairs of points taken



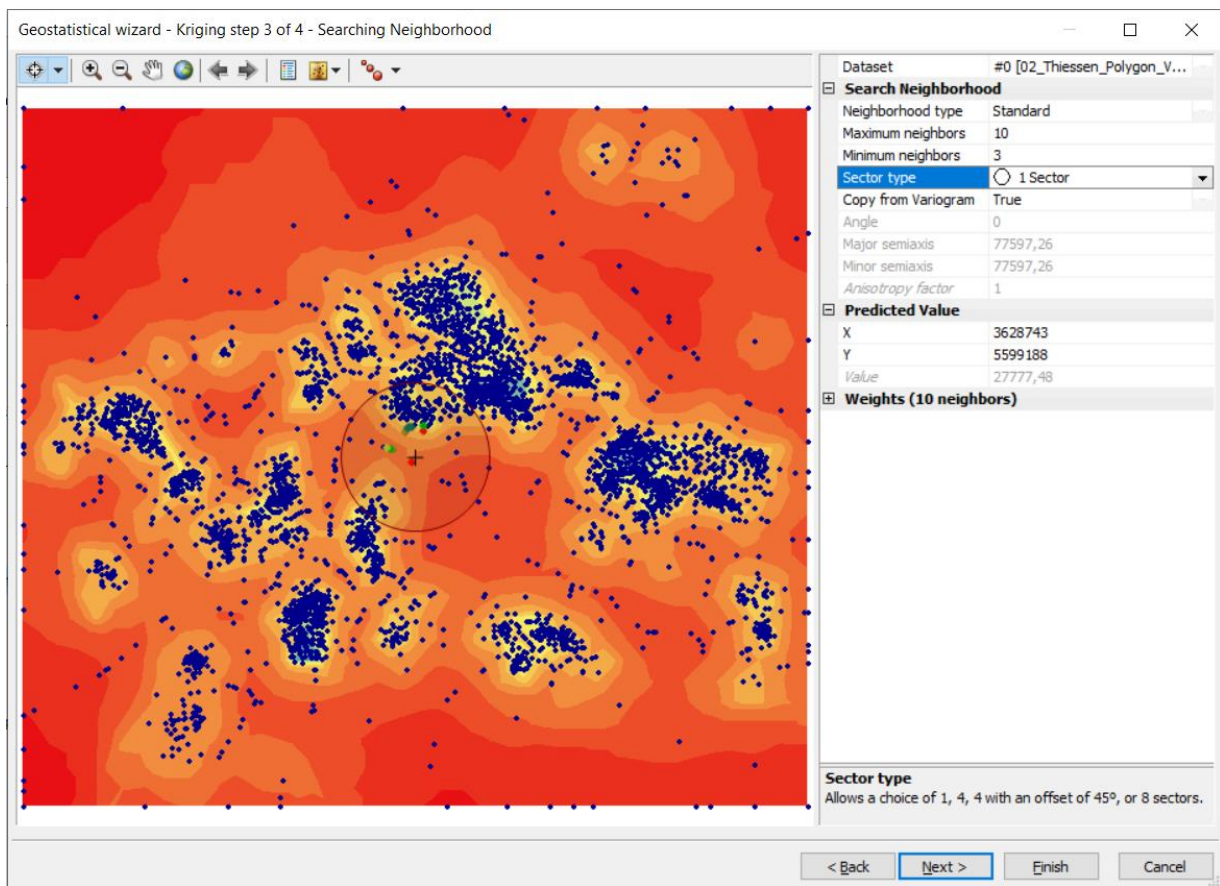
into account) may be set between 20 and 40.

**Remark:** According to the Cologne Protocol the Major range, should be set to the first peak of the distribution of the variance. This, however, is not possible in ArcGIS since the map in the top left pane does not display variance (but either covariance or lag pairs). But the same effect can be modelled by setting the Major Range to a value at

which the fit (black line) follows the lower bottom of the distribution. Here this effect is reached if Major Range is set to ca. 8000.

- In the next window, the search neighbourhood is defined. A preview of the Kriging model is given in the top left pane. In the right pane, three values need to be edited: Maximum neighbours should be set to “10”; Minimum neighbours should be set to “3”. Sector type defines the number of directions in which neighbours are searched. For a better compatability with other GIS software (MapInfo, R, QGIS) set the number of sectors to “1”. For a more finegrained Kriging interpolation and smaller isoline area volumes (cf. step 10), use 4 or 8 sectors. Here, 1 sector is used.
- After pressing Next, a list of values is given with measurements, predictions and errors for the individual sites.

Press Finish to proceed.

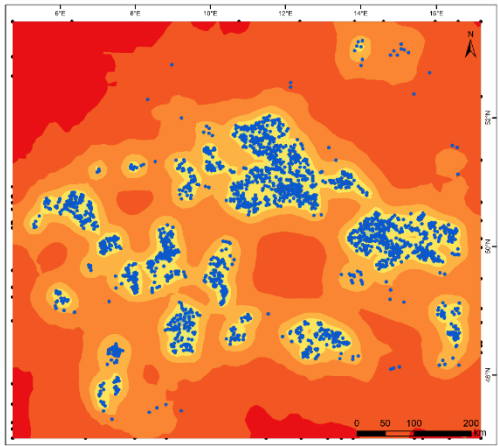


## Step 8: Kriging - inspect and export raster output

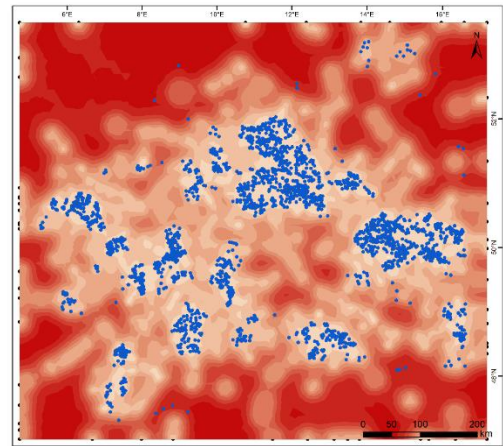
It is worth taking a closer look at the GA Layer's options. Via a right mouse button click on the resulting Kriging map there are too more interesting options available in the dropdown menu. Change Output to Prediction Standard Error switches the map view (when done an option to Change Output to Prediction becomes available in the same place). The other

interesting option is the second last entry in the dropdown menu: *Method Properties*. This entry enters the *Geostatistical Wizard* again and allows to modify the Kriging parameters.

The resulting Kriging interpolation map is a temporary “GA Layer” that should be saved as a grid file for further use. This can be done in two ways, either by using the tool */Geostatistical Analyst / GA Layer To Grid*, or via a right mouse button click on the Kriging interpolation map -> Data -> Export To Raster. While exporting, an *Output Cell Size* should be chosen that fits the envisaged distance of contour lines in the next step, i.e. if the resulting isolines should be in intervals of 500 m, choose cell size smaller than 500 m. In the following steps we assume the Kriging map is saved as a layer named *kriging.tif* (ArcGIS



The Prediction map obtained by Kriging using the LEC radius values



The same map switched to Standard Error view.

does not allow numbers at the beginning of filenames when exporting raster files).

## Optimally Describing Isolines

On the basis of the kriging results we will create isolines and we will select the “Optimally Describing Isoline” (ODI). The selection of the ODI is based upon several statistical parameters of the isolines (Zimmermann *et al.* 2004, 53–55).

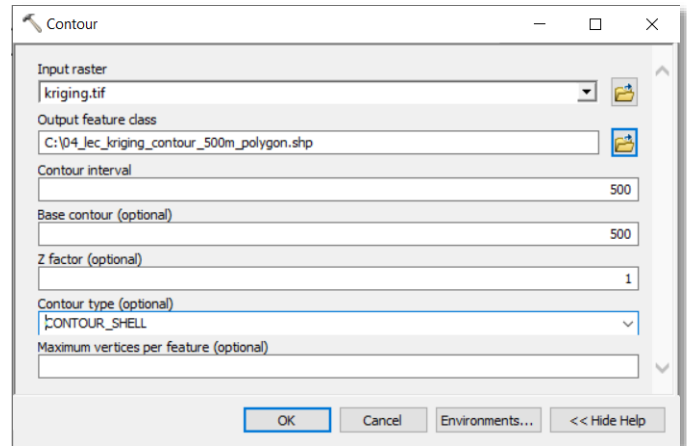
### Step 9: Creating Contour Lines (Isolines)

Isolines will be created between 500 m and 20 km with an interval of 500m using the tool */Spatial Analyst /Contour*. The starting distance of 500 m is chosen to neglect clusters at smaller distances (0–500m). In the subsequent [step 10](#) we will identify some characteristics of the different isolines, such as the volume of the area or the number of sites included. This task requires the isolines to be polygons. Another issue concerns the way polygons are created by the *Contour* tool. In ArcGIS 10.6 and above, the *Contour Type*:

CONTOUR POLYGON creates neighboring polygons: 0 – 500; 500 – 1000 etc. But we need to calculate the increase in area volume and archaeological sites between the separate isolines, and hence overlapping polygons: 0 – 500; 0 – 1000 etc. This can be accomplished using Contour Type: CONTOUR SHELL.

#### 9.a ArcGIS Desktop 10.6 and above

- Input Raster [kriging.tif](#) from the previous [step 8](#).
- Output feature class: Use the browser to name and store the file (here



[04\\_lec\\_kriging\\_contour\\_polygon\\_500m](#)). Note: specify the meter/km of the interval, in case you calculate several sets.

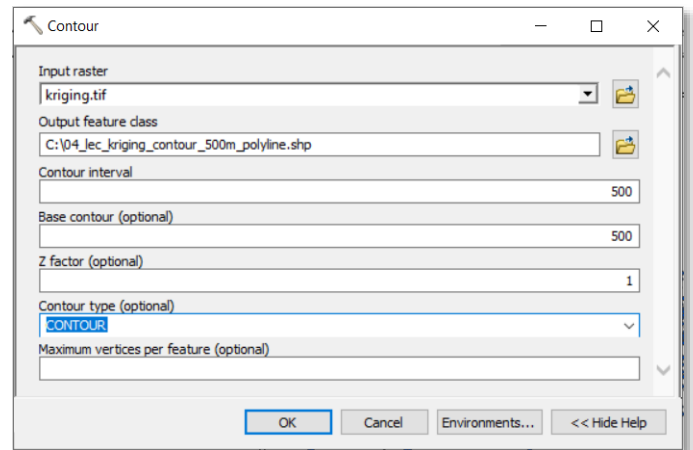
- Contour interval to be chosen dependent on size of the study area and distances between sites. Here: 500 m
- Base-Contour, i.e. the starting contour line, we also choose 500 m.
- Contour Type: CONTOUR SHELL

#### 9.b ArcGIS Desktop 10.5 and below

In case you are using ArcGIS 10.5 or earlier, the tool is only capable of producing polylines:

- Input Raster: [kriging.tif](#) from previous [step 8](#).

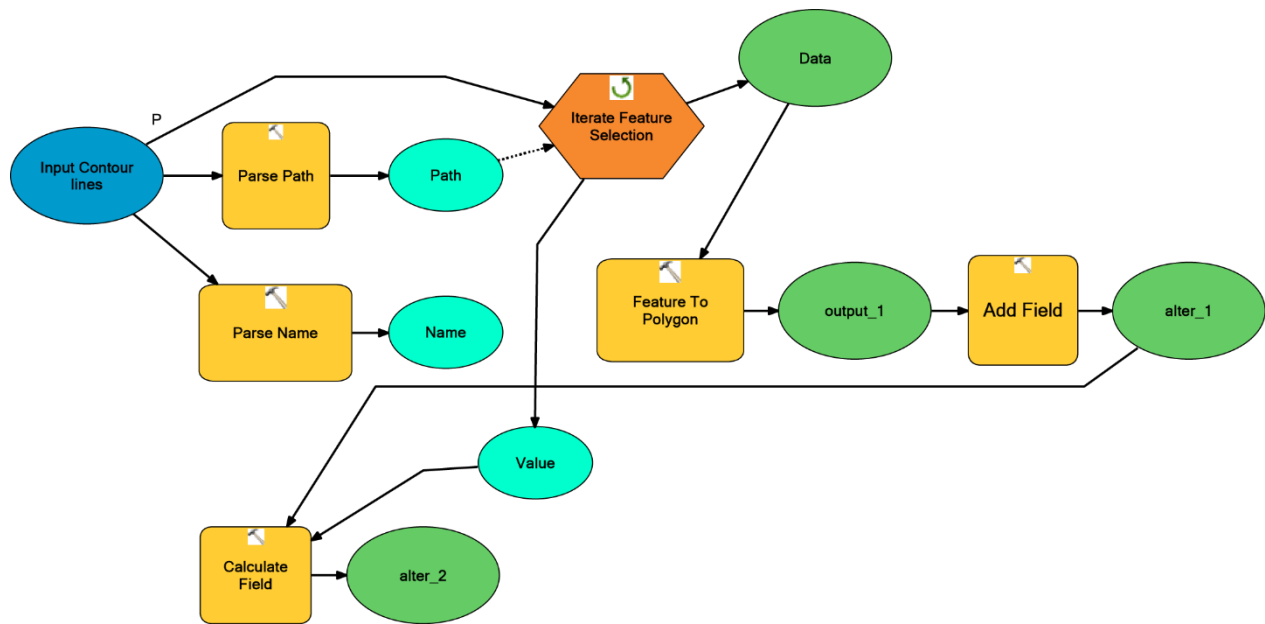
- Output feature class: Use the browser to name and store the file (here



04\_lec\_kriging\_contour\_polyline\_500m). Note: specify the meter/km of the interval, in case you calculate several sets.

- Contour interval to be chosen dependent on size of the study area and distances between sites. Here: 500 m.
- Base-Contour, i.e. the starting contour line, here 0.
- Contour Type: CONTOUR

Since we need to calculate the area volume per contour line (isoline), the individual contour line features need to be transformed into polygons. Well, transforming polylines to polygons is a simple task with the tool [/Data Management/Feature To Polygon](#). However, for some reason the latter tool deletes all data columns in the resulting data set, even if the option Preserve attributes (optional) is ticked on. For this reason, the transformation has to be done for each contour line separately! To do this, we recommend to select single values in the Layer Table (e.g. select all rows where CONTOUR = 500, e.g. using the *Select by attributes* option in the attribute table and the formula "Contour" = 500) at once and to . After each export, it is recommended to open the attribute table of the resulting layer and add a new column named Contour with the value of the currently exported Contour value (e.g. 500). Since this procedure may become highly time-consuming when the number of contour lines is high (as it is in this example), we recommend to automate this process using the [Modelbuilder](#):



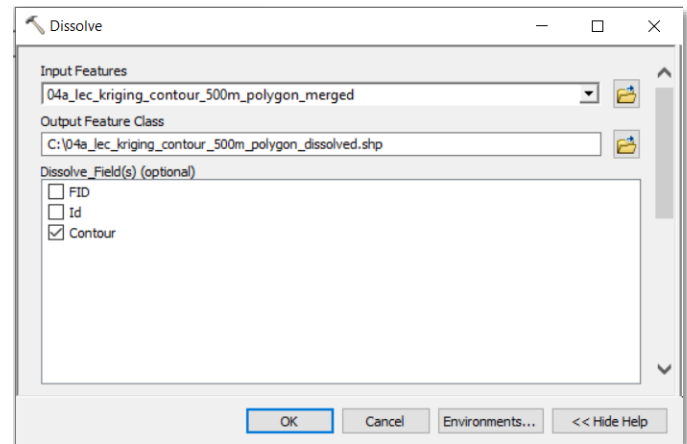
This process can be downloaded as an ArcGIS toolbox at [Github](#). After running the script, one polygon feature class exists per contour value (500, 1000, 1500 etc.). Regardless whether you do this step manually or using the model builder, at the end you should have a series of shapefiles named [04\\_lec\\_kriging\\_contour\\_polygon\\_XXXXm](#).

All these files now must be merged to a single shapefile using the tool [/Data Management /Merge](#). Using the folder icon next to the *Input Datasets* dropdown allows you to choose all the contour line files at once. Pick an output file name (we assume [04a\\_lec\\_kriging\\_contour\\_polygon\\_merged](#)) and start the process. Now you can delete the series of [04\\_lec\\_kriging\\_contour\\_polygon\\_XXXXm](#) files (In case you used the Modelbuilder toolbox these files are also marked with “temp” in their filename).

If you check the resulting the layer [04a\\_lec\\_kriging\\_contour\\_polygon\\_merged](#) you will realize that it still contains a series of rows per isoline value. But for the envisaged calculations in the next step, we need one row per isoline. Hence, we use [/Data Management /Dissolve](#) to collapse identical isoline values into multipart features:



- Input feature:



04a\_lec\_kriging\_contour\_500m\_polygon\_merged

- Output Feature Class:  
e.g. 04b\_lec\_kriging\_contour\_500m\_polygon\_dissolved
- Dissolve Fields:  
Contour

## Step 10: Calculating the Area and Number of Sites per Isoline

In order to be able to select the optimally describing isoline (ODI), it makes sense to look at the statistical properties of the isolines. These are, for example, the number of archaeological sites within the isolines, their difference in number per interval, the number of distinct areas per isoline or the area increase per interval. Here, we will focus on two of these characteristics: the number of archaeological sites per isoline interval and the increase in area per isoline interval.

### 10 a counting sites per isoline

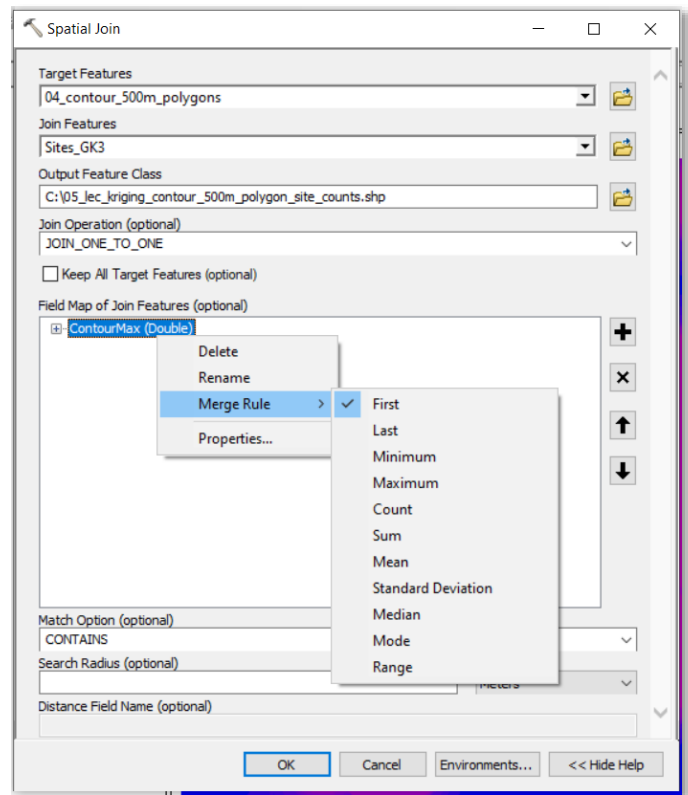
The number of sites per isoline can be computed via a spatial join of LEC polygons from [step 9](#). Two ways exist, both making a spatial join between the polygons and the archaeological sites, either following this [workflow](#), or using the tool [/Analysis /Spatial Join](#):

- Target-Feature: 04\_lec\_kriging\_contour\_polyline\_500m (ArcGIS 10.6 and above)  
04b\_lec\_kriging\_contour\_500m\_polygon\_dissolved (ArcGIS 10.5 and below)
- Join-Feature: Sites\_GK3.



- Output Feature Class: 05\_lec\_kriging\_contour\_500m\_polygon\_site\_counts.
- Join operation: Join One To One.
- Untick Keep all target features to delete polygons which do not contain any sites.
- Field Map of Join Features: Keep the columns Contour / ContourMax. Delete others to avoid nonsense data in the resulting data set.
- Check that the Merge Rule for your Contour / ContourMax set to First.
- Match Option: Contains
- Other fields are left empty.

Hit OK to run the tool.

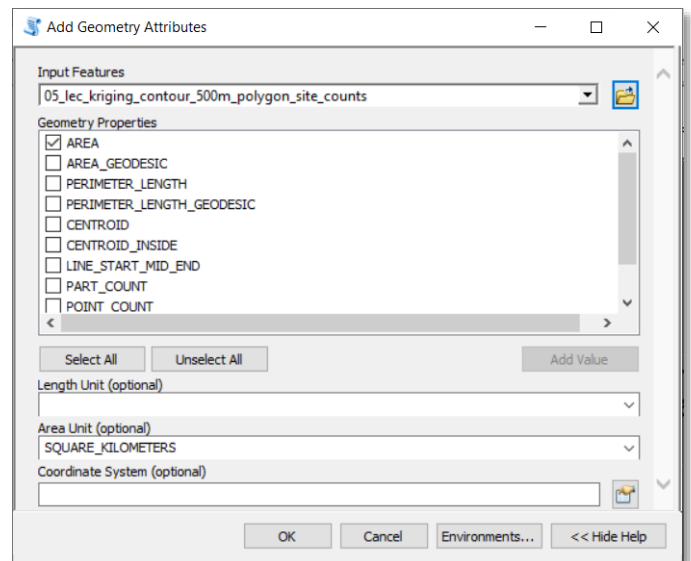


## 10 b calculate area volume per isoline

Counting the area volume is a comparably easy task that is accomplished using again the tool

[/Data Management /Add Geometry Attributes:](#)

- Input Feature:



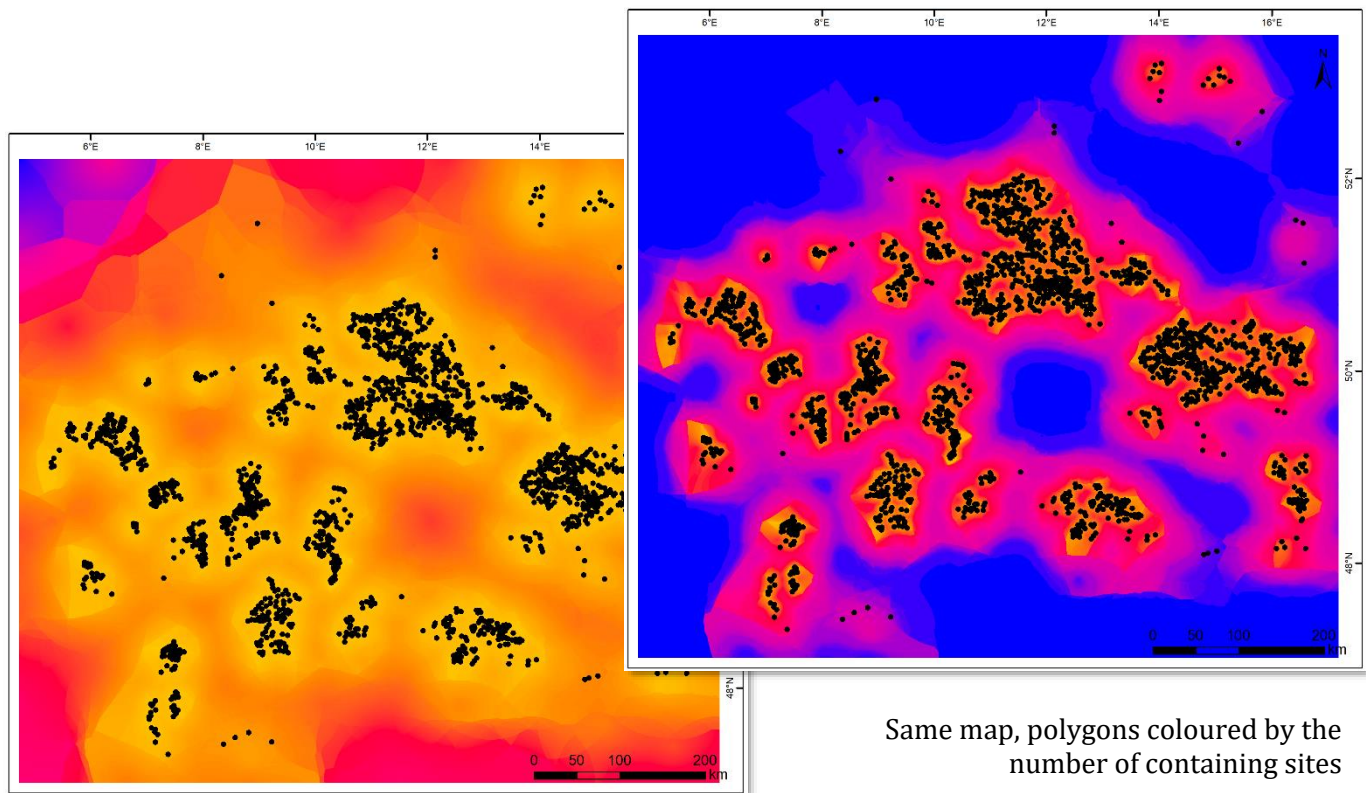
[05\\_lec\\_kriging\\_contour\\_500m\\_polygon\\_site\\_counts.](#)

- Since we have selected an area feature, we now can select under Geometry Properties: Area.
- Leave Length Unit may remain empty.
- Area Unit should contain a measure, either square meter or square kilometre.

After running the tool, area volume should be present in the Attribute table of [05\\_lec\\_kriging\\_contour\\_500m\\_polygon\\_site\\_counts](#):

Table						
05_contour_500m_polyg						
FID	Shape	Join Count	TARGET FID	ContourMax	POLY AREA	
544	Polygon	636	544	500	112,83725	
543	Polygon	637	543	1000	362,190933	
542	Polygon	642	542	1500	871,865057	
541	Polygon	685	541	2000	2198,594284	
540	Polygon	980	540	2500	6222,159204	
539	Polygon	1407	539	3000	12600,576549	
538	Polygon	1714	538	3500	19952,185395	
537	Polygon	1925	537	4000	27609,574277	
536	Polygon	2031	536	4500	34921,245591	
535	Polygon	2091	535	5000	41506,543366	
534	Polygon	2150	534	5500	47652,406172	
533	Polygon	2189	533	6000	53487,472268	
532	Polygon	2214	532	6500	59158,747489	
531	Polygon	2242	531	7000	64471,230176	
530	Polygon	2266	530	7500	69613,594263	
529	Polygon	2281	529	8000	74336,882961	

In the resulting table, column “Contour” or “ContourMax” contains the isoline values, “Join Count” contains the number of sites per isoline, and “Poly Area” the area volume in the chosen distance measure (here kilometre).



Resulting polygons coloured by area volume

Same map, polygons coloured by the number of containing sites

## Step 11: Data export

The final table can be exported e.g. to an Excel spreadsheet using the tool [\*/Conversion /Table to Excel.\*](#)

## Step 12: Selecting the Optimally Determining Isoline

Please refer to the workflow provided in the MapInfo manual. It is worth noting that the ODI should not be selected automatically based on a maximum value of included space because distinct archaeological cultures may display two maxima which need an archaeological interpretation (e.g. patterns of fission and fusion in hunter/gatherer societies, cf. Kretschmer et al. 2016). Moreover, in some cases it is not possible to observe a maximum and instead with increasing distance between sites a continuous increase of space is to be observed. This would indicate a data set indicating a poor archaeological record (\*cf. Zimmermann et al. 2009, 10\*).

## Bibliography

Hengl, T., **2007**. A Practical Guide to Geostatistical Mapping of Environmental Variables. (Luxembourg 2007).

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