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B – data collection
C – statistical analysis
D – data interpretation
E – manuscript preparation
F – literature search

Selection of a semivariogram model in the study of spatial distribution of soil moisture

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Abstract

The paper presents a selection of a semivariogram model in the study of spatial variability of soil moisture in a loess agricultural catchment. Soil moisture tests were carried out in the Moszenki village, 15 km northwest of Lublin. Soil moisture measurements were performed at two dates at 104 points, located on a rectangular surface measuring 700 × 1200 m. These points were laid out in the corners of a grid of squares with sides 100 m. In addition, 6 measurements were made at a distance of less than 100 m from the nearest points. Soil moisture was measured in the soil surface (0–5 cm). ArcGis software with Geostatistical Analyst extension was used for modelling semivariograms. In both terms, five models of semivariograms were used: stable, circular, spherical, exponential and Gaussian. Kriging was used for the estimation of soil moisture values. Among the semivariogram models analyzed in this study, the largest errors in the determined values of soil moisture relative to the empirical data were observed for the exponential model, and the smallest for the Gaussian model. However, it should be emphasized that the values of the analysed errors for the individual semivariogram models were similar. Application of the ordinary kriging method for interpolation of spatial distribution of soil moisture yields good results, but it has to be kept in mind that the final shape of the spatial distribution is influenced by the choice of the semivariance function model.

Key words: *geostatistics, modelling of semivariogram, semivariogram, soil moisture, variogram*

INTRODUCTION

Knowledge of spatial distribution of soil moisture plays an important role in hydrological and meteorological modelling [ANCTIL *et al.* 2002; BARDOSSY, LEHMANN 1998; BROCCA *et al.* 2007; HERBST, DIEKKRUGER 2003; LAKHANKAR *et al.* 2010; WANG *et al.* 2001; WESTERN, BLOSCHL 1999; WESTERN *et al.* 1998]. This knowledge is also necessary for the calibration and validation of satellite images used in remote sensing studies of soil moisture [GHERBOUDJ *et al.* 2017]. Soil moisture is one of the factors that greatly influence the growth, development and yielding of plants. The spatial and temporal distribution of soil moisture depends mainly on precipitation, soil properties, terrain, evapotranspiration and vegetation growing in the area. Measurements of soil moisture are made in the surface layer or at selected depths of the soil profile [GREGO *et al.* 2006; USOWICZ 1999; WALCZAK, USOWICZ 1994]. Such measurements are performed in farming fields, selected topographic elements of the terrain or in larger areas, such as hydrological catchments [HERBST, DIEKKRUGER 2003; OBROŚLAK 2011; STACH 1998]. Soil moisture analysis is increasingly making use of geostatistical methods in addition to statistical methods. Geostatistics is a collection of tools that can be used to analyse and predict spatial or temporal variability of values of spatially correlated data. The use of geostatistic methods for analysing experimental results allows a more precise description of the phenomena occurring in the environment and makes it possible to gain a better understanding of them. Above all, these methods make it possible to estimate the value of the variable tested in places where no measurements or observations have been made. In geostatistical analyses, the main problem is to properly determine the spatial variability structure of the examined feature.

One of the basic geostatistical tools used for estimating spatial distribution is the semivariogram, also called the variogram. It represents variation in the value of the parameters observed as a function of the distance between the points in which these observations were made. The semivariogram calculated is equal to half the variance of the differences in the value of a metric at two different positions. It is calculated on the basis of the observation values obtained at measuring points [CHILÈS, DELFINER 1999; OLEA 1999].

Modelling a semivariogram is an important but also a difficult step of geostatistical analysis. Semivariogram models and their parameters provide information about the range, size, direction and type of spatial correlations. Modeling of semivariograms involves fitting a suitable semivariogram model to experimental values. For this purpose, positive-definite functions are used. Several functions can be used in combination to better describe the shape of the experimental semivariogram and take into account the nugget effect. In practice, the most commonly used functions are nugget effect, spherical, exponential, Gaussian, linear and power functions.

The aim of the present study was to select a semivariogram model in the study of spatial variability of soil moisture in an agricultural loess catchment.

MATERIAL AND METHODS

Soil moisture measurements were performed in Moszenki village, 15 km northwest of Lublin (51°18'12" N, 22°21'30" E), in the eastern part of the Nałęczów Plateau (the Lublin Upland). This area is a loess landscape, which is characterized by a dense network of dry valleys. A small hydrological catchment area of 0.4 km ^{2} with an average slope of about 3% was selected for the study. The maximum relative height difference in the area is 17 m. The catchment area is dominated by agricultural land, occupying 90% of the total area, of which about 75% is arable land. Soils occurring in this area have been developed from loesses and are mainly classified as luvisols [BOROWIEC, URBAN 1985; UZIAK, TURSKI (ed.) 2008; ZUBALA, PAŁYS 2008].

Soil moisture measurements were performed at 104 points spread over a rectangular area measuring 700 × 1200 m. The points were located in the corners of a grid of squares with a side length of 100 m. Additionally, six measurements were made at a distance of less than 100 m from the nearest points. Moisture was measured in the surface layer of soil (0–5 cm) using ThetaProbe type ML2x. Moisture content values were expressed as percent by volume. Two series of measurements were carried out in two dates. For each series, geostatistical analyses were preceded by the determination of classical statistical measures: mean, standard deviation, coefficient of variation, skewness, kurtosis, minimum value, first quartile, median, third quartile, and maximum value. The statistics were calculated on the basis of commonly used equations. Prior to geostatistical analyses, the data were tested for stationarity, and trend analysis was performed. The trend, if detected, was removed.

Spatial variability in soil moisture was assessed using the basic and most frequently used geostatistical function – the semivariogram, which is given by the formula [OLEA 1999; WEBSTER, OLIVER 2001]:

$$\gamma(x) = \frac{1}{2n_h}\sum_{i=1}^{n_h}[z(x_i+h) - z(x_i)h]^2 \qquad (1)$$

where: $\gamma(x)$ = empirical semivariogram; $z(x_i + h)$, $z(x_i)$ = soil moisture values at sample points x_i and $x_i + h$, spaced apart at distance h; n_h = number of pairs (x_i, $x_i + h$,) of soil moisture values at points spaced at distance, used for calculating the semivariogram function.

The following functions were used to model the empirical semivariogram: stable, circular, spherical, exponential and Gaussian . As a next step, mathematical models which best fitted the empirical semivariograms were selected and compared with one another. On assessing the goodness of fit of the model to the empirical data, the following prediction errors were analysed: mean, root mean square, mean standardized, root mean square standardized, average standard error.

The semivariograms were modelled using ArcGis software with the Geostatistical Analyst extension. This program provides eleven models of semivariograms. On each test date, five of these models were used for the analysis: the stable, circular, spherical, exponential and Gaussian.

RESULTS AND DISCUSSION

Selected descriptive statistics of the soil moisture measurements are presented in Table 1.

Statistical analysis showed that the soil moisture values obtained in the first series of tests were more

Table 1. Statistic of soil moisture in the first and second series of tests

Parameter	I series of tests	II series of tests
Number, pcs	110	110
Mean, % v/v	25.7	40.9
Standard deviation, % v/v	7.2	4.8
Variation coefficient, %	28.0	11.7
Skewness	0.23	1.02
Kurtosis	2.34	3.16
Minimum, % v/v	13.3	34.0
1-st Quartile, % v/v	20.1	37.9
Median, % v/v	25.6	39.2
3-rd Quartile, % v/v	30.2	43.4
Maximum, % v/v	41.9	53.9

Source: own study.

varied (coefficient of variation, 28.0%) than those found in the second experimental series (11.7%). The median of the examined parameter in the first experimental session was similar to the arithmetic mean, while in the second session it was 1.73 lower than the mean, which indicates that values measured were asymmetrically distributed. This is confirmed by the histogram in Figure 1a, which shows that the distribution is skewed right. Skewness calculated for the first experimental series was 0.23 and for the second it was 1.02 (Fig. 1b). In the first series of tests, soil moisture content ranged from 13.3 to 41.9% v/v. The mean value for the whole area was 25.7% v/v. In the second series of measurements, soil moisture content was higher than in the first series and ranged from 34.0 to 53.9% v/v. The mean moisture content was 40.9% v/v. The standard deviation calculated for the second test session was 4.8 and was 2.4 lower than the value of this parameter measures on the first date.

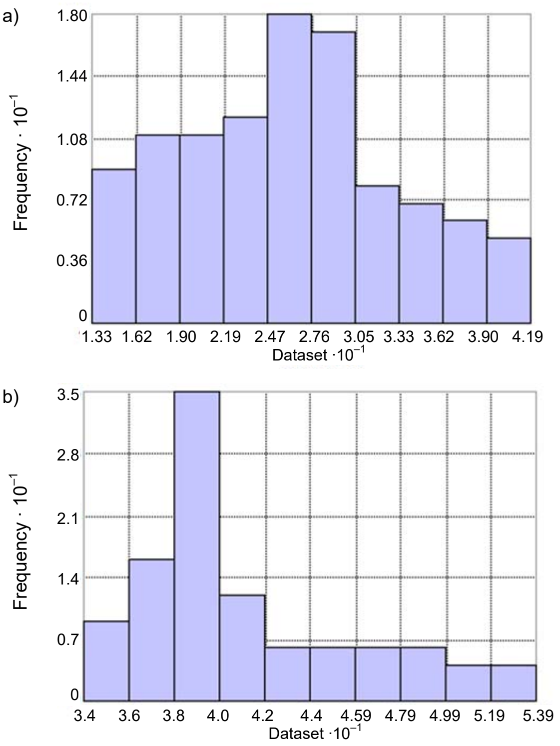

Fig. 1. Histogram of soil moisture values in the: a) first series of tests, b) second series of tests; source: own study

As part of structural analysis, spatial relationships were studied using the semivariogram. This tool describes the degree of variation between data points depending on the distance between them. Before the semivariogram was generated, the trends which were present in both test series were removed. In the second series of measurements, the data were additionally transformed to normality using the Box–Cox transformation. Because an experimental semivariogram cannot be used to estimate the spatial distribution of the analysed parameter by kriging, the distribution is modelled using appropriate functions or combinations thereof. The following functions were used to model the semivariograms in this study: stable, circular, spherical, exponential and Gaussian.

Figure 2 shows the soil moisture semivariograms obtained for the first experimental series and an approximation of the semivariograms by theoretical models. An analysis of the semivariance graphs shows that in the first experimental series, the range of spatial autocorrelation was the lowest in the case of the Gaussian model and the highest for the exponential model. Semivariance graphs for the second series of measurements are presented in Figure 3. Similarly to the first experimental series, the smallest value of the spatial autocorrelation range was recorded for the Gaussian model and the largest for the exponential model.

In the first series of tests, the largest difference between the minimum and the maximum values of prediction errors at the measurement points was observed for the exponential model, and the lowest for the stable model. The exponential model was characterized by the largest values of mean standard error and mean squared error. The lowest values of these errors were recorded for the Gaussian model (Tab. 2).

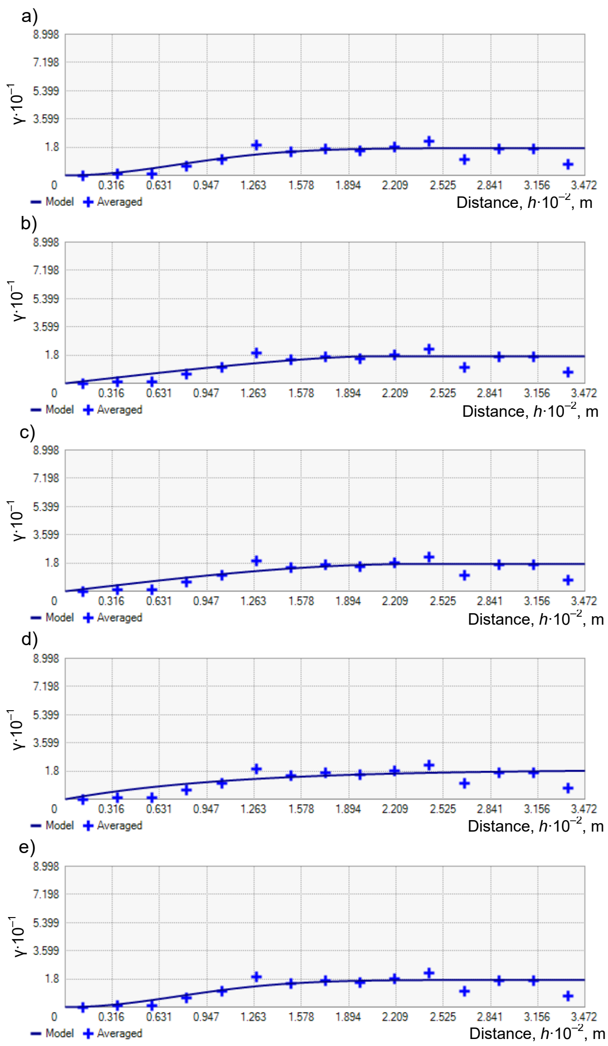

Fig. 2. Semivariogram of soil moisture determined for the first series of studies and their approximate theoretical models: a) stable, b) circular, c) spherical, d) exponential, e) Gaussian; source: own study

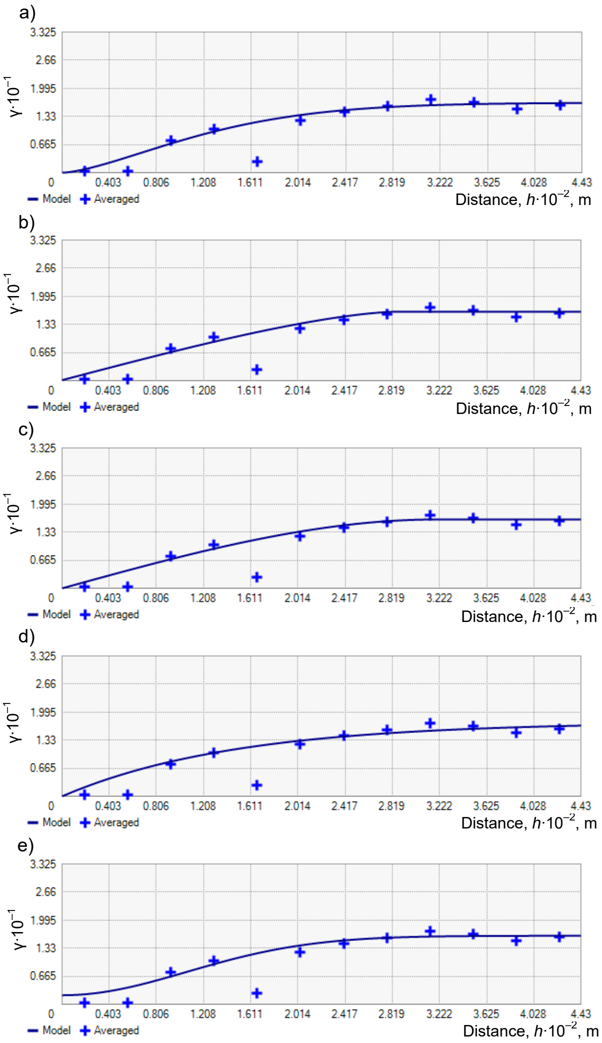

Fig. 3. Semivariogram of soil moisture determined for the second series of studies and their approximate theoretical models: a) stable, b) circular, c) spherical, d) exponential, e) Gaussian; source: own study

In the second series of measurements, the largest difference between the lowest and highest values of prediction errors was found for the exponential model, and the smallest for the Gaussian model (Tab. 2).

Analogously to the first series of tests, the highest values of mean standard error and mean squared error were recorded for the exponential model. The lowest mean squared error was recorded for the stable model, and the mean standard error was the smallest in the Gaussian model.

Soil moisture in the analysed area was estimated using the most commonly employed geostatistical method called kriging. In both measurement series, a spatial distribution of soil moisture was generated for each semivariogram model used. The distributions obtained are presented in Figure 4. When the moisture distributions from the first series of measurements are compared, it can be seen that they are similar despite the fact that semivariances of different functions were used. The same can be said of the distributions generated for the second series of tests (Fig. 5). However, it should be stressed that the differences in spatial distributions are greater in the first experimental series compared to the second one. This is most evident in places where extreme values of soil moisture occur in the distributions. One example is the middle part of the analysed area, in which surfaces with the largest moisture content have different shapes and sizes. In the southern part of the study area, where the surfaces have the lowest moisture content, they also vary in shape and size.

CONCLUSIONS

1. The analysed area was found to have varied soil moisture content. The highest values of soil moisture were recorded in the lowest lying areas, while the lowest values occurred in the highest-situated areas.
2. Among the semivariogram models analysed in this study, the largest errors in the determined values of soil moisture relative to the empirical data were observed for the exponential model, and the smallest for the Gaussian model. However, it should be emphasized that the values of the analysed errors for the individual semivariogram models were similar.
3. Application of the ordinary kriging method for interpolation of spatial distribution of soil moisture yields good results, but it has to be kept in mind that the final shape of the spatial distribution is influenced by the choice of the semivariance function model.

Table 2. Prediction errors for selected models semivariograms soil moisture in the first and second series of tests

Series number	Prediction errors	Model semivariogram				
		stable	circular	spherical	exponential	Gaussian
First	Min, % v/v	–7,3717	–8,5794	–8,4905	–8,4168	–7,3717
	Max, % v/v	7,6470	7,0385	7,8071	8,6811	7,6570
	Mean, % v/v	–0.0084	–0.0062	0.0332	–0.0028	–0.0085
	Root-mean-square, % v/v	2.7476	2.8707	2.8666	3.0173	2.7475
	Mean standardized	0.0165	–0.0024	0.0109	–0.0011	0.0165
	Root-mean-square standardized	1.0197	0.9953	0.9655	0.8373	1.1978
	Average standard error, % v/v	2.5832	2.9031	2.9840	3.5753	2.5829
Second	Min, % v/v	–6,1921	–5,8941	–5,9889	–6,3560	–5,8619
	Max, % v/v	4,5897	4,9987	4,9194	5,0346	4,3059
	Mean, % v/v	–0.0250	–0.0147	–0.0194	–0.0395	0.0190
	Root-mean-square, % v/v	2.0343	2.0644	2.0550	2.1302	2.04895
	Mean standardized	–0.0244	–0.0190	–0.0107	0.0132	–0.0310
	Root-mean-square standardized	1.0198	1.0041	0.9658	0.8105	1.1000
	Average standard error, % v/v	2.4412	2.4132	2.4765	2.8700	2.2864

Source: own study.

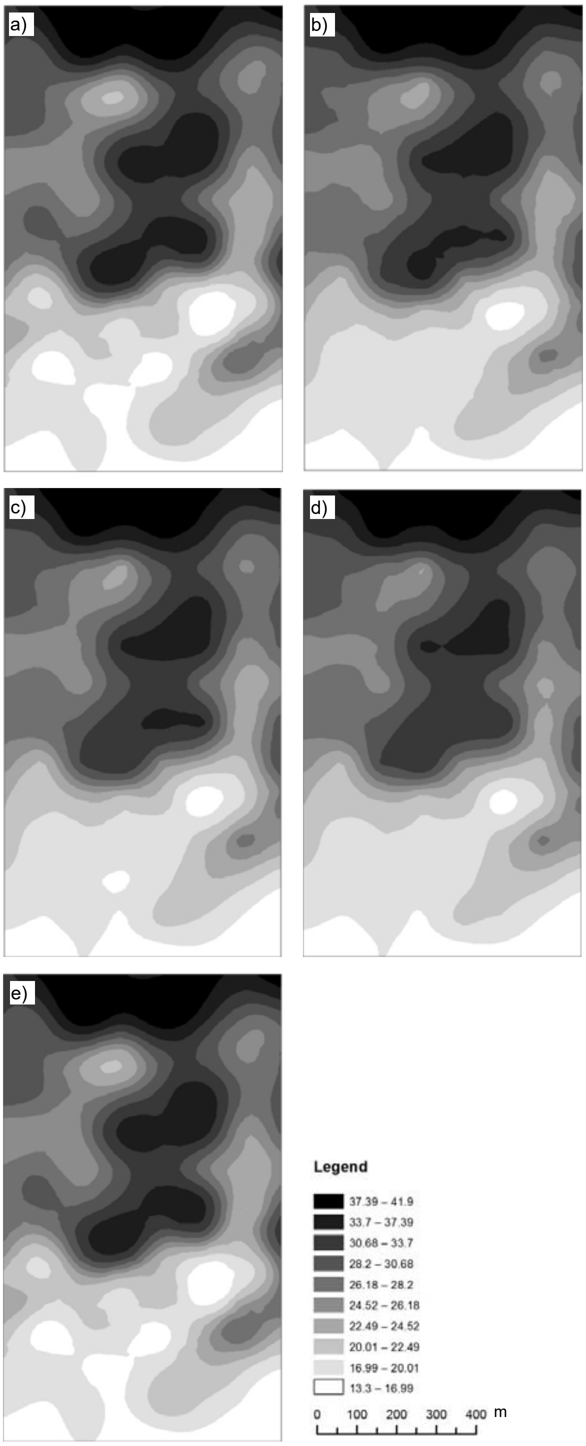

Fig. 4. Spatial distribution of soil moisture in the first series of tests generated by ordinary kriging on the basis of semivariogram models: a) stable, b) circular, c) spherical, d) exponential, e) Gaussian; source: own elaboration

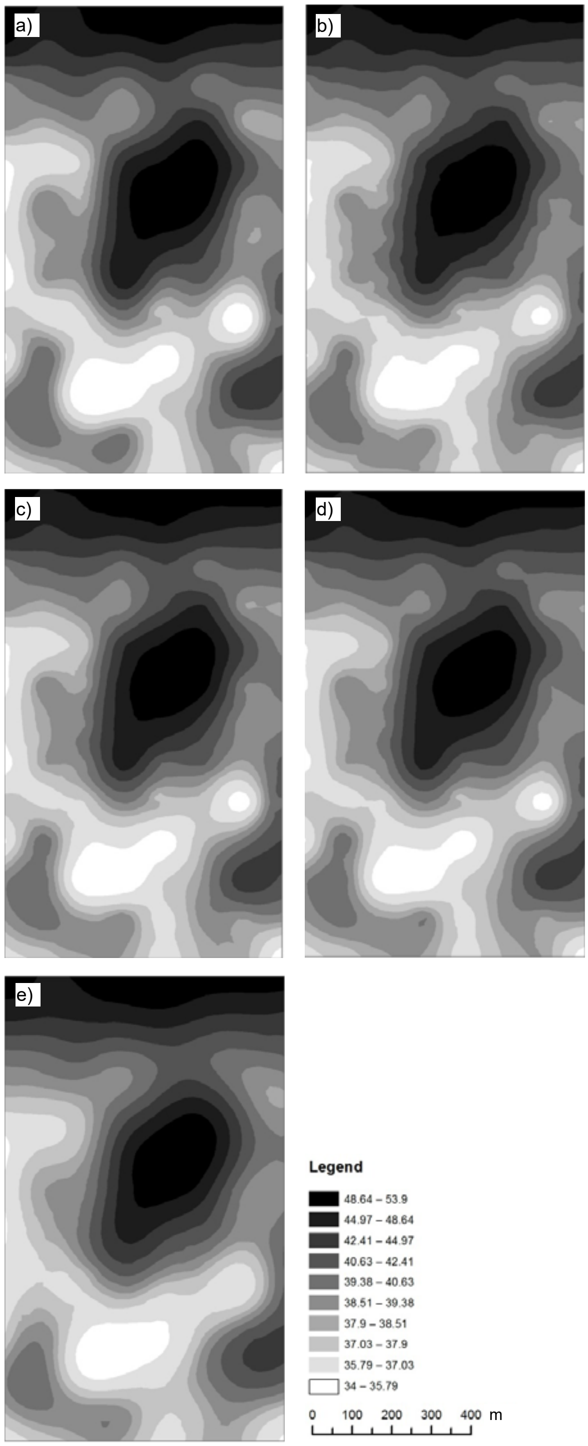

Fig. 5. Spatial distribution of soil moisture in the second series of tests generated by ordinary kriging on the basis of semivariogram models: a) stable, b) circular, c) spherical, d) exponential, e) Gaussian; source: own elaboration

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Dobór modelu semiwariogramu w badaniach przestrzennego rozkładu wilgotności gleby

STRESZCZENIE

W pracy zaprezentowano dobór modelu semiwariogramu w badaniach przestrzennej zmienności wilgotności gleby w lessowej zlewni rolniczej. Badania wilgotności gleb przeprowadzono na terenie wsi Moszenki, 15 km na północny zachód od Lublina. Pomiary wilgotności gleby przeprowadzono w dwóch terminach w 104 punktach, rozmieszczonych na powierzchni w kształcie prostokąta o wymiarach 700 × 1200 m. Punkty te wytyczono w narożnikach siatki kwadratów o bokach 100 m. Dodatkowo wykonano 6 pomiarów zlokalizowanych w odległości mniejszej niż 100 m od najbliższych punktów. Wilgotność mierzono w powierzchniowej warstwie gleby (0–5 cm). Do modelowania semiwariogramów wykorzystano program ArcGis z rozszerzeniem Geostatistical Analyst. W obu terminach do analiz wykorzystano pięć modeli semiwariogramów: stały, kołowy, sferyczny, wykładniczy, Gaussa. Do estymowania wartości wilgotności na analizowanym obszarze wykorzystano kryging zwyczajny. Spośród analizowanych modeli semiwariogramów największe błędy wyznaczonych wartości wilgotności gleby w stosunku do danych empirycznych zanotowano dla modelu wykładniczego, natomiast najmniejsze dla modelu Gaussa. Wykorzystanie krygingu zwykłego do interpolacji rozkładu przestrzennego wilgotności gleb daje dobre rezultaty, jednak na efekt końcowy rozkładu przestrzennego wpływ miał dobór modelu funkcji semiwariancji.

Słowa kluczowe: *geostatystyka, modelowanie semiwariogramu, semiwariogram, wariogram, wilgotność gleb*