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Spatial variability of soil moisture in grassland*

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Abstract. The paper evaluates spatial moisture variation in research sites in Poland - Pszczew (Wielkopolska Province), Pawłowice (Dolny Śląsk Province), and in Slovakia - Tatranska Kotlina. The sites are grassland. In each site, point-wise moisture measurements were conducted at 25 cm below the surface in seven squares of varied size. The sides of the squares (*D*) in each site were: 0.5, 1, 2, 4, 6, 10 and 25 m, and their location was random. Soil moisture measurements were carried out using a field moisture and salinity recorder, D-LOG/ms. Field works provided the data which was then analyzed by means of statistical procedures. They showed a linear relationship between moisture variance and the logarithm of the studied area. The analysis of classical dispersion measures and semivariograms demonstrated that moisture differentiation up to a certain point grows along with the increase in the area under study. The highest differentiation was observed in Pszczew and Tatranska Kotlina. High values of the calculated fractal dimensions point to high randomness in moisture distribution in surface soil. The work presents a tentative hypothesis on a linear relationship between moisture dispersion and dispersion of selected physical properties of soil. The hypothesis has not been verified so far.

Keywords: soil moisture, geostatistical methods, fractal analysis

INTRODUCTION

The knowledge of some soil parameters is indispensable for applying models prognosticating cultivated plant crops. For example, retention curves are manifest in 93% of such models, unsaturated and saturated water conductivity in 40 and 33%, respectively, and packing or porosity in 32% (Walczak *et al*., 1999). These parameters become input data for the Richards equation used in such models. With this equation, one can prognosticate air-water relationships in the root layer of soil (Reinhard, 1992). However, the literature has mentioned the fact that in soils considered homogeneous, the values of these parameters can be highly varied (Walczak and Usowicz, 1994; Warrick and Nielsen, 1980) as in the case of the boggy soil of the mineral-boggy subtype. Its filtration coefficient for an area of about 1 ha varied approximately from 200 to 1000 cm d^{-1}, while soil density ranged from 0.8 g cm^{-3} to slightly over 1 g cm^{-3}, confirming the rule that soil density undergoes the slightest changes, whilst the filtration coefficient – the largest (Brandyk *et al*., 1993; Słowińska-Jurkiewicz *et al*., 2001).

With animal-formed macropores, root atrophy, soil expansion and shrinkage, impermeable elements like stones or agromelioration treatments like loosening, soils once considered homogeneous may reveal remarkable differentiation of their physical properties (Bykowski *et al*., 2001; Walczak *et al*., 1998). Soil misidentification ensuing from such differentiation leads to inadequate solutions selected for prognosticating and adjusting air-water relations in a soil and, subsequently, to quite an inaccurate crop prognostication.

AIM AND ASSUMPTIONS

The study was designed to show how spatial variability of soil moisture corresponds to the size of the area for which this variability was calculated. To this aim, field works were conducted and appropriate statistical procedures were applied. The work also deals with the tentative and as yet unverified hypothesis on the linear nature of the relationship between spatial variability of selected soil physical properties and spatial variability of soil moisture. The hypothesis is

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*The experiment was conducted with students from Prof. S. Bac Students' Science Organization.

applicable to those areas which meet the following conditions:

- The water level should be the same at every point of the area (in the ground-water management type) or the water level is located so deeply that it has no effect on the moisture of the surface soil (the precipitation-water management type).
- The area is covered with similar vegetation.
- Weather conditions (precipitation, insolation, wind, temperature) are identical at every point of the area.
- The area is plain.

Meeting condition 1 means that the supply by capillary rise will be identical at every point of a given area and its impact on the moisture at every point of the area will be similar. Condition 2 ensures uniform evapotranspiration at every area point and, likewise, a uniform effect on the moisture of surface soil. Condition 3, when fulfilled, provides equal net precipitation at every point of the area uniformly affecting the moisture in surface soil across the area. Under condition 4, the runoff of rain water is held, and the precipitation influences moisture equally at every point of the area.

MATERIAL AND METHODS

The study was conducted in 2002 and 2003 in two localities in Poland-Pszczew (Wielkopolskie Province) and Pawłowice (Dolnośląskie Province), and in one in Slovakia - Tatranska Kotlina. Each area is grassland meeting the four conditions above. The soil in the experimental site in Pszczew was loamy sand, in Pawłowice – silty clay loam, and in Tatranska Kotlina – silt. In each site, pointwise moisture measurements were conducted at 25 cm below the surface in seven squares of varied size. The sides of the squares (*D*) in each site were: 0.5, 1, 2, 4, 6, 10 and 25 m, and their location was random. An exemplary location of squares in Pszczew is given in Fig. 1.

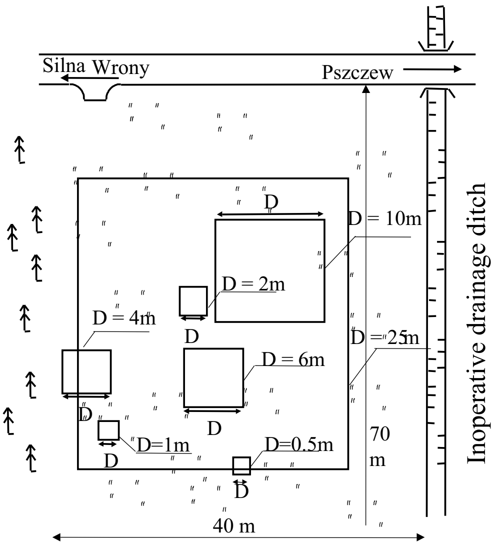


Fig. 1. Location of squares in Pszczew.

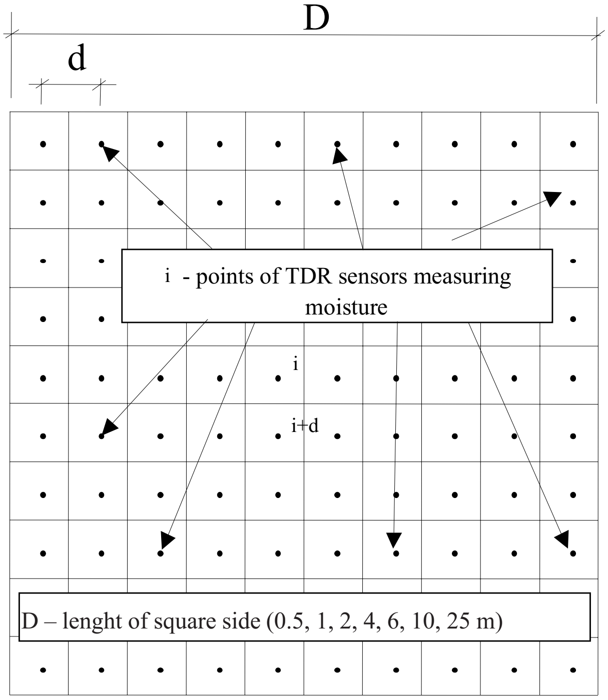


Fig. 2. Placement of TDR sensors in squares.

Soil moisture measurements were carried out using a field moisture and salinity recorder – D-LOG/ms (Malicki, 1990). TDR sensors were placed in each square in the same way, as shown in Fig. 2, and moisture measurements were taken at 100 points for each of the seven squares, and for each site. The application of the TDR technology allowed us to take the measurements for each square within 1.5 h and therefore to minimize daily changes in soil moisture following fluctuating weather conditions. In order to evaluate the spatial moisture variability, the analysis of the moisture data and histograms, classical statistical characteristics, the geostatistical methods and the fractal dimension theory were adopted and modified to the research purposes (Brandyk *et al.*, 1995; Mandelbrot, 1983; McBratney and Webster, 1986; Rieu and Sposito, 1991; Sławiński *et al.*, 2002; Usowicz, 1999; Usowicz and Rejman, 2000; Wajs, 2003). Classical statistical characteristics were calculated separately for each site and were considered in respect of the size of the analyzed surface, whereas variograms – functions $\gamma(d)$ – were calculated from the formula:

$$\gamma(d)=\frac{1}{2m(d)}\sum_{i=1}^{m(d)}\left(\theta_i-\theta_{i+d}\right)^2, \qquad (1)$$

where: $\gamma(d)$ – the variogram, $m(d)$ – the number of the compared pairs of moisture values at distance d, d – distance between the compared points, θ_i – the i-th value of moisture in a selected square, θ_{i+d} – the moisture value at distance d from point of moisture measurement θ_i.

The measurement points shown in Figs 1 and 2 allowed to calculate the function $\gamma(d)$ for d = 0.05, 0.1, 0.2, 0.4, 0.6, 1, 2.5, 5, 7.5 and 10 m by comparing each time 90 pairs of moisture values and using squares of sides equal to 0.05, 0.1, 0.2, 0.4, 0.6, 1, 2.5, 5, 7.5 and 10 m. Similarly, the function $\gamma(d)$ was also calculated for d = 15 m by comparing 80 pairs; for d = 20 m by comparing 40 pairs and for d = 22.5 m by comparing 20 pairs of moisture values from the square of side d = 25 m. With the variograms drawn, fractal dimensions were calculated for each of the three sites. A fractal dimension (D_{fr}) was obtained from the formula (Kossowski and Usowicz, 2000; Sokołowska, 1989; Usowicz, 1999):

$$D_{fr} = 2 - \frac{H}{2}, \tag{2}$$

where: H – the slope of the semivariogram straight line in the logarithmic coordinate system.

RESULTS AND DISCUSSION

Spatial variability of moisture

The measurements taken in the sites of Pszczew, Pawłowice and Tatranska Kotlina allowed to perform an analysis of spatial variability of soil moisture. To this aim, mean, mean deviation, variance, asymmetry, kurtosis and variability coefficient were applied (Table 1). Mean moisture values calculated for the three sites do not correspond significantly to the area size from which they were calculated. Mean deviation values, as well as those of variance and variability coefficient, grow alongside the increase in the analyzed surface, which fact implies that moisture dispersion growth is accompanied by an increase in the surfaces studied. For instance, moisture variance for Pszczew grows from 0.0022 $(m^3\ m^{-3})^2$ – square surface (F) = 0.25 m^2 to 0.0087 $(m^3m^{-3})^2$ – square surface (F) = 625 m^2, for Pawłowice from 0.004 to 0.020 $(m^3m^{-3})^2$ for Tatranska Kotlina from 0.0007 to 0.0060 $(m^3m^{-3})^2$. Simultaneously, comparing dispersion measures for identical squares in various sites, one can observe that the values of these measures vary. The most significant differentiation in moisture is in Pszczew, lower in Tatranska Kotlina, and the least in Pawłowice. The values of the asymmetry coefficient in Pszczew are slightly below 0 for almost all the squares, which fact points to minute left-sided asymmetry, whilst in Pawłowice and Tatranska Kotlina in the majority of cases assumes values above 0, which denotes right-sided asymmetry. The kurtosis values, positive and highest, are observed in Pawłowice (K_{max} = 31.3367 for square surface (F) = 0.25 m^2), which makes the moisture distribution for this site more slender than a normal distribution. In the other sites, the kurtosis values fall close to 0, being either negative or positive, which signifies

Table 1. Statistical parameters of soil moisture depending on the area size

Square surface F (m^2)	0.25	1	4	16	36	100	625
Length of square side D (m)	0.50	1	2	4	6	10	25
				Pszczew			
Mean ($m^3\ m^{-3}$)	0.64	0.60	0.58	0.54	0.60	0.66	0.63
Mean deviation ($m^3\ m^{-3}$) 10^{-2}	3.73	4.12	4.82	4.62	5.93	6.70	7.59
Variance $(m^3\ m^{-3})^2\ 10^{-2}$	0.22	0.32	0.33	0.34	0.51	0.66	0.87
Skewness	-0.64	-0.43	0.51	-0.70	-0.04	-0.36	-0.81
Kurtosis	0.89	1.76	-0.87	0.77	-0.61	-0.54	0.83
Variability coefficient (%)	7.30	9.30	9.90	10.80	11.80	12.30	14.80
				Pawłowice			
Mean ($m^3\ m^{-3}$)	0.35	0.34	0.30	0.32	0.29	0.29	0.32
Mean deviation ($m^3\ m^{-3}$) 10^{-2}	1.16	1.27	1.96	1.73	2.26	3.65	3.20
Variance $(m^3\ m^{-3})^2\ 10^{-2}$	0.04	0.05	0.09	0.10	0.08	0.22	0.20
Skewness	-3.11	-3.56	3.12	3.44	0.06	0.94	0.87
Kurtosis	16.02	31.34	19.95	17.61	-0.23	0.81	6.96
Variability coefficient (%)	5.90	6.60	10.10	9.90	9.60	15.80	13.80
				Tatranska Kotlina			
Mean ($m^3\ m^{-3}$)	0.32	0.27	0.27	0.22	0.2987	0.27	0.29
Mean deviation ($m^3\ m^{-3}$) 10^{-2}	2.26	4.09	4.59	4.21	4.83	5.00	6.45
Variance $(m^3\ m^{-3})^2\ 10^{-2}$	0.07	0.23	0.36	0.36	0.38	0.37	0.60
Skewness	-0.04	0.22	0.07	0.37	0.19	-0.33	0.47
Kurtosis	-0.62	-0.94	0.71	1.05	1.37	-0.42	0.26
Variability coefficient (%)	8.50	17.80	22.20	26.70	20.50	22.10	27.00

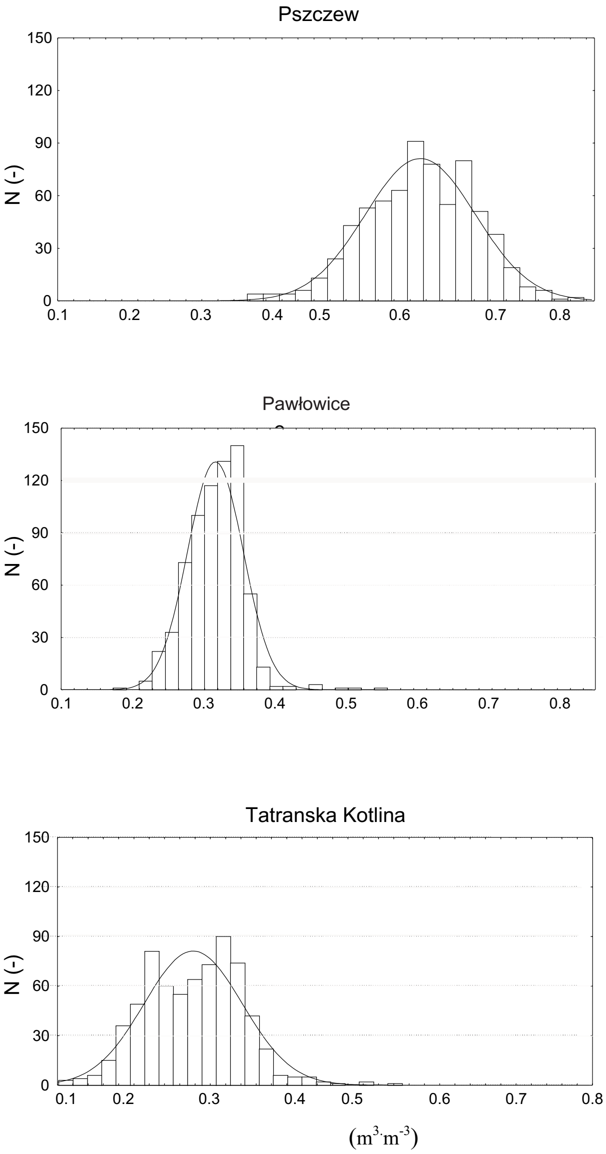


Fig. 3. Moisture histograms for all data from: Pszczew, Pawłowice, and Tatranska Kotlina sites. N – number of the measured soil moisture ($m^3 m^{-3}$) in selected ranges.

that the slenderness of moisture distribution in these sites is similar to a normal one. Figure 3 demonstrates histograms built on all the data available for the particular sites. The analysis of those histograms confirms the smallest differentiation of measurement data in Pawłowice.

The moisture variability in the sites was further estimated with the geostatistical methods, yet in order to apply them, the stationary condition had to be checked. To this aim, moisture trends determined individually for each square in the sites were analyzed. The direction coefficients of the trend line given in Table 2, take alternately both positive and negative values close to 0, which implies that the stationary condition was met. Figure 4 shows variograms calculated with the function $\gamma(d)$ (Eq. (1)). The values of the function $\gamma(d)$ were calculated for various distances between the points of the compared moisture pairs for d varying from 0.05 to 22.5 m, separately for each site. For each case, we chose the function $\gamma_m(d)$, best fitting the empirical data. Three models were analyzed – linear, spherical and exponential. Applying the smallest squares criterion, the spherical model proved to be the best one:

$$\gamma_m(0) = 0,$$

$$\gamma_m(d) = c_0 + c\left[1.5\frac{d}{a} - 0.5\left(\frac{d}{a}\right)^3\right] \quad \text{for } 0 < d \le a,$$

$$\gamma_m(d) = c_0 + c, \tag{3}$$

where: c_0 – the value of a nugget (the effect of a nugget), $c_0 + c$ – sill, a – the autocorrelation range (a distance over which semivariance becomes approximately a constant value), d – the distance between the compared points.

Table 3 gives the values of parameters c_0, $c + c_0$ and a read from the semivariograms in Fig. 4. The values of the effect of a nugget c_0 point to moisture diversification for distances between the compared points smaller than minimal distances which were used for calculating the semivariograms (d_{min} = 0.05 m). The smallest minimal differentiation was observed in Pawłowice, higher values –

Table 2. Direction coefficients of the trend line of surface moisture distribution calculated for perpendicular directions

D (m)	F (m^2)	Pszczew		Pawłowice		Tatranska Kotlina	
		A_x	A_y	A_x	A_y	A_x	A_y
0.5	0.25	0.0792	0.1293	-0.0642	0.0274	-0.0163	-0.0112
1	1	0.0331	0.0291	-0.0144	0.0018	0.0057	0.0260
2	4	0.0019	-0.0394	0.0007	0.0078	-0.0027	0.0074
4	16	0.0099	-0.0139	0.0029	0.0026	-0.0009	-0.0256
6	36	-0.0017	0.0199	0.0036	-0.0002	0.0029	0.0102
10	100	-0.0007	0.0139	0.0053	-0.0063	0.0023	0.0031
25	625	0.0068	0.0074	-0.0005	-0.0035	-0.0024	0.0049

A_x; A_y – direction coefficient of the trend line in perpendicular directions.

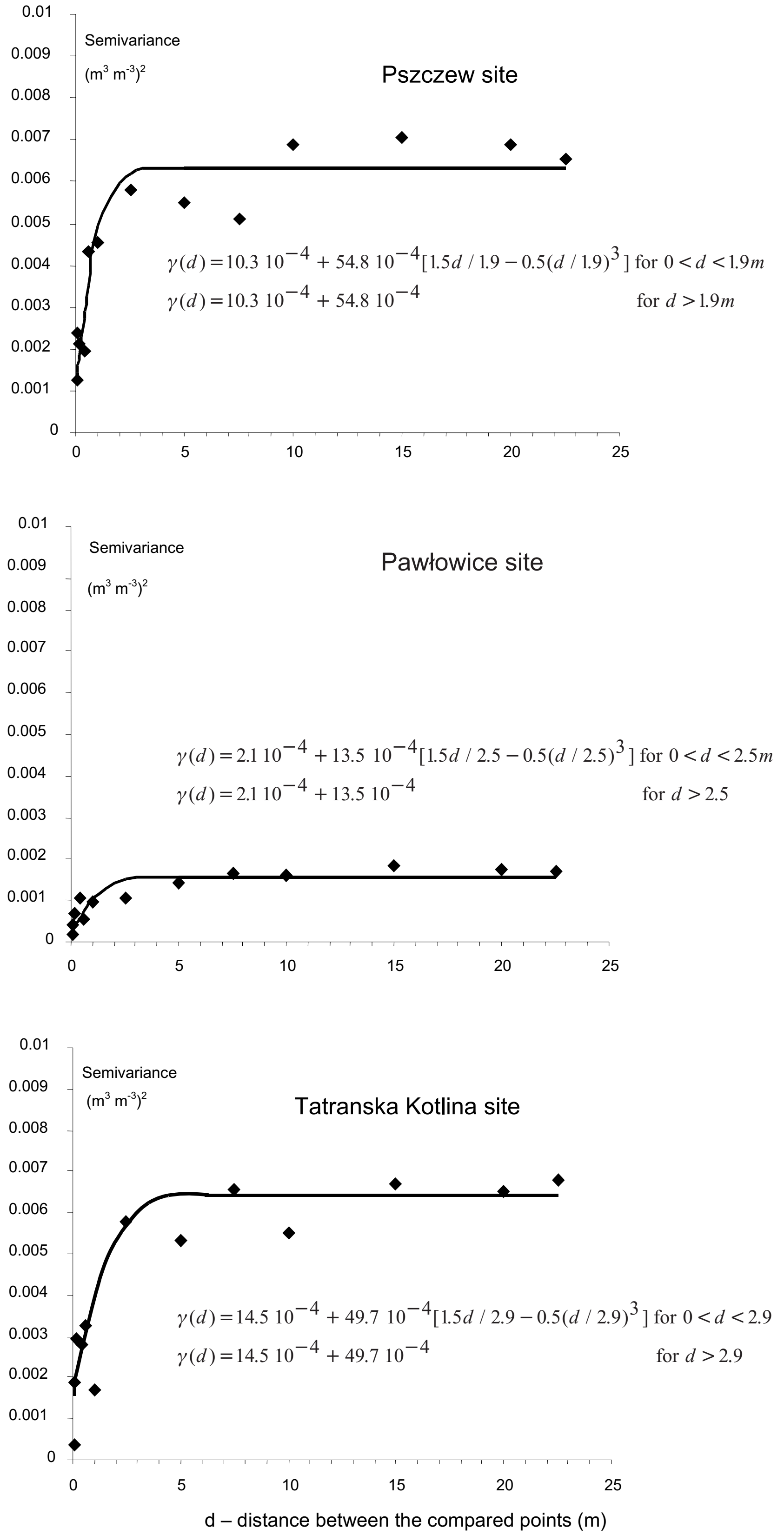
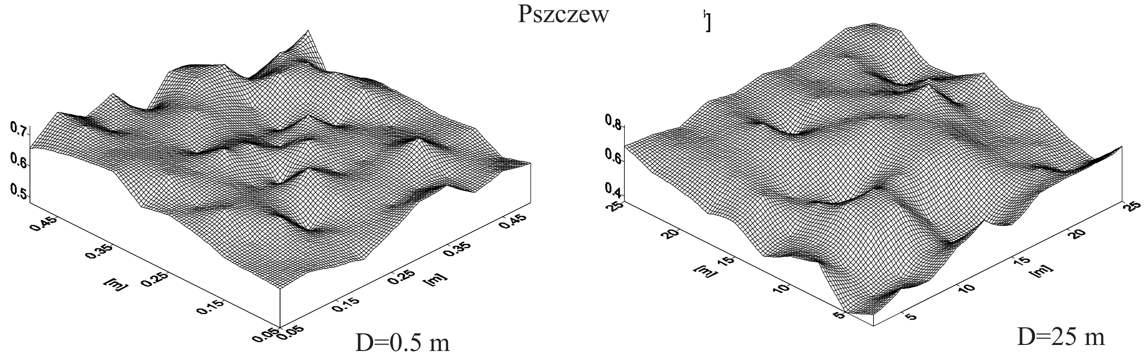


Fig. 4. Moisture variograms for: Pszczew, Pawłowice and Tatranska Kotlina sites.

T a b l e 3. Moisture semivariogram parameters for the sites in Pszczew, Pawłowice and Tatranska Kotlina

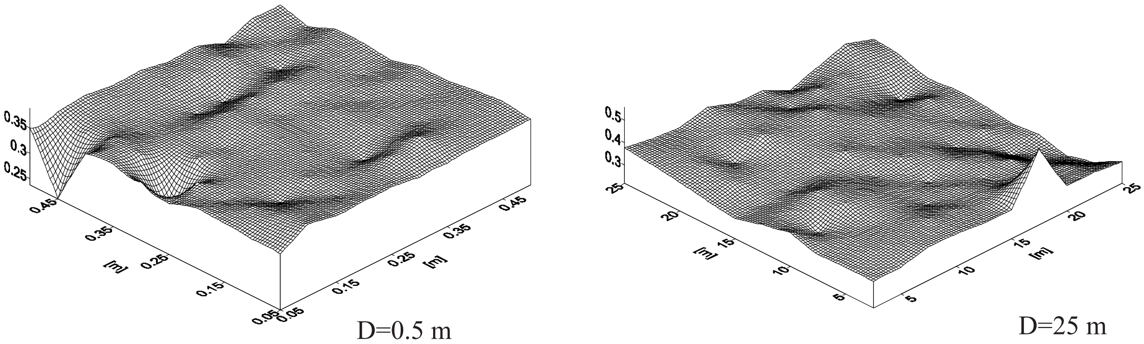
Parameter	Pszczew	Pawłowice	Tatranska Kotlina
nugget c_0 (m^3 m^{-3})^2	10.3 10^{-4}	2.1 10^{-4}	14.5 10^{-4}
sill $c + c_0$ (m^3 m^{-3})^2	65.1 10^{-4}	15.6 10^{-4}	64.2 10^{-4}
range a (m)	1.9	2.5	2.9

Pszczew



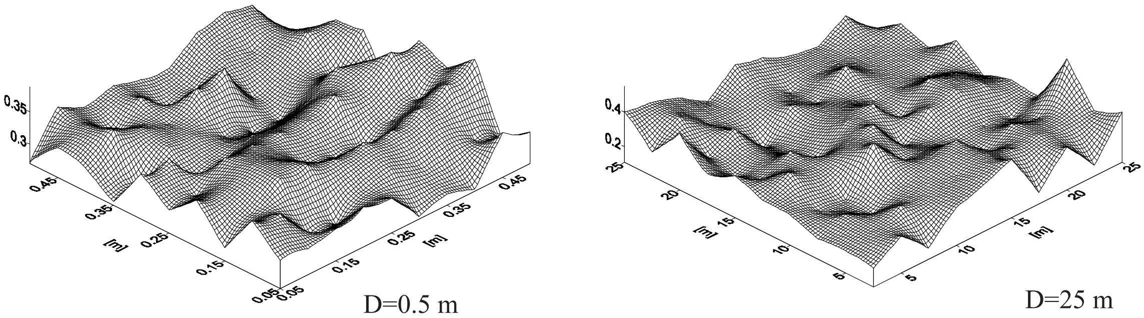
D=0.5 m D=25 m

Pawłowice



D=0.5 m D=25 m

Tatranska Kotlina



D=0.5 m D=25 m

Fig. 5. Maps of soil moisture estimated with the kriging method.

in the other places. The so-called sill $(c_0 + c)$ takes the lowest values in Pawłowice and much higher in the two other localities. These observations imply that the possible maximum moisture diversification is the lowest in Pawłowice and higher in Pszczew and Tatranska Kotlina. The last semivariogram parameter described is the autocorrelation range *a*. This value imposes a border distance, *d*, over which there occur changes in the values of the function $\gamma_m(d)$. It means that there exists such a border distance between the points that its exceeding does not significantly affect moisture variance. The autocorrelation range values (Table 3) are similar – from 1.9 to 2.9 m. For the sake of a better visual presentation of spatial variability of soil moisture, moisture maps were drawn for the largest and smallest squares in each site under study. The maps, made by means of the kriging method, are given in Fig. 5.

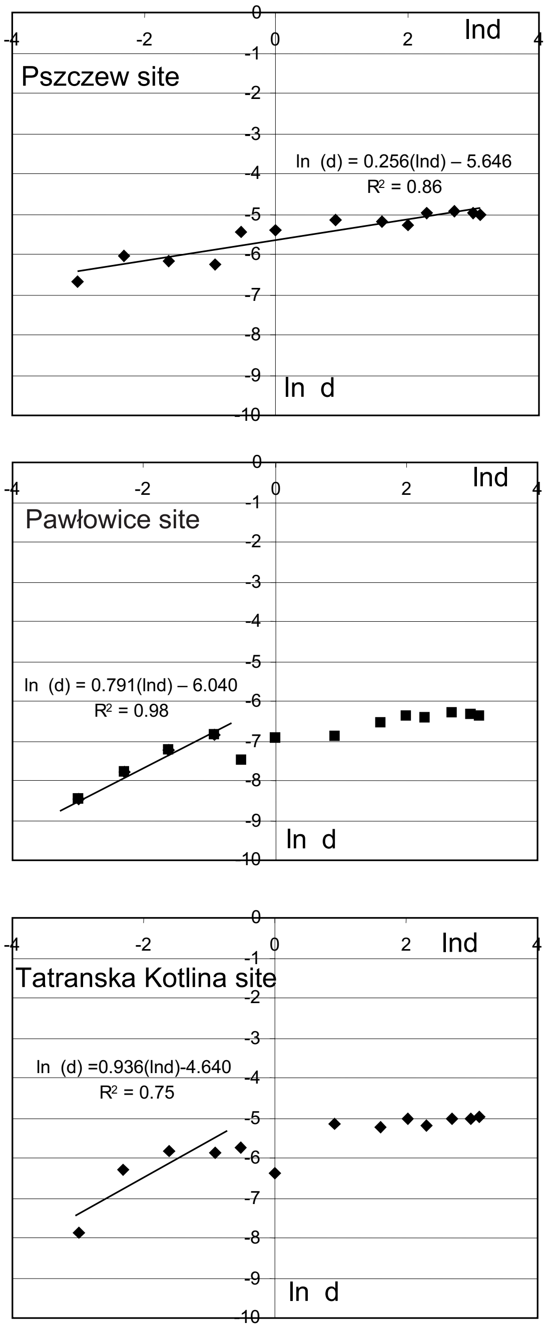


Fig. 6. Moisture variograms for: Pszczew, Pawłowice, and Tatranska Kotlina sites in the logarithmic coordinate system.

The moisture semivariograms for the three localities are also given in the logarithmic coordinate systems (Fig. 6). For these charts, straight lines of the variograms were drawn using all the points for Pszczew, and autocorrelation range points for the remaining places. With direction coefficients of these straight lines, we were able to calculate fractal dimensions for the three sites. Fractal dimensions (D_{fr}) were calculated using Eq. (2) and their values are as follows: for Pszczew – D_{fr} =1.87; for Pawłowice – D_{fr} = 1.64 and for Tatranska Kotlina – D_{fr} = 1.53. High values of fractal dimensions ($1<D_{fr}<2$ for linear ranges) testify to their highly random character in the moisture distribution in the sites studied.

In Figure 7, the average deviation (*P*), variance (S^2), and the variability coefficient (*Z*) in respect to the analyzed areas was given. Comparing these figures, as well as the respective determination coefficients (R^2), one can observe that moisture dispersion measures which are best described as linear regression are, in sequence, average deviation, variance and finally the variability coefficient *Z*.

The research conducted in Pszczew, Pawłowice and Tatranska Kotlina shows a proportional-linear relationship between the moisture variance and the logarithm of the sites studied. The relationship between the variance of soil physical properties and the logarithm of the examined area has not been empirically verified yet. However, numerous studies confirm that this relationship is linear (Brandyk *et al*., 1993; Peck, 1983). These two facts imply that for areas meeting the four conditions mentioned above, there exists a linear relationship between the dispersion of soil physical properties and moisture dispersion. At this stage of research, the hypothesis remains unverified.

CONCLUSIONS

1. The analysis of moisture maps drawn for those three sites and the analysis of the classical dispersion measures showed that moisture dispersion at a given depth increases proportionally to the logarithm of the site studied. This relationship was observed for each site, yet the highest moisture dispersion was to be seen in the Pszczew and Tatranska Kotlina sites and remarkably lower in the Pawłowice site.

2. In order to analyze moisture dispersion in respect of the distances of the comparison points, moisture semivariograms were used. It was shown that each site has a border distance between square points, whose exceeding does

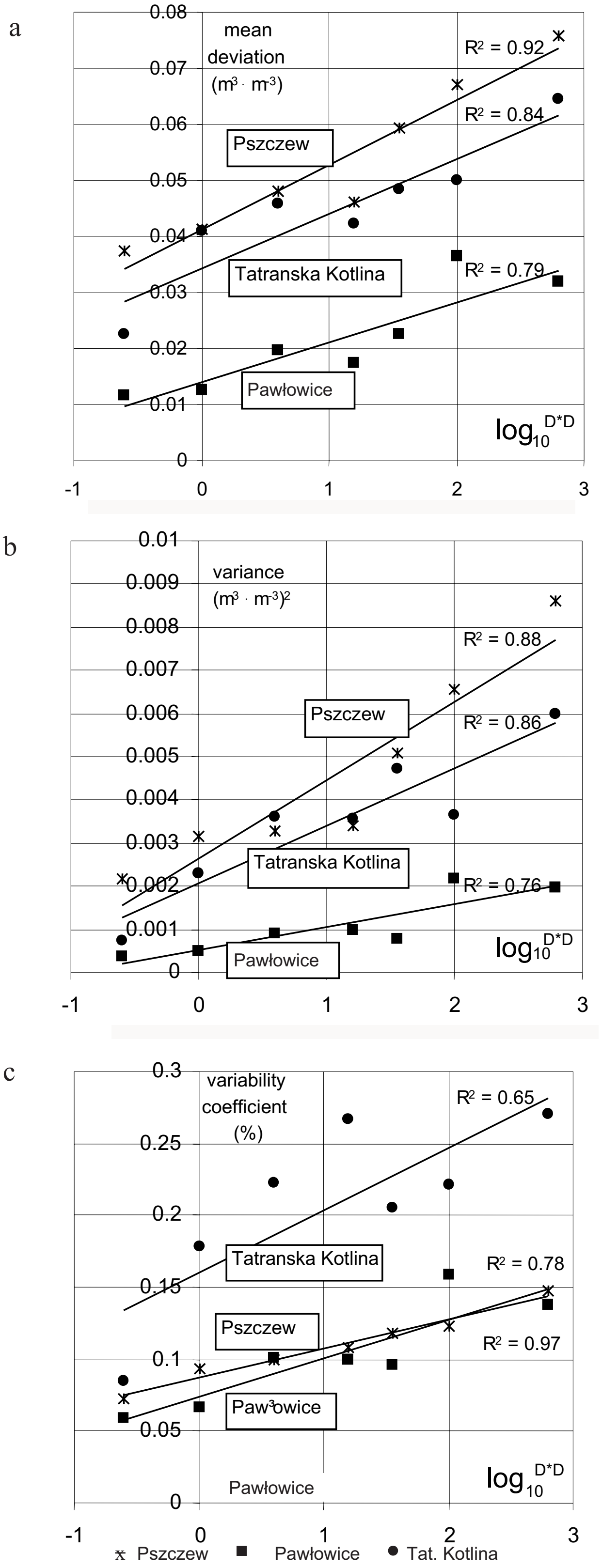


Fig. 7. Moisture mean deviation (a), moisture variance (b), variability coefficient (c) and the regression lines in respect of the logarithm of the sites under study in Pszczew, Pawłowice, and Tatranska Kotlina.

not bring significant changes in moisture dispersion. Autocorrelation range is the widest for the Tatranska Kotlina site and the narrowest for the Pszczew site.

3. The areas under study revealed high randomness in moisture dispersion, which is best visible in high values of fractal dimensions (the highest in Pszczew).

4. The unverified hypothesis on a linear relationship between moisture dispersion and dispersion of soil physical properties was presented.

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