GEOSTATISTICAL MODELING OF WATER INFILTRATION IN URBAN SOILS

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Abstract: The post-communist period (after 1989) caused important changes within the urban space of Iaşi municipality. The partial dismantling of the industrial zone, the urban sprawl against the periurban and rural areas, the new infrastructure works (water and sewage network) led to significant changes in soil morphology and physical properties, including in the infiltration rate (IR). The objectives of this study are: 1) to analyze the spatial variability of IR in urban soils of Iaşi municipality; 2) to identify correlations between IR and some auxiliary physical properties; 3) to choose the optimal geostatistical model, which will accurately estimate the IR in locations with no measurements, enabling the best version of cartographic representation. Technosols are characterized by high spatial variability of infiltration rate, when compared to other soils. Their physical properties differ from one location to another, even in the same landforms, fact that is also confirmed by a high coefficient of variation of IR (82.6%). There is no direct correlation between the IR and the auxiliary properties, and thus the co-kriging method will not useful here. Due to the high values of skewness, we have transformed the original data and used the lognormal ordinary kriging. A comparison between the predicted IR values for the unmodified grid with the measured values do not reveal significant differences, having obtained N/S=0.1798 and R^2=0.5184. The elimination of the maximum values of IR or their replacement with some interpolated values for similar conditions of soil and relief are not desirable tasks. Their consideration will lead to high values of the mean square error (MSE) and low goodness of prediction (G).

Keywords: infiltration rate, statistical analysis, soil properties, urban soils

1. INTRODUCTION

Decreasing the infiltration rate (IR) in urban area will increase the volume of drained water, will increase the risk of flooding and will reduce the groundwater recharge within watersheds (Gregory et al., 2006). Knowing the IR in urban soils within Iaşi town has an economic importance, mainly due to the increasing the surface of the human covered soils and the rise of heavy rains that also increase the flooding risk (e.g. 2010, particularly in some sectors of the Bahlui River floodplains).

The scientific approaches referring to the water infiltration in soils usually aim at identifying the infiltration rate in different environmental conditions (Kroulik et al., 2007; Miyata et al., 2010; Neris et al., 2012) and analyzing the influence of soil physical properties on the associated hydrological processes (Doerr & Moody, 2004; Govindaraju et al., 2012).

Most scientific studies focused on analyzing the natural soil changes in urban environment and landscape (Burghardt, 1994), evaluating the chemical characteristics of urban soils exposed to pollution (Mass et al., 2010), assessing the human induced compaction of soils (Glinski & Lipiec, 1990).

Many and various studies show that the soil properties are heterogeneous and heavily modified by human activities (Hagan et al., 2012). Water infiltration within the urban soils has different values from a place to another, being determined by the variability of soil surface properties (Wright & Carter, 2010).

The spatial representation of data raises questions for selecting the best interpolation method. In the scientific literature there are three interpolation methods: statistical (e.g. regression tree and multiple regressions), geostatistical (e.g.

ordinary kriging and universal kriging) and hybrid (e.g. co-kriging and regression kriging) (Zhu & Lin 2010). Inverse Distance Weight (IDW), ordinary kriging (OK) and co-kriging methods are the most frequently used methods.

The optimal method for soil properties mapping is based on analyzing the relationship between the statistical accuracy of data and the suitability of the interpolation technique (Kravchenko & Bullock, 1999).

The skewness coefficient is a measure of asymmetry for a probability distribution. The higher the coefficient is in the absolute value, the more asymmetric is the corresponding distribution. For a high absolute value of the skewness coefficient, the normality requirement of the distribution is more unlikely. In such cases, one should transform the data or use lognormal kriging (Robinson & Metternicht, 2006). In our case, an increase in the skewness can be driven by high values of IR, which are determined by changes in soil's properties, either on its surface or in the whole width of its profile. The optimal solution is to transform the original data and to change the original distribution in a relatively symmetrical one. The kriging is applied on the transformed data and then we proceed to transform back into the original scale of measurement (Goovaerts et al., 2010; Yamamoto 2010).

Comparing kriging with IDW, Kravchenko & Bullock (1999) showed that the kriging with an optimal number of neighboring points and a carefully chosen model of the variogram provides more precise estimation than IDW.

The purpose of this study is to: (i) describe the variability of water infiltration in urban soils; (ii) emphasize the relationship between the auxiliary physical properties and IR; (iii) choose the optimal geostatistical model to accurately estimate the IR in points without measurements.

1. MATERIAL AND METHODS

2.1. Study area and soil sampling

Iaşi municipality, located in the north-eastern Romania, developed in a hilly area, with altitudes ranging from 35.2 m in the Bahlui River floodplain up to 196 m on interfluves (Fig. 1).

For the spatial analysis of IR in urban soils of Iaşi, we set up a standard grid (750 m x750 m) and we obtained 69 points in which we made the field and laboratory measurements. Because the urban soil compaction is common at soil surface, the sampling with metallic cylinders was done for 0-10 cm depth to determine the soil moisture. Additional

soil samples were collected from the top 25 cm for the soil texture analysis.
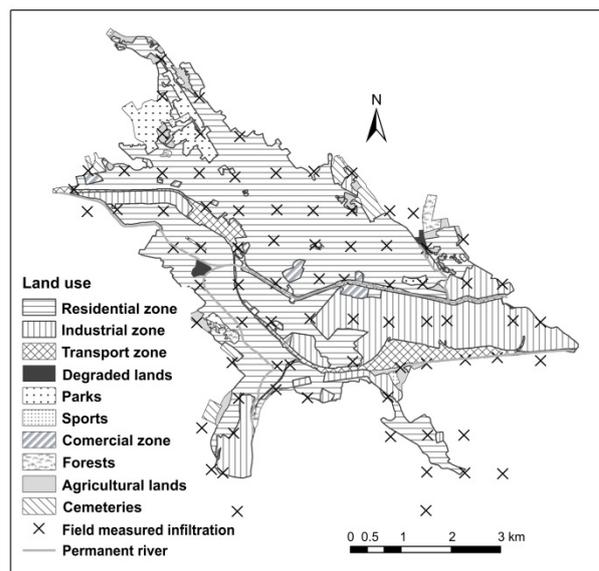

Figure 1. Land use in Iasi municipality and points of field measured infiltration

For the research region, with an area of 33.3 km^2, we mapped the soil cover and we classified it according with the WRB (2014). Thus, there have been identified 5 soil references: Technosols, Regosols, Fluvisols and Chernozems, which occupy the largest area (Fig. 2), followed by small areas with Gleyosols and Anthrosol (Secu, 2011).
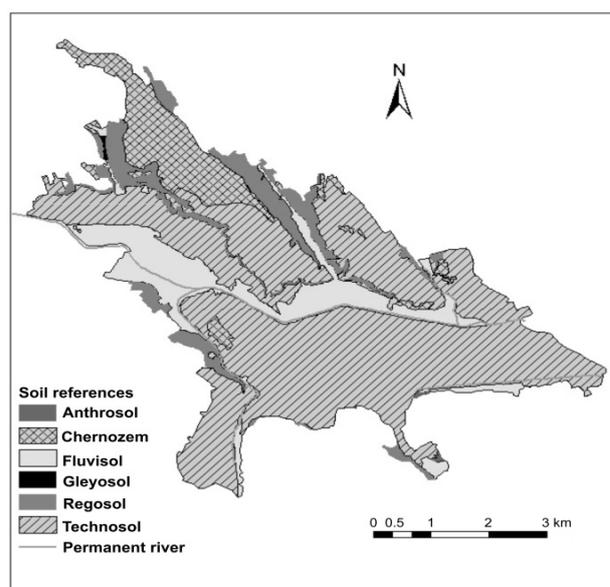

Figure 2. Urban soil maps of Iasi municipality

2.2. Field measurements and laboratory determinations

The initial and the final infiltration rate (mm/h) for urban soils were measured using the

Turf-tech infiltrometer that has double rings (the diameter of inner ring is 6.03 cm and the one of the outer ring is 10.79 cm). This device has smaller dimensions than the classic double ring infiltrometer and enable better site variability to be determined than if one larger unit was used (Pitt et al., 1999).

The Penetration Resistance (PR) was determined using the Eijkelkamp penetrolloger with conical head having an area of one cm^2 and angle of 60°, which allow obtaining a graphical representation of penetration resistance (MPa) in relation to the soil depth (80 cm maximum depth).

For each plot, we made two measurements, the results being obtained through averaging for first 25 cm. The soil resistance increases consistently together with the soil moisture diminishing (Grunwald et al., 2001). Therefore, the measurements were made three days after any common rainfall, when the soil is close to the field capacity. The field activities were conducted between the second half of April and the first half of June (2011-2012), during days with average temperatures of 18-25^{0}C.

Water content is expressed as ratio of the mass of sample water content (ring 100 cm^3) before drying to the mass of the sample after it has been dried (8 hours) to a constant mass at 105^{0}C (Topp & Ferré, 2002). The volumetric moisture content (VMC) and soil moisture deficit (SMD) has been determined for the first five cm of soil with ThetaProbe with MP2x sensor, calibrated for each type of soil, before each measurement of IR.

The gravimetric water content is more used than the volumetric one because it is influenced by bulk density (BD), directly correlated with PR (Vaz, et al., 2011). Soil porosity was calculated after measurement the volume of the soil particles with the air pycnometer according to Lang method (Eijkelkamp), using sampling ring and then we calculated particle density and bulk density (Table 1). Urban soils may contain inclusions therefore we preferred analyzing each sample instead using an average value (2.65 g/cm^3). To determine the soil texture, we sampled soils (500-1000 g) and fractions of clay, silt and sand were determined by pipetting method the results being interpreted according to the particle size classes, accepted by WRB (2014).

The data were statistically processed in Statistica (State Soft) and Matlab. The spatialization was realized using the Geostatistical Analyst module of Arc Gis that allows applying the kriging technique for IR. Later we used the cross validation to compare the results obtained for standard grid (750 x 750m) with those resulted from direct measurements within the modified grid. Analyzing the point distribution on the two grids shows that 22 points spatially overlap. The results were interpreted in relation to the land use, in detail mapped according to the Corine Land Cover methodology (Bossard et al., 2000).

Table 1. Description of the points sampling

Functional zones	Zone	No. of samples	Estimated soil age (year)*	Vegetation	Total porosity (%)	Bulk density (g/cm^3)	Penetration resistance (MPa)
Residential zones (Technosols)	I	29	>50	Herbaceous and ornamental trees	45[a]±6.9[b]	1.33[a]±0.15[b]	2.53 [a]±0.71[b]
Industrial zones/ Transportation zones (along roads)	II	8	5-50	Herbaceous	43.7±5.1[b]	1.4±0.11[b]	2.62±0.75[b]
Degraded lands	III	7	<5	Ruderal vegetation or without vegetation	46.4±10.5[b]	1.17±0.26[b]	2.4±0.42[b]
Recreational zones (parks, botanical gardens, sports and commercial areas)	IV	17	5-50	Herbaceous, shrubs and ornamental trees	45.2±7.4[b]	1.25±0.13[b]	2.31±0.72[b]
Forests	V	6	>50	Nemoral forests	40.16±1.4[b]	1.31±0.07[b]	2.5±0.61[b]
Heterogeneous agricultural lands and other lands (e.g. cemeteries)	VI	2	>50	Cultivated vegetation	54±7.0[b]	1.12±0.15[b]	1.93±0.24[b]

Note: [a] average, [b] standard deviation, * <5 years, recent soils (mixic, copertic), 5-50 years, middle aged soils (the industrialization phase of Iaşi municipality), >50 years, old soils.

3. RESULTS AND DISCUSSION

3.1. Variability of water infiltration rate in urban soils

The field experiment, although carried out after 2-3 days after the rainfall, proves that the field capacity of the soil at the surface is different from a soil to another (e.g. Chernozems and Technosols) even at similar values of total porosity. Other factors contributing to changes in soil moisture in urban areas are the partial removal of topsoil during development and construction, and the changes in soil structure resulting from the use of heavy machinery (Marsalek et al., 2007). As a consequence of structure destruction, it can be notices the PR increasing and higher variation coefficient of IR for Technosols than for Chernozemss (Table 2).

At local scale, the water infiltration experiments prove that the settlement of sedimentary layer significantly reduces water infiltration (Lassabatere et al., 2010), this situation being observed also by us for Fluvisols within Bahlui River floodplain. The water infiltration in soils is influenced by the silty clay texture of Fluvisols (56% clay in A horizon), and silty clay loam for Chernozems (29.5-34.9% clay in A horizon). The Technosols have a variable texture to the surface, from sandy clay loam (25.5% Independence Park) to sandy clay (34-36% in the industrial area), but IR can be influenced by the presence of soil inclusions and also due to number of evaluated soil samples.

The general variation curve of water IR in soils indicates a downward trend from the first timeframe (1 minute) with high values that range between 5000 and 60 mm/h, diminishing gradually to the 5-10 minutes timeframe (1000-30 mm/h) and finally, alleviating for higher temporal values (within the range of 50-60 minutes, the infiltration rate varies between 142 and 4 mm/h).

Anthrosols within Iasi urban area have the highest value of the initial IR (more than 1650 mm/h), showing their heterogeneous character (Fig. 3). The

accumulation of organic waste in the city earlier periods of evolution led to the formation of a terric horizon (WRB, 2014), with intense activity of the fauna, that creates anomalies for the initial IR. At the present, the anthrosols are found only in restricted areas, where the soil has been used for gardening.

The subunitary values for BD are not typical for the area that we have studied. One of the samples contained fragments of coal and wood from a former warehouse of fuel. In these particular situations, the initial values of IR may increase. For example, the excavation of clay materials for locating pipelines in the meadow of river Bahlui has changed the structure and the porosity of the soil in its upper part, and thus reducing IR. In contrast to them, the Chernozems are characterized by much lower initial values of IR (less than 1250 mm/h), due to the conservation of the physical property of soils (structure and porosity), consequence of evolution in natural condition under forest vegetation. The final rates of IR vary from 47 to 54 mm/h, except the Regosols, which have the lowest values (less than 25 mm/h), because the limited time of pedogenetical evolution.
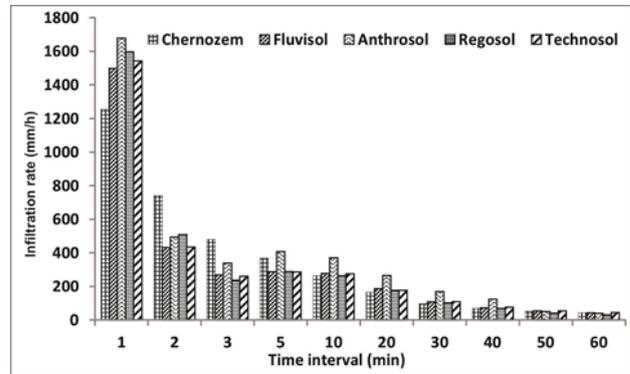

Figure 3. IR in soils of Iaşi municipality

3.2. Data structure and choice of the representation method

The coefficient of variation (CV) was calculated in relation with the physical properties of each soil type identified and described within the urban area.

Table 2. Mean values (μ), standard deviation (σ) and coefficient of variation (CV) for soil types in urban soils (real values)

Soils parameters		Infiltration Rate (mm/h)			Soil Moisture Deficit (SMD) (mm)			Volumetric moisture content (VMC) (% vol.)			Total Porosity (%)			Penetration Resistance (MPa)		
		μ	σ	CV	μ	σ	CV	μ	σ	CV	μ	σ	CV	μ	σ	CV
References (WRB, 2014)	Technosols(a)	54.3	44.9	82.6	7.39	2.61	35.3	22.3	5.74	25.7	45.8	7.16	15.6	2.52	0.55	21.8
	Regosols (b)	25.4	6.56	25.8	6.5	3.4	52.3	25.4	6.56	25.8	43.8	4.25	9.7	2.91	0.72	24.7
	Fluvisols (c)	47.7	18	26.4	8,25	2,83	34,3	21.2	5.52	26	43	6.77	15.7	2.38	0.56	23.5
	Chernozems (d)	51.9	13.8	26.5	4.85	2.94	60.6	29.2	6.92	21.5	45.1	8.09	17.9	1.87	0.67	35.8
	Anthrosols (e)	*	*	*	6.5	0.5	7.6	25.6	1.05	25.8	45	4	8.8	2.24	0.13	5.8
Urban soils		56.3	45.6	80.9	7.18	2.88	40.1	23.2	6.29	27.1	45	6.98	15.4	2.46	0.63	25.6

Note: Number of samples for each soil type: (a)=41, (b)=7, (c)=12, (d)=7, (e)=2, * not calculated

The high variability of soil properties is reflected in high values of CV (Utset et al., 2000) and the Technosols with CV of 82.6 % indicates an internal variability higher than other soils (CV 25%). Reduced coefficients of variations (36.5%) were determined by Ersahin (2003) for relatively close values of IR on well drained alluvial field. The high coefficients of variation for Technosols were explained through the different internal characteristics of soils from one point to another. For example, the excavation of clay materials for locating pipelines in the Bahlui flood plain has changed the structure and the porosity of the soil in its upper part, and thus reducing IR.

IR varies greatly even in relatively homogeneous landforms. In the Bahlui floodplain, IR values range between 36.1 and 110 mm/h. Distance between the sampling points was modified because of the characteristics of urban environment (presence of boulevards, spaces occupied by commercial units, parking, housing spaces etc.). Relatively homogenous soils (Chernozems) are generally characterized by low CV of the internal properties, except the moisture deficit and penetration resistance that have high values.

Overall, the urban soils are characterized by lower CV for other physical indicators comparing to IR. The bulk density is one of the least variable soil properties compared with the other physical characteristics (Warrick & Nielsen 1980). Therefore, in Iaşi, BD takes values in the range between 0.84 and 1.71 g/cm^3. The subunitary values for BD are not typical for the area that we have studied. One of the samples contained fragments of coal and wood from a former warehouse of fuel. In these particular situations, the initial values of IR may increase.

For the three data sets (Table 3), the distribution was verified based on skewness and kurtosis, emphasizing a higher frequency of IR low values than the high ones. This situation reflects the pedestrian traffic on the urban soils. The negative values of skewness for the surface were related to human activities (Ngailo & Vieira 2012), but we appreciate that the positive values may have the same explanation for urban soils.

For the geostatistical interpretation, we used a data set in three ways: (i) water infiltration and other soil properties resulting from field and laboratory analysis using the grid corrected according to landscape characteristics; (ii) the extreme infiltration values were removed (5 points with > 150 mm h^{-1}), (iii) the maximum values infiltration were manually replaced with values obtained by averaging two points with close characteristics of terrain and soil, as they result by overlapping points on Digital Elevation Model (DEM).

Changing the data string by removing peaks or by introducing data interpolated based on terrain and soil factors will reduce the skewness and kurtosis. High distribution of skewness values indicate that the ordinary kriging (OK) is not viable (Delbari et al., 2011), because data distribution in urban soils record both extremely low and extremely high values. By eliminating peaks for 5 points (Table 4), skewness and kurtosis decrease to normal values. The same trend is observed equally by replacing the maximum values with the manually interpolated points.

The maximum values are determined by the important changes of soil physical properties. Two points with infiltration values over 210 mm h^{-1} are adjacent to points with values in the range 50-80 mm/h.

Table 3. Results of the statistical analysis for the studied parameters.

Variables	Infiltration Rate – measured values*				Infiltration Rate – values without maximum**				Infiltration Rate – maximum values manually modified according to DEM and soil map**			
	max	min	sk	kt	max	min	sk	kt	max	min	sk	kt
Infiltration Rate (measured values) (mm/h)	221.4	4.5	2.15	4.9	110	4.5	0.14	-0.12	110	4.5	0.03	-0.12
Soil Moisture Deficit (mm)	14	1	-0.2	-0.51	14	1	-0.19	-0.6	14	1	-0.19	-0.6
Gravimetric Moisture Content (%)	40.6	9.1	0.40	-0.11	40.6	9.1	0.44	-0.19	40	9.1	0.44	-0.19
Total Porosity (%)	66	32	0.84	0	66	32	0.51	-0.12	66	32	0.51	-0.12
Penetration Resistance (MPa)	4.57	0.9	0.36	0.94	4.5	0.9	0.32	0.76	4.5	0.9	0.32	0.76
Bulk Density (g/cm^3)	1.7	0.84	-0.11	0.74	1.7	0.84	-0.17	0.73	0.84	1.7	-0.17	0.73

Note: *For 69 values; **For 64 values

Table 4. Skewness, R^2, N/S, sill and range for the three types of datasets

	Method	Skewness		Excess Kurtosis		Extremes (for log(Z_i))		R^2 (for variogram)	N/S	sill	range
		Z_i	log(Z_i)	Z_i	log(Z_i)	Min	Max				
IR (measured values)	LOK	2.1564	-0.619	4.944	0.664	1.5041	5.4000	0.5184	0.1798	0.7026	1332.9
IR (values without maximum)	OK	0.1646	-1.246	-0.120	0.845	4.5000	110.10	0.6017	0.1878	538.4188	1275.4
	LOK					1.5041	4.7014	0.5020	0.226	0.5303	1057.1
IR (values with maximum manually replaced)	OK	0.0304	-1.351	-0.117	1.147	4.5000	110.10	0.6330	0.2011	515.0093	1190.3
	LOK					1.5041	4.7014	0.4962	0.2352	0.5058	1015.2

The accuracy of soil physical properties mapping depends highly on the spatial structure of the data. Soil data sets with strong and medium spatial structure can be mapped with relative accuracy even with a small number of samples (Stafford & Werner, 2003) and urban space imposes restrictions for field measurements.

The spatial structure of data can be characterized through the geostatistical method, namely the variogram. The nugget over sill (N/S) ratio indicates the spatial structure of data and Cabardella et al., (1994) defined three classes (strong spatial structure ≤ 25%, moderate 25-75% and low ≥75%), while Kravchenko (2003) mentioned values from 0.1 to 0.6, values obtained by us (Table 4).

The spherical model is probably the most widely used (Pandey & Pandey 2010) and it indicates the spatial continuity if the construction of variogram provides high nugget or high nugget over sill (Schloeder et al., 2001).

If the skewness coefficient is above 1, then the logarithmic transformation of data (Robinson & Metternicht, 2006) and the Lognormal Ordinary Kriging (LOK) should be used as alternative for the Ordinary Kriging (OK). The backward transformation of data causes errors (Kravchenko & Bullock, 1999) that can be reduced using the exponential function with the formula:

$$\hat{Y}(x_i) = \exp[\hat{y}(x_i) + \frac{1}{2}\sigma^2(x_i) - \lambda_i] \quad (1)$$

where:
- $\hat{Y}(x_i)$ are the back-transformation of the lognormal estimates for infiltration
- $\hat{y}(x_i)$ are the lognormal kriging estimates
- $\sigma^2(x_i)$ are the kriging variances
- λ_i are the Lagrange multipliers

We have found no evidence of statistically significant autocorrelation in the observed data for IR, therefore we may assume isotropy with respect to the infiltration rate. Variograms for the three types of data: a) measured; b) measured without maximum values; c). measured for manually interpolated data, were performed for the spherical model (Fig. 4). The best N/S ratio for IR based on field measurements was obtained using Lognormal Ordinary Kriging, while removing or replacing maximum values generates a weak spatial structure.

3.3. Spatial relation between the infiltration rate and the auxiliary soil properties

Infiltration was used as target variable while other physical properties represent auxiliary variables that allow investigating the effect of the spatial structure. Usually, for each property, the values of any neighboring points will be closer than those situated at two points distance (Pandey & Pandey, 2010), but this situation is valid only in small measure for urban soils.

IR is expected to have high values for industrial and residential areas with soils heavily modified by human actions and to be lower for the moderately modified land (agricultural lands, parks). Soils covered by forests have higher values of IR than those anthropogenically modified due to the high level of permeability that is determined by the activity of invertebrates (earth worms) or other types of fauna (Schmidt & Michael, 2004).

The low correlation between IR and other physical properties is attributed to the high variability of urban soil properties from one place to another. For agricultural soils with hardpan layer (plow layer) Ersahin (2003) indicates negative correlation between moisture and infiltration, while in urban soils this feature is associated with compacted soils in the area of green spaces, which were subsequently covered. Richard et al., (2001) highlight a number of correlations between IR and the BD for the

agriculturally used soils, but we did not identify a clear correlation for urban soils, since IR has higher variability than BD. The lack of clear correlation between the auxiliary properties (VMC, SMD, BD, PR, and Clay) and IR cannot explain the spatial variability of IR and does not allow to apply the co-Kriging (Table 5).
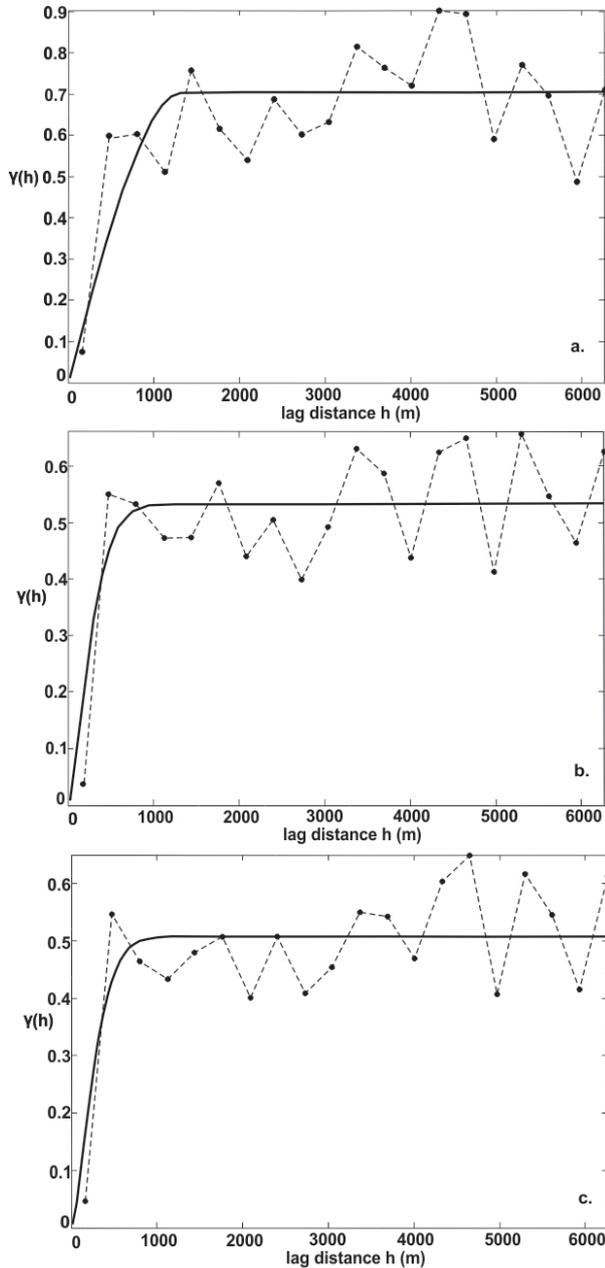

Figure 4. Lognormal variograms for IR: a. measured; b. measured without maximum values; c. measured for manually interpolated data.

Data accuracy was evaluated based on two criteria: mean square error (MSE) and goodness of prediction (G). For G, Kravchenko (2003) uses the formula:

$$G = (1 - MSE / MSEavg) \times 100 \quad (2)$$

where: MSEavg is the average of mean square errors calculated based on the field determinations, MSE is the mean square errors obtained based on estimations.

Table 5. Correlation matrix between IR and auxiliary properties*

Correlation	Regression coefficient (slope)	Std error of regression coefficient	Covariance	R^2
IR-VMC	0.04	0.41	4.8	0.0003
IR-SMD	0.2	0.9	1.2	0.0001
IR-BD	-7.1	16.1	-0.8	0.0111
IR-PR	0.6	4.1	-2.1	0.0054
IR-Clay	0.8	1.0	-22.5	0.0043

Note: *for 69 values

If G has negative or close to zero values, it means that the average field values predict IR for the location without samples with higher accuracy than those estimated on grid (Kravchenko, 2003). In this study, G is 91% indicating a high accuracy of predicted values to the detriment of the average field values. Out of the three models (LOK, OK and IDW) applied for the standard grid (750 x 750 m) LOK is the best one, being also verified through G. For our study, MSE values and G show that LOK is the best way to represent continuous data (Table 6).

Table 6. Mean square error (MSE), Mean absolute error (MAE), sums of square (SQ) and goodness of prediction (G %)*

Property	MSE	MAE	SQ	G (%)
RI field	2088	28.55	144070	-
RI-LOK for 750x750m grid	169.81	12.34	11707	91.87
RI-OK for 750x750m grid based on measured values	383.06	14.08	26431	81.65
RI-IDW	1381.3	22.38	95307	33.85
RI-OK based on values without maximum	833.2	24.4	54158	60.10
RI interpolated values for the same relief and soil conditions	1291	29.5	89079	38.17

* the values of MSE, MAE, SQ and G was statistically processed in Matlab

Graphic representation of the IR values for each 3 models show us that the map obtained using LOK model is closer to the values measured in the field (Fig. 5).
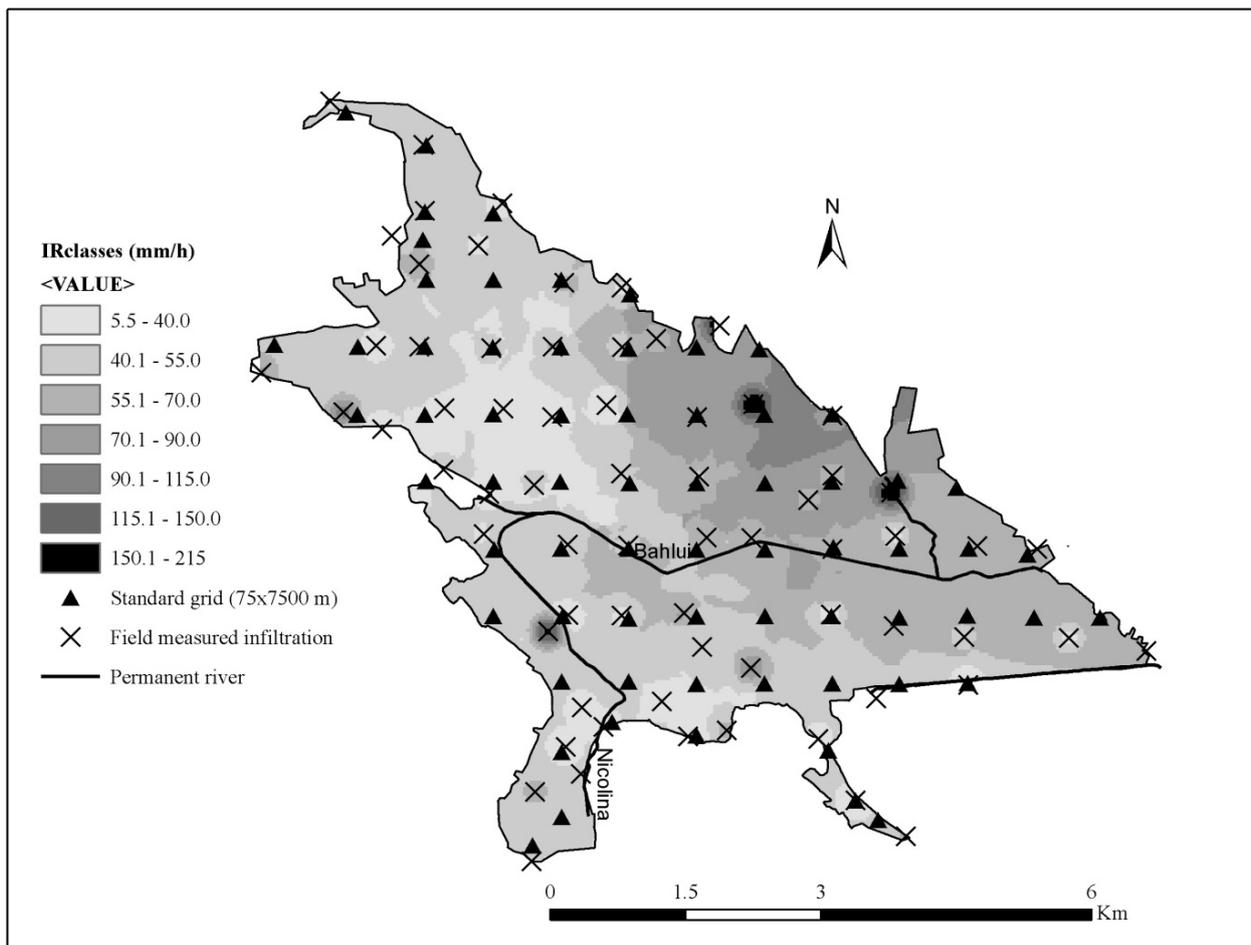
Figure 5. IR in the urban soils of Iasi after lognormal transformation

4. CONCLUSIONS

In the urban soils within Iasi municipality, IR is characterized by high spatial variability, driven primarily by human influence on soils, by the functional areas and to a lesser extent by the soil texture. This is reflected in the high CV for Technosols and normal CV for the other soils.

IR varies greatly even in relatively homogeneous landforms (e.g. Bahlui floodplain) dominated by Fluvisols, but for different land use (e.g industrial and residential areas).

In urban areas there can be measured very high IR values which are normally characteristic for sandy soils. This can be explained by the presence of inclusions and cracks in the soil profile (residential and industrial areas) with higher frequency at depths greater than 20 cm, identified in soil profiles and ditches for the urban utilities. In some points of the residential area, the initial IR is high and then decreases sharply, because of a covering layer of natural soil material used as green space. The initial soil behaves like the plow layer specific to the agricultural land use.

The high value of skewness for IR imposed logarithmic transformation of data and use of LOK. Removing the maximum values from the dataset or replacing them with data manually interpolated for the same features of relief and soil is not a good solution, which is confirmed by the G values. For the continuous data representation at the points where no measurements exist, the spherical model based on LOK allows obtaining the best values of G, compared with the results of OK and IDW.

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