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MUNICIPAL WASTE IN POLAND: ANALYSIS OF THE SPATIAL DIMENSIONS OF DETERMINANTS USING GEOGRAPHICALLY WEIGHTED REGRESSION

Abstract. This article provides a quantification of the territorially varied relation between socio-economic factors and the amount of municipal waste in Polish districts. For this purpose, eight causes were identified: revenue budgets, the number and area of uncontrolled dumping sites, population density, the share of working-age population, average gross monthly wages, registrations for permanent residence, and the number of tourists accommodated. The preliminary data analysis indicated that to understand waste generation in Poland at the local level it is necessary to consider regional specificity and spatial interactions. To increase the explained variability of phenomena, and emphasise local differences in the amount of waste, geographically weighted regression was applied.
Key words: municipal waste, Polish districts, regional heterogeneity and spatial interactions, socio-economic factors, geographically weighted regression.

1. INTRODUCTION

The identification of the key factors affecting the amount of municipal waste[1], waste prevention, and eco-innovation is becoming one of the most significant challenges for contemporary science dedicated to the paradigm of smart, sustainable, inclusive growth, and to the decoupling theory in the context of waste management. The decoupling theory proposes that fewer resources be used and less waste per unit of economic activity be generated, and suggests the possi-

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[1] Municipal waste includes waste generated by households (excluding end-of-life vehicles and hazardous waste) and waste from other generators that, due to its nature or composition, is similar to household waste (European Commission, 2008).

bility of de-linking economic growth from resource use through resource efficiency; that is, 'doing more with less' (European Commission, 2008; Jaligot and Chenal, 2018; United Nations Environment Programme, 2011). Municipal waste management (MWM)[2] is one of the most urgent environmental issues which Poland faces. According to the 2022 National Waste Management Plan, Poland lacks a waste monitoring system, including a comprehensive waste database, and a sufficient number of installations for the recovery and disposal of waste other than landfills (landfills remain the most common MWM method used in the country) (Council of Ministers, 2016). Moreover, rapid adaptive amendments to EU regulations have resulted in an applicable 'litter law' unaccompanied by a tight, coherent, rational and effective management model in Poland. MWM, including installations for waste collection and treatment, is very fragmented, since the tasks associated with it are the responsibility of local districts and communes (municipalities). This change, introduced in 2013, made municipalities the owners of municipal solid waste generated in their jurisdiction, and held them responsible for waste collection and treatment. Several private companies collect residential and commercial waste, often in parallel within the same commune, and dispose of it at several facilities (Koszewska, 2016; the Organisation for Economic Co-Operation and Development, 2015). Waste quantities are defined by weighing delivery vehicles at landfills, and sorting or composting facilities. Such a system generates uncertainty about the accuracy of the waste data collected (as noted by den Boer *et al.*, 2010), as well as notable problems with identifying the factors underlying waste generation and the range of their regional impact on waste.

As a result, studies intended to identify the factors determining the amount of municipal waste in Poland have been rather scarce and mainly theoretical. An example of an empirical analysis was Tałałaj's (2011) study, which assessed the influence of selected factors on changes in waste generation across the districts of the Podlaskie Voivodeship. Another study employed a multi-criteria analysis, which could be helpful in planning waste management procedures in European cities or regions with a variety of waste disposal methods (Generowicz *et al.*, 2011). Cheba's (2014) study forecast changes in municipal waste generation in Polish cities by considering the impact of various factors. Kukuła (2016) applied a multidimensional comparative analysis to describe the diverse conditions impacting the municipal waste economy in Poland. Klojzy-Karczmarczyk and Makoudi (2017) analysed the waste generation rates in urban and rural areas, estimating the causes of the differences in the municipal waste generation rate between Poland and other European countries.

[2] Municipal waste management involves waste generation, collection, treatment, transport, disposal and trade processes (European Commission, 2008).

However, the majority of the contemporary literature regarding MWM neglects the possible impact of spatial processes (spatial autocorrelation,[3] spatial non-stationarity[4] and spatial heterogeneity[5]) on the quantity and quality of collected waste, see Bach *et al*., (2004), Hockett *et al*. (1995), Hage and Söderholm (2008), Khan *et al.* (2016), Schultz *et al.* (1995), and Sterner and Bartelings (1999). Nevertheless, the influence of particular characteristics may vary according to geographical location at the national, regional or local levels. The analyses dealing with spatial variation in municipal waste data have been rather limited to date, vide Antczak (2014), Hung *et al*. (2007), Ioannou *et al*. (2010), Ismaila *et al*. (2015), Keser *et al.* (2010), Keser (2012), Rybova *et al.* (2018), and Rybova (2019). In general, the results obtained in these studies indicated that the quantity of waste is positively correlated with population projections, population density, national economy entities, the size of a district, urban population, the number of people in working age, tourist numbers, and the number of people working in construction and industry. However, household size, gender ratio, migration, average household size, employment in agriculture, infant mortality rate and the revenue and expenditures of local budgets have not been found to be positively correlated with the quantity of waste; that is, they have a negative, or no, influence on the quantity of municipal waste.

This paper contributes to the existing literature by identifying the regionally divergent relation between selected socio-economic determinants and the amount of municipal waste in Poland. Local-level data for 379 districts from 2008–2016 was used. That analysis was extended further by examining the spatial aspects of the relation. It was found that the amount of municipal waste in Polish districts was spatially dependent (the volume of garbage in one district was correlated with the quantity of waste in another district). That ascertainment indicated that geographical differences could be considered when investigating empirical relations between selected factors and waste generation. In other words, the evidence of the spatial non-stationarity and spatial autocorrelation of waste at the aggregate level warrants the application of a geographically weighted regression (GWR) for

[3] Spatial autocorrelation measures the correlation of a variable with itself through space; that is, it indicates the degree to which a set of spatial features and their associated data values tend to be clustered together (positive spatial autocorrelation) or dispersed (negative spatial autocorrelation) in space (Anselin, 2010).

[4] Spatial non-stationarity is a condition associated with spatial variability in which varying economic conditions, natural resource endowments and other geographical-area measures can lead to a situation in which the relationships between dependent and independent variables are not constant over a space, varying along the spatial context (Brunsdon *et al*., 1996).

[5] The uneven distribution of a trait, event or relationship across a region (Brunsdon *et al*., 1996). Spatial heterogeneity can also be modelled through spatial panel data models (Ertur and Le Gallo, 2008). However, panel data analysis utilising geography focuses primarily on treating geography as an 'agent' for dependence among cross-sectional observations, whereas spatial heterogeneity is very much determined by distance (Fotheringham *et al*., 2002; Lu *et al*., 2018).

the dataset. GWR can evaluate the spatial processes of waste production, as per to its determinants. This territorial disaggregation shows how the causes of waste generation differ (are not spatially stable) across districts and identifies the determinants of the growth in waste quantity. This approach represents a new way of analysing municipal waste production in Poland; that is, such an analysis has not been performed previously.

2. MUNICIPAL WASTE IN POLAND. PRELIMINARY DATA ANALYSIS

2.1. Regional disparities and spatial heterogeneity in the quantity of waste

Poland is divided into three regional classification levels (NUTS, Nomenclature of Territorial Units for Statistics) and two levels of local administrative units (LAU-1 and LAU-2). As of 1 January 2016, there are six regions (NUTS-1), containing 16 provinces (NUTS-2), also known as voivodeships, and 72 subregions (NUTS-3), containing 379 districts (NUTS-4, LAU-1) and 2478 communes (NUTS-5, LAU-2). The average area of a LAU-1 district is 825 sq. km, which approximates to 0.3% of the total area of Poland. At the district level, residents generated an average of 209 kg of municipal waste per capita in 2008. In 2016, more than half of the districts (53%) were characterised by a municipal waste quantity higher than the country's average of 208 kg per capita (Fig. 1). In the European Union as a whole (EU-28), the amount of municipal waste generated per person amounted to 500 kg on average in the years 2008–2016. With an average of below 310 kg per person, Poland has the lowest amount of municipal waste generated in that time span. However, the quantities of collected waste are actually greater than statistically reported, with the missing tonnage usually being dumped illegally in forests. The main factors behind such behaviour are low ecological awareness and low effectiveness of the waste management system. These hypotheses have been confirmed by studies conducted by the Ministry of the Environment (2017).

In 2016, noticeably more waste was generated by the residents of cities (characterised by a higher development level), and inhabitants of north-western Poland (a wealthier area of Poland, especially attractive to tourists), north-eastern Poland and the Silesian Voivodeship (an area in the south of Poland characterised by high population density and strong urban and industrial centres). In general, changes in the quantity of collected municipal waste showed a downward spatial trend towards the east of Poland and an increasingly notable upward trend in the north-western direction, from 2008 to 2016 (Fig. 1, Table 1).

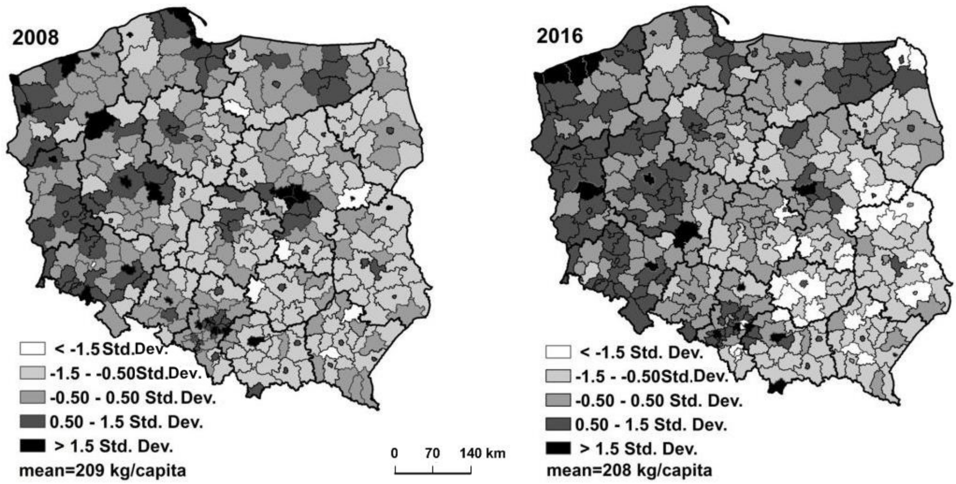

Fig. 1. Standard deviations in the quantity of municipal waste (kg per capita) in the years 2008 and 2016, n = 379

Source: own work based on Statistics Poland data.

Table 1. Correlation between municipal waste and geographical direction (coordinates)

	Coor.	**2008**	**2009**	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**
Correlation coefficients: waste amount and geographical coordinates										
NUTS-2	X	-0.73***	-0.81***	-0.77***	-0.82***	-0.83***	-0.81***	-0.77***	-0.78***	-0.77***
	Y	0.42	0.34	0.31	0.37	0.36	0.42	0.43*	0.52**	0.48**
NUTS-3	X	-0.48***	-0.56***	-0.53***	-0.57***	-0.59***	-0.60***	-0.60***	-0.61***	-0.61***
	Y	0.19	0.15	0.12	0.17	0.16	0.22**	0.24**	0.30***	0.29***
NUTS-4	X	-0.36***	-0.40***	-0.39***	-0.40***	-0.43***	-0.49***	-0.49***	-0.51***	-0.49***
	Y	0.09	0.11	0.13*	0.12**	0.11**	0.17***	0.20***	0.24***	0.24***
NUTS-5	X	-0.39***	-0.39***	-0.32***	-0.36***	-0.42***	-0.45***	-0.32***	-0.31**	-0.25**
	Y	0.11	0.19	0.18	0.33**	0.29**	0.23*	0.10	0.25**	0.26**

Source: own work.

From a regional perspective, the level of LAU-1 is characterised by large distortions in the amounts of waste generated per capita and provides the most significant territorial variation in the quantity of waste (Fig. 2).

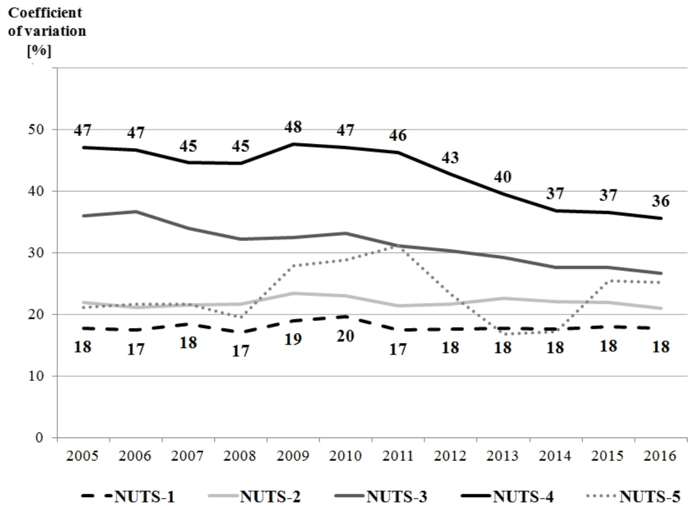

Fig. 2. Regional heterogeneity in municipal waste at different administrative levels (coefficients of variation)

Source: own work based on Statistics Poland data.

2.2. Spatial interactions in the volume of municipal waste

In the 2008–2016 period, an average of 61% of the collected waste in Poland was disposed of at landfills (compared to 35% in EU-28), with a low level of thermal processing and energy recovery (4.8% in Poland compared to 23.2% in EU-28), or export to places technologically prepared to recycle it (the rate of materially-recycled municipal waste was 12.8% in Poland compared to 25.3% in EU-28). In fact, in 2016, only seven municipal waste-to-energy incineration plants operated in the country, while there were over 450 such facilities in Europe at that time. In 2014, only 300 entities were generally involved in municipal waste management in Poland. Those included associations and companies handling the collection and transport of municipal waste, and networks running or building waste processing facilities that were able to process only 33% of the total collected municipal waste (Kołsut, 2016). In such a situation, the trans-boundary shipment of waste has been, and remains, popular in Poland; that is, its export, import or transit over short or long distances (Cyranka *et al.*, 2016). This movement of waste can result in spatial interactions – the volume of garbage in one unit may be correlated with the waste quantity in another unit. However, the ranges of operation of facilities can exceed commune boundaries, and this fact, coupled with the number of waste treatment installations available (necessary for the collection of accurate waste statistics), gave rise to the need to aggregate the data at a higher level. Hence, the district level was utilised.

To examine the extent of the spatial interactions in the quantity of municipal waste at the LAU-1 level, the global Moran's I statistic[6] was applied (Table 2). To explore the intensity of spatial interactions, several fixed-distance spatial weights matrices (**W**) were used (Table 2). Each **W** was a quantification of the spatial relationships that existed among features in a dataset or was at least a quantification of the way one conceptualised those relationships (Getis and Aldstadt, 2004). Each fixed-distance matrix represented a distance cut-off as a step function, with a value of 1 for neighbours with $d_{ij < \delta}$, and a value of 0 for the rest, where d_{ij} is the distance between observations i and j, and δ is the bandwidth. In that case, **W** was defined as a row-standardised binary matrix ($n \times n$), with non-zero diagonal elements, in which each element in the -th row was divided by the row's sum. The elements of the row-standardised matrix took values between 0 and 1, and the sum of the row values was always 1.

In all years of the analysed period, and for all distances, the quantity of waste was characterised by positive spatial autocorrelation; in spatial terms, this finding meant the clustering of units with similar amounts of the variable. The significant spatial dependencies increased over time and decreased with distance (Table 2). However, the distance extended to 150 km, which confirmed the findings of Kołsut's study regarding the distances between the bodies involved in processing and collecting waste in Poland (Kolsut, 2016). A remarkable increase in the distances for waste transportation to disposal facilities was also observed (Pasiecznik *et al.*, 2017; Zemanek *et al.*, 2011).

Table 2. Spatial autocorrelation of municipal waste measured by Moran's I statistic, using distance **W** matrices for the time span 2008–2016

	Fixed distance (bandwidth) in kilometres					
Ws	30	60	90	120	150	190
2008	0.33***	0.19***	0.12***	0.07**	0.02*	0.01
2009	0.37***	0.23***	0.13***	0.08**	0.02*	0.01
2010	0.37***	0.21***	0.13***	0.08**	0.02*	0.008
2011	0.35***	0.21***	0.14***	0.08***	0.03*	0.02
2012	0.39***	0.26***	0.18***	0.10**	0.04*	0.02
2013	0.46***	0.35***	0.25***	0.18**	0.05*	0.02
2014	0.49***	0.36***	0.26***	0.20***	0.07*	0.006
2015	0.48***	0.33***	0.25***	0.21***	0.11**	0.03*
2016	0.45***	0.30***	0.23***	0.19***	0.10**	0.02*

Note: significance level α = 0.10*, 0.05**, 0.01***.
Source: own work.

[6] Moran's I is a commonly used measure for testing the presence of global spatial relationships (Moran, 1950).

2.3. Potential causes of waste generation in Poland

Many variables can be possible determinants of waste generation in Polish districts. Taking into account the availability and comparability of data and those variables defined in literature, this paper suggests the following eight factors: district revenues in Polish zloty per capita (*R*); uncontrolled dumping sites per 100 sq. km (*UDS*); total area of uncontrolled dumping sites per 100 sq. km (*AUDS*); population density (*PD*); share of the population at working age as a percentage of the total population (*PWA*); average gross monthly wages and salaries in PLN (*GW*); registrations for permanent residence per 10,000 people (*PRP*); and tourists accommodated per 1,000 capita (*T*). The data was collected from the Local Data Bank of Statistics Poland. Table 3 displays the summary statistics for these variables.

Table 3. Summary statistics (mean values, 2008–2016) of the potential determinants of waste generation

	PWA	GW	UDS	AUDS	R	RPR	T	PD
Mean	63.6	3,162.8	1.9	213.8	3,294.1	768.6	1,731.2	378.4
Max	71.0	7,170.2	453.4	6,458.0	8,505.6	21,886.0	55,553.0	4,084.1
Min	57.8	1,992.5	0.0	0	2,000.1	63.0	0.0	0.0
Standard deviation	1.6	558.7	13.0	1,847	834.5	1,328.3	4,621.9	674.9
Coefficient of variation in %	2.5	17.7	680.5	864	25.3	172.8	267.0	178.4
Skewness	0.1	1.6	23.9	23	1.7	8.8	5.9	2.4
Range	13.2	5,177.7	453.4	64,580	6,505.5	21,823.0	55,553.0	4,084.1
Kurtosis	3.1	9.0	648	1,287	7.6	113.4	45.1	8.4

Note: $n = 379$, $t = 9$, $N = 3411$.
Source: own work.

Most of the variables had large relative variability. All variable distributions were right-skewed. The values of all the potential determinants were visibly focused around their means, demonstrating leptokurtic distributions. These shortcomings indicated a strong temporal variability in the data, resulting in two research questions: firstly, whether lag times in changes in the variables impact waste quantity; and secondly, whether spatial interactions can account for the differences in municipal waste at the LAU-1 level? Based on ANOVA, a significant correlated lag time between changes in the socio-economic factors impacting waste volume was confirmed, and significant differences in correlation strength were identified.[7] To capture all temporal influences, the dependent variable used in this study was the per-capita municipal waste generation in 2016. The explanatory variables were population density in 2014, share of the population at working age in 2014, average wages and salaries in 2016, number of uncontrolled dumping sites in 2010 and the area of uncontrolled dumping sites in 2010, district revenues in PLN per capita in 2016, the number of registrations for permanent residence per 10,000 people in 2016, and the number of tourists accommodated per 1000 of the population in 2016.

3. METHODOLOGY

The conventional approach to the empirical analysis of spatial data is to build a global model that assumes homogeneous (stationary) cross-spatial relationships between dependent and independent variables. Doing so means that the same stimulus provokes the same response in all parts of the studied region. The regression equation can be expressed as:

$$y_i = \beta_0 + \sum \beta_k x_{ik} + \varepsilon_i \tag{1}$$

Where y_i is the dependent variable at location i, x_{ik} is the k-th independent variable at location i, β_{i0} is the intercept for location i, β_{ik} is the local regression coefficient for the k-th independent variable at location I and ε_i is the random error at location i.

However, in practice, the relationships between variables might be non-stationary and may vary geographically (Matthews and Yang, 2016). GWR is a non-stationary technique that models spatially varying relationships (over space). Compared to the basic (global) regression (Eq. 1), the coefficients in GWR are functions of spatial location. Thus, the coefficient β_k takes different values for each location. This method generates a separate regression equation for each location. Fotheringham *et al.* (1998, 2002) presented the general form of a basic GWR model as:

$$y_i = \beta_0(u_i, v_i) + \sum \beta_k(u_i, v_i) x_{ik} + \varepsilon_i \tag{2}$$

where (u_i, v_i) are the location coordinates.

The model parameter estimation is achieved by using the weighted least square method and assigning different weights to each unit. The parameter estimation obtained for each location is:

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[7] Available via e-mail.

$$\hat{\gamma} = (\mathbf{X}^{\mathbf{T}}\mathbf{W}(u_i, v_i)\mathbf{X})^{-1}\mathbf{X}^{\mathbf{T}}\mathbf{W}(u_i, v_i)\mathbf{Y} \tag{3}$$

where $\hat{\gamma}$ is the vector of elements k, $\mathbf{X}^{\mathrm{T}}\mathbf{W}(u_i,v_i)\mathbf{X}$ is the geographically weighted variance-covariance matrix, $\mathbf{W}(u_i,v_i)$ is the diagonal matrix $(n \times n)$ of spatial weights with non-zero diagonal elements, and w_{ij} is the geographical weight, referring to the surroundings of location i defined by coordinates (u_i,v_i). Most commonly, the coordinates (u_i,v_i) indicate location i's geographical centre and the location of each point where an observation was made, so that $\mathbf{W}(u_i,v_i)$ = diag elements $(w_{i1}, w_{i2}, ..., w_{in})$.

Here, the weighting scheme $\mathbf{W}$ is calculated with a kernel function based on the proximities between regression point i and the N data points around it. Several options are possible for the estimation of the bandwidth in GWR models. For this study, used to explore local relations, the fixed Gaussian kernel weighting function was employed because it best fits the model (Charlton and Fotheringham, 2009; Fotheringham *et al.*, 2000):

$$w_{i,j} = \exp\left[-\frac{1}{2}\left(\frac{d_{ij}}{b}\right)^2\right] \tag{4}$$

where d_{ij} is the Euclidean distance between locations i and j in geographical space and b is the bandwidth; that is, the radius of the circle containing points which are considered as still having influence on the formation of model parameters. An optimum bandwidth can be found by minimising a model goodness-of-fit diagnostic (Loader, 1999), such as the cross-validation (CV) score (Bowman, 1984; Cleveland, 1979; Fingleton, 1999), which accounts for model prediction accuracy only, or the Akaike information criterion (AIC) (Akaike, 1973), which accounts for model parsimony (i.e. a trade-off between prediction accuracy and complexity). Thus, for a GWR model with a bandwidth b, its CV of bandwidth can be found by minimising the following expression (Cleveland, 1979):

$$CV = \sum_{i=1}^{n}\sum_{j=1}^{n}\left[y_i - \hat{y}_{j\neq i}(b)\right]^2 \tag{5}$$

where $\hat{y}_{j\neq i}$ is the theoretical (estimated) value of the observation y_i.

As with any GWR study, it is important to estimate the parameters of the global non-spatial regression (Eq. 1), so that this benchmark model can be compared to its GWR counterpart. However, as there is no single agreed upon functional form in modelling, several statistical tests were conducted, using a pseudo-stepwise procedure, to explore the data with a limited number of ordinary least squares (OLS) regression analyses (Fotheringham *et al.*, 2002). To test for multicollinearity, the variance inflation factor measure was used (Gollini *et al*., 2015). To test the spatial dependency on the residuals, Moran's I measure and the Lagrange multiplier tests for both dependence error and missing spatially lagged dependent variable were used (Leung *et al*., 2000). To identify the spatial non-stationarity, Koenker's statistic (Koenker's studentised Bruesch-Pagan test) was applied (Andy, 2005).

The dynamic development of GWR has enabled the method to be used in many scientific disciplines, including waste studies (e.g. in Turkey – Keser, 2012; Keser *et al*., 2010; in Nigeria – Ismaila *et al*., 2015; and in the Czech Republic – Rybova, 2019; Rybova *et al*., 2018). Nonetheless, studies using GWR for analysing the impact of socio-economic factors on the collected municipal waste quantity in Poland are still not prevalent.

4. RESULTS AND DISCUSSION

Having identified eight potential determinants of the waste generation process in Poland over the years 2008–2016, and having conducted stepwise regression to identify the most appropriate tool with which to overcome the problems of spatial non-stationarity[8], I used GWR to determine the model, as follows, via ArcGIS and GWR4:

$$Waste_{2016,i} = \gamma_0(u_i, v_i) + \gamma_1(u_i, v_i)PD_{(2014,\,i)} + \gamma_2(u_i, v_i)PWA_{(2014,\,i)} + \\ + \gamma_3(u_i, v_i)GW_{(2016,\,i)} + \gamma_4(u_i, v_i)R_{(2016,\,i)} + \gamma_5(u_i, v_i)T_{(2016,\,i)} + \varepsilon_i \qquad (6)$$

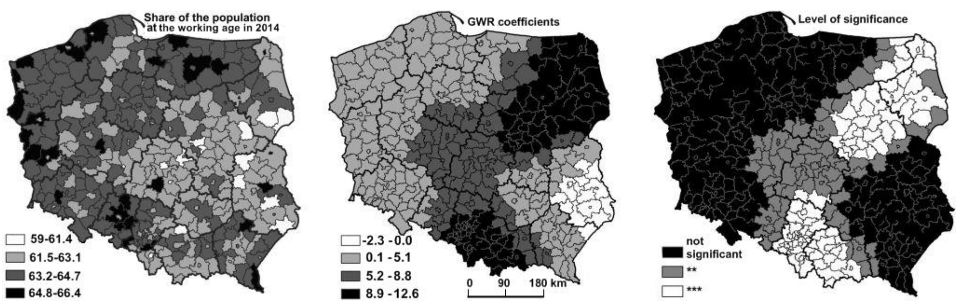
where (u_i,v_i) denotes the coordinates (longitude, latitude) of a destination location *i,* for $i = 1, 2,\ldots, 379$ districts, $\gamma_k(u_i,v_i)$ are structural parameters of the weighted regression model and ε_i is the random error at location *i*. Here, $Waste_{2016}$ was the municipal waste quantity collected in 2016, PD_{2014} was the population density in 2014, PWA_{2014} was the share of the population at working age in 2014, GW_{2016} where the average wages and salaries in 2016, R_{2016} was district revenue in PLN per capita in 2016, and T_{2016} was the number of tourists accommodated in 2016.

Preliminary (non-spatial) regression results indicated the absence of a statistically significant relationship between the quantity of municipal waste collected in 2016 and the increased number of uncontrolled dumping sites in 2010, their area in 2010, and the number of registrations for permanent residence in 2014. All variables were expressed in natural logarithms. To select the optimum bandwidth in the model (Eq. 6), the minimum CV was employed. The bandwidth value was

[8] The stepwise procedure for this model selection is available via e-mail.

121,580.62, with a minimum CV of 0.02. This statistic exhibits the smallest value deemed to be optimal (Table 4).

The first empirical finding suggested that the share of individuals at working age in the general population was, in terms of its strength rather than regional range, the factor that most considerably affected the quantity of municipal waste collected annually. An increase by 1% in the share of that economic age group in the population generated an average increase in the quantity of waste collected from around 5% to as much as 13% (*ceteris paribus*). Such a situation occurred in the Warmińsko-Mazurskie and Podlaskie Voivodeships (north-eastern Poland), the Silesian and Lesser Poland Voivodeships (southern-central Poland) and the Mazowieckie and Łódzkie Voivodeships (central Poland) (see Fig. 3). The districts located in those regions featured stimulated socio-economic development (especially Mazowieckie) and intense, ongoing urbanisation due to their high potentials and realistic investment attractiveness (Advisory Group TEST Human Resources, 2014). In fact, those regions also have the greatest concentrations of the population's wealth and have the lowest rates of unemployment. Then again, Łódzkie and Podlaskie (including Białystok, the largest city in and the latter, and the capital of the voivodeship) include strong academic and tourist centres. One should bear in mind, however, that the working-age population accounts for about 64% of Poland's population. Nonetheless, given the spatial distribution of the variable's impact, it was statistically significant ($p < 0.01$) in only 34% of the units (see Fig. 3).

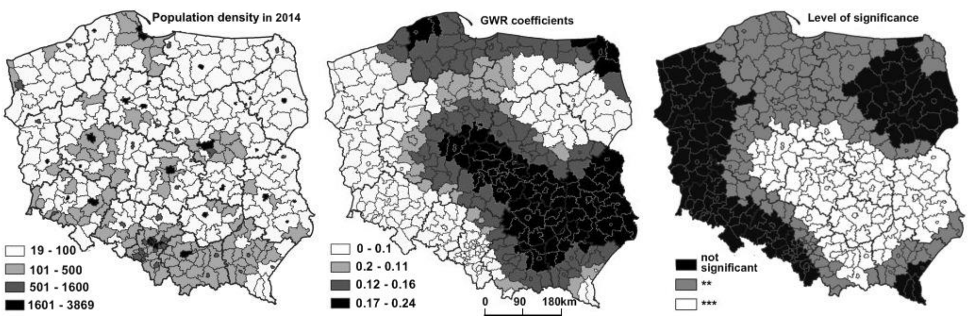


Note: significance level α = 0.05 (**), |t-Stat| ≥ 1.648, and α = 0.01 (***), |t-Stat| ≥ 2.336; df = 373.

Fig. 3. GWR results for the quantity of waste in 2016 and share of the working-age population in 2014

Source: own work.

Moreover, population density and average gross wages had the greatest spatial range of impact affecting the phenomenon fundamentally. In about 68% of the districts, a statistically significant impact of an increase in population density by 1% resulted in a rise in the amount in municipal waste from 0.11% to 0.24% (*ceteris paribus*), especially in districts located in the Mazowieckie, Świętokrzyskie, Lesser Poland, Łódzkie and Pomorskie Voivodeships (see Fig. 4). The impact, however, was the strongest in the northern, central and south-eastern parts of the country. In central Poland, where the richest, as well as the largest, towns are located (such as Warsaw, Poznań, Bydgoszcz and Krakow[9]), the highest population density was observed in 2014 – with up to as many as 3,355 residents per sq. km (districts in the Mazowieckie and Lesser Poland Voivodeships). The districts situated in the east of the country have rates of economic development that are greater than in the rest of Poland, mostly due to funding from the European Regional Development Fund between 2007 and 2013 (2.3 billion euros was invested in the Lubelskie, Podkarpackie, Podlaskie and Świętokrzyskie Voivodships) (EC, 2018). I also found that a rise in the population density in 2014 (*ceteris paribus*) in the northern parts of Poland significantly influenced the sharpest increase in the quantity of waste (from about 0.16% to 0.24%). Generally, such an increase could be determined by the location on the Baltic Sea. In the Zachodniopomorskie, Pomorkie and Kujawsko-Pomorskie Voivodeships, the major cities, which are particularly attractive in investment terms (and therefore in people's willingness to settle there), are Szczecin, Kołobrzeg, the Tri-City (i.e. Gdańsk, Gdynia and Sopot), as well as Toruń and Bydgoszcz. Finally, an increase in the population densities of districts located in north-eastern Poland, including the city of Suwałki (which is accessible from Tallinn (Estonia), Riga (Latvia) and Vilnius (Lithuania)), also resulted in an increase in the quantity of waste (*ceteris paribus*).



Note: significance level α = 0.05 (**), |t-Stat| ≥ 1.648 and α = 0.01 (***), |t-Stat| ≥ 2.336; df = 373.

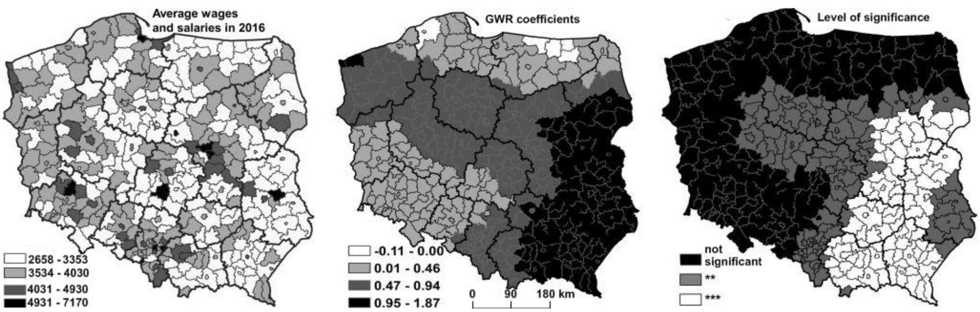
Fig. 4. GWR results for the quantity of waste in 2016 and population density in 2014

Source: own work.

In turn, a 1% increase in salaries in 2016 triggered a statistically significant rise in the amount of waste in 2016 in 58% of the districts, ranging from 0.5%

[9] The area encompassing Krakow is characterised by a high population density caused mainly by a large number of small, family-run farms clustered together (Advisory Group TEST Human Resources, 2014).

to 1.9% (see Fig. 5). A particularly strong relationship ($p < 0.01$) was found in districts located in the Mazowieckie Voivodeship, south-eastern Poland (the Lesser Poland, Świętokrzyskie, Podkarpackie and Silesian Voivodeships) and eastern Poland (the Lubelskie and Podlaskie Voivodeships). According to Statistics Poland, the highest growth in gross average monthly wages was observed in some of those voivodeships – Lesser Poland, Świętokrzyskie, Silesian and Podlaskie. Moreover, many foreign companies have their headquarters in the Mazowieckie Voivodeship, resulting in higher incomes for most families; thus, their private consumption usually increased as well, which increased the quantity of waste.

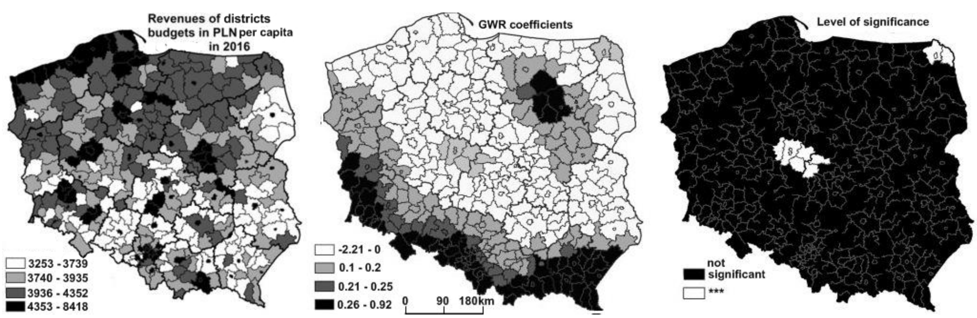


Note: significance level α = 0.05 (**), |t-Stat| ≥ 1.648 and α = 0.01 (***), |t-Stat| ≥ 2.336; df = 373.

Fig. 5. GWR results for waste in 2016 and the average gross monthly wages and salaries

Source: own work.

The smallest impact on the quantity of municipal waste was exerted by district revenues in PLN per capita, which was found in only 4% of the units; that is, Suwałki, and districts in the Greater Poland and Łódzkie voivodeships (see Fig. 6).



Note: significance level α = 0.05 (**), |t-Stat| ≥ 1.648 and α = 0.01 (***), |t-Stat| ≥ 2.336; df = 373.

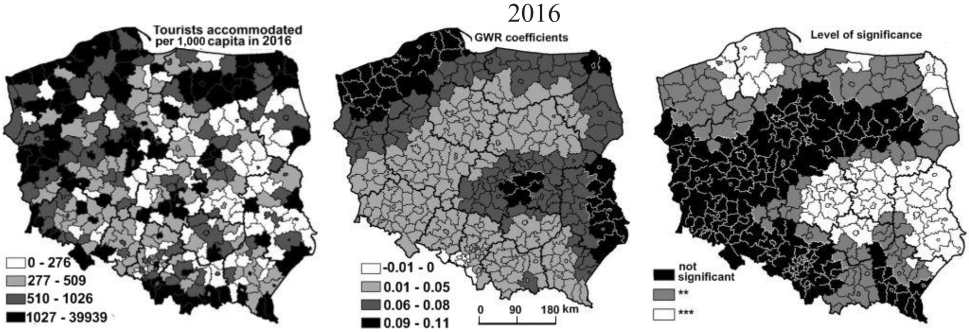
Fig. 6. GWR results for waste in 2016 and district revenues in 2016

Source: own work.

In those districts, a 1% increase in revenue per capita in 2016 resulted in a slight rise in the quantity of waste of about 0.2% in that year (*ceteris paribus*). For example, Konin (in the Greater Poland Voivodeship) has one of the largest opencast mines in Poland, whereas the city of Łęczyca (in the Łódzkie Voivodeship) was the location of one of the biggest municipal waste dumping sites in the region. For the majority of districts (about 97%), an increase in revenue generated a decline (or absence of change) in the quantity of waste. According to Beigl *et al*. (2004, 2008) and Tałałaj (2011), the trend of a diminishing relationship between economic development and the quantity of waste has been observed in Poland since the beginning of rapid economic growth; that is, since 1990 and the transition period. Such a declining correlation (or even the lack of one) occurs when the well-being of a society is increasing –the higher the level of prosperity, the stronger the decoupling observed.

Finally, districts attractive to tourists, especially regions in northern Poland (such as the Pomorskie, Zachodniopomorskie and, partly, Warmińsko-Mazurskie Voivodeships) and districts located in the east of the country, generated the highest increases in the quantity of waste in the investigated period (see Fig.7).

2016



Note: significance level α = 0.05 (**), |t-Stat| ≥ 1.648 and α = 0.01 (***), |t-Stat| ≥ 2.336; df = 373.

Fig. 7. GWR results for waste in 2016 and tourists accommodated per 1,000 capita in

Source: own work.

A 1% increase in the number of tourists accommodated per 1000 capita in these regions in 2016 resulted in an increase of about 0.11% in the quantity of waste in 2016 (*ceteris paribus*). The greatest asset northern Poland has is its location on the Baltic Sea. The impact, moreover, was the strongest in districts also located in the north-east, in particular the Suwałki and Augustów districts of the Podlaskie Voivodeship. The bays, rivers and lakes found there make excursions to those parts of Poland attractive to many. Then again, a rise in the number of tourists accommodated per 1,000 capita (*ceteris paribus*) significantly influenced an increase in the volume of municipal waste in the Łódzkie and Mazowieckie Voivodeships. Central Poland is becoming an increasingly attractive destination not only for leisure, but also for business travel, due to its accommodations, public and regional transport, and international airports. Moreover, the empirical findings suggest that an increase in the number of tourists resulted in a lower increase in the phenomena (of about 0.01% to 0.06%, *ceteris paribus*) in the southern part of the country in districts located in the Lesser Poland Voivodeship, which is a popular destination thanks to its mountainous landscape.

For a robustness check of the results, the OLS model results were compared to those of the GWR model (Table 4).

Table 4. Diagnostic statistics for GWR compared to OLS

Global regression results (OLS)

Residual sum of squares:	8.78
Number of parameters:	6
ML based global sigma estimate:	0.15
Unbiased global sigma estimate:	0.15
-2 log-likelihood:	-351.50
Classic AIC:	-337.50
AICc:	337.19
BIC/MDL:	-309.94
CV:	0.02
R square:	0.34
Adjusted R square:	0.33

Variable	Estimate	Standard Error	t(Est/SE)
Intercept	-13.82	1.98	-6.99
$\boldsymbol{T_{2016}}$	0.07	0.01	5.06
$\boldsymbol{PWA_{2014}}$	6.72	1.04	6.45
$\boldsymbol{GW_{2016}}$	0.57	0.18	3.20
$\boldsymbol{R_{2016}}$	0.45	0.18	2.53
$\boldsymbol{PD_{2014}}$	0.07	0.02	3.22

Diagnostics for spatial dependence of residuals
Test Value Prob
Moran's I (residuals) 0.18 0.00***

Geographically varying coefficients (GWR)

Bandwidth size:	121580.62
Residual sum of squares:	5.24
ML based sigma estimate:	0.12
Unbiased sigma estimate:	0.13
-2 log-likelihood:	-546.85
Classic AIC:	-428.55
AICc:	-406.23
BIC/MDL:	-195.64
CV:	0.02
R square:	0.68
Adjusted R square:	0.64

GWR ANOVA

Source	SS	DF	MS	F
Global Residuals	8.78	373.0		
GWR Improvement	3.54	73.57	0.05	
GWR Residuals	5.24	299.43	0.02	2.75

Summary statistics for varying (Local) coefficients

Variable	Mean	STD	Median
Intercept	-7.42	4.77	-6.10
$\boldsymbol{T_{2016}}$	0.05	0.02	0.05
$\boldsymbol{PWA_{2014}}$	3.92	2.55	3.34
$\boldsymbol{GW_{2016}}$	0.69	0.38	0.66
$\boldsymbol{R_{2016}}$	-0.05	0.37	-0.02
$\boldsymbol{PD_{2014}}$	0.12	0.05	0.12

Diagnostics for spatial dependence of residuals: Moran' I: -0.001, Prob.: 0.16;

Source: own work.

As to their merits, using GWR in relationship modelling increased the quality of the assessments considerably over using global OLS regression, and had a lower sum of squares of the residuals; for example, Adj.$R_{sq.GWR}$ = 0.64 *vs.* Adj.$R_{sq.OLS}$ = 0.30, and AICc of GWR = −406.23 *vs.* AICc of OLS = −337.19 (Fig. 7, Table 3). Moreover, the residuals of the GWR model were free of spatial autocorrelation. Furthermore, the GWR model equations were characterised as providing an insufficient fit to the data for only 26% of the districts located in the south-central and south-western parts of the country, whereas the fit was best in north-western and eastern Poland.

5. CONCLUSIONS

In contrast to previous studies, this research represented the first attempt at studying the strength of, and regional variations in, the socio-economic factors impacting the changes in the quantity of municipal waste in Polish districts. The selected variables explained the values of the quantity of municipal waste in 2016 in about 80% of the regions. Those variables were, in order from the most influential to the least, while taking into account the spatial range and strength of the influence: population density; average salaries; share of individuals at working age in the general population; and the number of tourists. A progressive weakening relationship between economic development and the quantity of waste was observed. There is no statistically significant relationship between the quantity of municipal waste collected and the increased number of uncontrolled dumping sites, the area those sites cover or the number of registrations for permanent residence.

Moreover, the results indicated that waste collection might be local (regional, social and urban economic development and waste policy determine the volume of waste streams) and global in nature. Spatial autocorrelation reached more than 150 km, undoubtedly due to the transboundary shipment of waste. This empirical study provides useful data for the relevant decision-makers and local governments in terms of urban planning. Knowledge of the spatial dimension in waste generation may form the basis for preparing reliable expert opinions and prognostic models, and for supporting local government in MWM decision-making processes.

Additionally, the finding of spatial non-stationarity is important for MWM planning. Even though the objectives of MWM policies are created at the national level, many decisions are made at local levels by local representatives who know the particular situations in their region best. The results of the study show that this approach is appropriate, and that there is no simple way of predicting the amount of generated municipal waste based on the experiences of other administrative units.

Finally, GWR proved to be an extremely effective instrument for identifying and modelling spatially-varying relationships between waste and its determinants. Local models were characterised by considerably better fit to empirical data than global ones. Nonetheless, there are still unexplained variations that must be addressed in future studies. Accounting for the determinants of municipal waste by taking into account their structures, as well as examining the directions of waste transport by constructing different (nonlinear or asymmetrical) spatial weights matrices, could enrich the analysis. Another stage in the research will be an attempt to identify more precise economic activity indicators at local levels of aggregation, and also to consider them from a decoupling theory perspective, with the delinking of economic growth from resource use. Further studies should also consider more spatial information, such as housing characteristics, the average income of households, environmental values, the psychological factors that influence the behaviour of the inhabitants, and the location of a municipality regarding metropolises and regional peripheries.

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