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A GIS and AHP-based approach to determine potential locations of municipal solid waste collection points in rural areas

Mateusz Malinowski[1)] ✉, Sylwia Guzdek[2)], Agnieszka Petryk[3)], Klaudia Tomaszek[4)]

[1)] University of Agriculture in Cracow, Department of Bioprocesses Engineering, Energetics and Automatization, ul. Balicka 116b, 30-149 Kraków, Poland

[2)] Cracow University of Economics, Department of Microeconomics, Kraków, Poland

[3)] Cracow University of Economics, Department of Spatial Management, Kraków, Poland

[4)] University of Agriculture in Cracow, Department of Mechanical Engineering and Agrophysics, Kraków, Poland

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Abstract: Municipal solid waste collection points (MSWCPs) are places where residents of municipalities can leave their waste free of charge. MSWCPs should operate in every municipality in Poland. The Geographic Information System (GIS) and analytical hierarchy process (AHP) were used in conjunction as tools to determine potential locations of MSWCPs. Due to possible social conflicts related to the location of MSWCPs, three variants of buffer zones for a residential area were adopted. As a result of the spatial analysis carried out using the GIS software, 247 potential locations were identified in variant no. 1 (which accounted for 7.1% of commune area), 167 for variant no. 2 (6.3% of commune area), and 88 for variant no. 3 (3.8% of commune area). The most favourable locations for MSWCPs were determined using the AHP method with additional criteria for which weights were calculated as follows: the area of a designated plot (0.045), actual designation of a plot in the local spatial development plan (0.397), distance from the centre of the village (0.096) and the commune (0.231), and population density of a village (0.231). The highest weights (over 50%) in the AHP analysis were obtained for 12 locations in variant no. 3, two of which had an area over 3 ha. The adopted methodology enabled to identify quasi-optimal solutions for MSWCP locations in the analysed rural commune. This research has the potential to influence future waste management policies by assisting stakeholders in the MSWCP location.

Keywords: analytical hierarchy process (AHP), Geographic Information System (GIS), rural areas, waste collection

INTRODUCTION

By 2030, European Union (EU) Member States are required to implement the circular economy (CE) system. In this new economic system, products, materials (raw materials), and resources circulate in the economy for as long as possible and municipal solid waste (MSW) generation is minimized [Głowacki *et al.* 2019]. However, MSW generation accompanies every human activity, and its management constitutes a significant challenge. CE also aims to implement solutions leading to the processing of the largest possible mass of recyclable waste [Bedla, Dacewicz 2019]. The quality of secondary raw materials, which depends mainly on collection methods and waste segregation, plays an important role in recycling [Grzesik 2015]. One of rational solutions (in accordance with CE) supporting high-quality recyclable raw materials is to set up a municipal solid waste collection points (MSWCPs) network. In 2016, Poland had 2,146 MSWCPs (6.6% more than in preceding year), of which 802 (37.4%) were located in cities and 1,344 (62.6%) in rural areas [GUS 2018]. Despite the legal obligation, almost 20% of municipalities still do not have their MSWCPs (mainly rural municipalities) [Malinowski *et al.* 2018a].

As shown by both Polish and global experience, the presence of such points results not only in environmental, but also economic benefits for the entire waste management system (e.g. they reduce costs of waste transport) [Carlos *et al.* 2019; Martinho *et al.* 2017; Sulemana *et al.* 2020]. In Europe, these points are most often called household waste recycling centres (HWRC).

The purpose of MSWCPs and HWRCs is to provide people with the possibility to leave free of charge their municipal solid waste (i.e. packaging, paper, glass, plastic, metal, bulky waste, such as furniture, used electrical and electronic equipment, construction and demolition waste, e.g. brick debris, and hazardous waste including outdated medicines, chemicals, batteries, accumulators, fluorescent lamps, paint and varnish packaging). MSWCPs should be equipped with marked containers or containers enabling selective collection of MSW. Such containers should be emptied at a frequency that will prevent their overfilling and odour emission. In Western European countries, green waste and kitchen waste, which are selectively collected in households, are very often disposed of by residents at MSWCPs [Báreková *et al.* 2020; Stejskal *et al.* 2017; Zemanek *et al.* 2009]. The area where an MSWCP is located should be paved, fenced, lit, monitored 24/7, and equipped with devices or systems ensuring the management of rainwater and industrial sewage.

MSWCPs should be stationary and available to inhabitants of a commune. The statutory obligation to build a stationary point results from the necessity to provide citizens with the possibility of continuous waste disposal and to increase the value of waste recycling [Malinowski, Religa 2016]. In current socio-economic situation, waste management has become a fundamental task for pro-ecological spatial management [Broniewicz (ed.) 2017]. Unfortunately, there are no precise legal provisions or strictly defined standards or procedures for designating potential locations for municipal waste management facilities [Malinowski *et al.* 2018b], and this also applies to MSWCPs. It is noteworthy that an unsuitable location of a MSWCP could have a negative impact on the ecosystem, residential areas (odours emission, noise), and land use.

MSWCPs are very often located on the premises of existing sewage treatment plants or municipal solid waste facilities. Advantages of these locations include the constant presence of personnel during working hours, access to utilities and roads, and fencing. These areas usually have the appropriate infrastructure and a monitoring system. The implementation of such installations in sewage treatment plants or plants dealing with waste management less frequently cause public protests. Unfortunately, these locations are most often distant from residential complexes, which causes problems to residents to deliver waste and discourages them due to the need to transport waste over a distance of several kilometres [Guzdek *et al.* 2020; Petryk *et al.* 2019]. The current process to select a location for the MSWCP in Poland is costly, time consuming, and conducted without a proper survey. The study presents a cost and time effective scientific process for the selection of MSWCP locations in rural areas.

The process of designating a location for new municipal waste management facility, including the MSWCP, should be based on multiple criteria, in a similar vein to the procedure used to select a location for a landfill. The multi-criteria decision making (MCDM) is a well-known technique for resolving complex decision-making problems while selecting a waste-disposal site [Demesouka *et al.* 2019]. Saaty [1990] as proposed the analytical hierarchy process (AHP). The latter is a type of a MCDM technique under which a problem is hierarchically decomposed. A combined GIS-AHP approach has been applied by various researchers for landfill-site selection, including Demesouka *et al.* [2013] and Kamdar *et al.* [2019], who evaluated the suitability of potential MSW landfill sites by applying GIS combined with AHP in Greece and Thailand respectively. Chabuk *et al.* [2016] selected a landfill site for Babylon, Iraq, using the GIS and AHP process, while Spigolon *et al.* [2018] used the AHP approach in a GIS environment for the siting of a sanitary landfill in Brazil.

The aim of the study was to develop a method for determining locations of potential stationary MSWCPs. In order to verify the method, spatial research was carried out for the rural commune of Liszki, where no stationary MSWCP had been located. The analysis took into account environmental conditions in the commune and the accessibility of the site for residents. The process identified and assessed the potential of the area, and its main difficulty was the need to adapt to relevant environmental and social conditions. Therefore, the process was based on specific location criteria.

To the best of authors' knowledge, no previous study has been conducted in rural areas to determine potential locations for MSWCPs using the AHP approach with GIS. The only such study was implemented by Malinowski and Religa [2016] in the buffer zone of the Świętokrzyski National Park. The study considered specific conditions of rural areas while selecting the location for the MSWCP. The novelty of the method described in this article is the combined GIS and AHP approach to create a universal methodology for determining of potential MSWCPs in rural areas.

MATERIAL AND METHODS

DATA COLLECTION

Spatial data related to surface water, road network, soil texture, residential areas, land use, etc. were collected from various online portals and institutions (i.e. the Marshal's Office of the Małopolska Province). Data for analyses (thematic layers for the Liszki commune) were obtained in their vector format.

BOUNDARY CONDITIONS FOR MSWCP LOCATIONS

Based on scientific articles [Chabuk *et al.* 2016; Kamdar *et al.* 2019; Spigolon *et al.* 2018] which discuss facilities having a potential impact on the environment, it was found that the procedure for setting the location of MSWCPs should include multiple stages and should take into account Geographic Information System (GIS) tools and the analytical hierarchy process (AHP) method [Artun 2020; Malinowski *et al.* 2018b; Malinowski, Religa 2016]. The following boundary conditions were taken into consideration in order to develop a method for designing MSWCPs for rural areas:
- location close to the commune centre (legal requirements);
- in the vicinity of local roads (<100 m, easy access);
- connections to technical infrastructure already available or possibility to install one (economic reasons);
- minimum area of 0.2 ha;
- the commune should be the owner of the plot or the site should be designated in the local spatial development plan (LSDP).

CRITERIA SELECTION

The selection of criteria is an important part of the evaluation process in any site selection project as the site reliability mainly depends on these criteria [Kamdar *et al.* 2019]. While selecting criteria for spatial analysis, results of the following studies were used: Zemanek *et al.* [2009], Malinowski and Religa [2016], Malinowski *et al.* [2018b] and Artun [2020]. Criteria for designating MSWCP suitable and unsuitable areas are presented in Table 1. The plot for the potential location of the MSWCP in a rural area must meet several basic environmental conditions, because the primary purpose is to improve the status of the environment, provide economic benefits, as well as mitigate conflicts related to waste collection, and to prevent the creation of illegal dumpsites. Apart from the availability of the plot, compliance of the project with the local spatial development plan, and access to road infrastructure, criteria for selecting the location must also take into account provisions of the construction law.

Table 1. Criteria excluding areas (plots) from locating MSWCPs

Name of the area	The width of the buffer zone (m)
Forests, green and protected areas (i.e. Natura 2000 network)	25
Landscape parks and areas	0
Agricultural Land Grade 1 and Grade 2	0
Water protected zones and recreation and sports areas	50
Rivers, surface water, floodplains	50
Amenities (schools, churches, cemetery, historical places, etc.)	50
Residential building areas – variant no. 1	10
Residential building areas – variant no. 2	100
Residential building areas – variant no. 3	300

Source: own elaboration.

Road network access to the site is an important criterion for the economic and efficient selection of an MSWCP site. The cost may decrease when infrastructure works are carried out close to main roads [Artun 2020]. Therefore, the only criterion adopted was a 100-meter buffer zone from paved roads to support transport of heavy waste to MSWCPs. The adopted width of the buffer zone ensures adequate visibility of the site, reduces the construction cost related to access roads, and it should also encourage inhabitants to deliver municipal waste rather than to dispose of it at dumpsites [Zemanek *et al.* 2009]. The analysis excluded areas covered by the A4 motorway.

Moreover, in order to determine detailed location criteria, an analysis of the existing MSWCPs in rural communes of southern Poland was carried out. The analysis mainly determined the buffer zone width for individual components of the environment which the planned MSWCPs may not border directly. Once determined, the distance will allow to expand the list of unsuitable areas (excluded from the analysis). In rural communes of southern Poland, the distances from the boundaries of existing MSWCPs are as follows:

- below 25 m to forest, green and protected areas;
- between 58 and 681 m to surface water, floodplain and rivers;
- between 10 and 290 m to residential areas;
- between 51 and 165 m to other social (historical places, schools, churches, cemeteries, etc.).

The buffer zones adopted for the analysis (expanding the list of unsuitable areas) are presented in Table 1. Widths of buffer zones were selected through the analysis and based on the sensitivity to the location of the waste collection site.

The exclusion criteria should take into account specific features and density of population in a given area. Therefore, three variants of buffer zones between MSWCPs and residential areas were introduced. The distance from MSW facilities to residential areas is not regulated by the law. Residential areas are inappropriate (unsuitable) for the location of MSWCPs. The not in my back yard (NIMBY) phenomenon is the factor primarily responsible for restricting the number of suitable sites for MSWCPs [Kamdar *et al.* 2019]. The proximity of a waste collection site to a residential area entails various environmental issues, such as human health, land prices, and future urban development [Kahraman *et al.* 2018].

In addition, previous studies and local experts consulted in this study suggested that a suitable locations for MSWCPs should be located at least 100 m from residential areas. Bearing in mind the above and the analysis of existing MSWCPs, the study proposes three different buffer zones of 10, 100 and 300 m from residential areas to avoid public protests.

THE USE OF GIS AND AHP

A flowchart of research methodology (using GIS and AHP) is shown in Figure 1. In this study, the main aim of applying the GIS environment (ArcView GIS. 10.2 software, ESRI) was to identify the potential location of MSWCPs. In the first step, road networks with a paved surface (100 m distance) were buffered. Thus, a map of all MSWCP suitable areas was created. In the second step, all buffered unsuitable areas (Tab. 1) were summed up (in three variants depending on the width of buffer zones separating them from residential areas). Then, the difference between the two areas (suitable areas minus unsuitable areas in three variants) was determined. This helped to produce three new maps with different potential locations for MSWCPs. If the number of potential areas was greater than one, an additional multi-criteria analysis was performed. Principles of this assessment are described below.

The AHP method is an important multi-criteria decision making method. It has been one of the most effective methods used in spatial planning in recent years [Artun 2020]. The AHP method enables users to determine the significance of parameters used in solving a multi-criteria problem. The AHP provides a platform for comparing parameters in pairs at each layer in a hierarchical structure and it can assess the comparative standard coefficient weights with alternative schemes [Shao *et al.* 2020]. In this case, the AHP was used to: 1) determine the weights of additional criteria (stage II allowing for the selection of quasi-optimal locations for MSWCPs, and 2) provide a comparative assessment of potential locations selected in stage I.

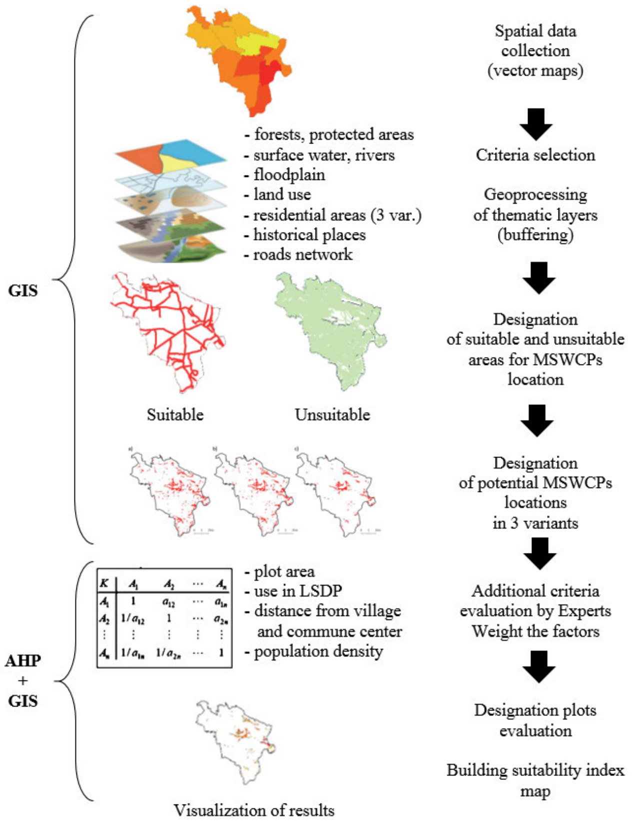

Fig. 1. Flowchart of the methodology; LSDP = local spatial development plan, MSWCPs = municipal solid waste collection points; source: own elaboration

Assessment criteria (parameters) should include: the area of plots designated in the AHP analysis (the larger, the better), their designation in the local spatial development plan, distance from the village centre and the centre of the commune (the smaller, the better), and population density. A very important element in the AHP method is the 9-point grading scale [SAATY 1980], in which grade 1 means equal importance of the compared features or facilities, while 9 means an extreme difference (extreme advantage of one of compared features over the other). The scale is universal and widely used. It allows for comparison and assessment of qualitative and quantitative factors [MALINOWSKI, RELIGA 2016]. In the AHP, so-called reversible pairwise comparisons are made, for which $a_{ij} = 1/a_{ji}$ and $a_{ii} = 1$ [SAATY 2001]. Comparisons on a scale of 1 to 9 are placed in a so-called square matrix of pairwise comparisons ($n \times n$) $A = [a_{ji}]$. This is the main tool of the AHP method. It presents assessments indicating the influence of the elements on the left side of the matrix on the elements at the top. In this matrix, $n(n - 1)/2$ pairwise comparisons are made. The number of these comparisons results from the fact that there are n 1's on the diagonal of the matrix of n elements, and half are reciprocals. The matrix of pairwise comparisons along with the weighting of the additional location criteria compared in the case of searching for potential MSWCP locations in rural areas are presented in Table 2. In the AHP method, the most important values calculated using the matrix include: λ_{max}, (the eigenvalue of the matrix, which is a measure of the compatibility of comparisons), *CI* (concordance index representing the consistency in comparing the characteristics) and *CR* (inconsistency index expressed as a percentage).

During pairwise comparison of additional criteria, the designation of a plot in the local spatial development plan (masterplan), population density of the area (village), and the distance from the commune centre are of paramount importance for the selection of optimal locations. It is considered that the provisions of the masterplan show a sufficient degree of consistency and that the assessment can be continued if the coherence index (*CI*) is lower than 0.10 [AKINCI *et al.* 2013; ARTUN 2020].

STUDY AREA

The research area covered the Liszki commune, Kraków County, west of the city of Kraków, in the southern part of the Kraków-Częstochowa Upland. The commune 72 km^2 is divided into 14 villages inhabited by over 15,000 people. Agricultural land constitutes over 70% of the commune's area. Arable land (3875 ha) accounts for the largest part of the area, while pastures the smallest (170 ha). The high share of agricultural land in the total area and the insignificant forest area (5.7%) confirm the agricultural character of the Liszki commune. Two nature reserves, two scenic parks and a water reservoir, which is a tourist attraction, are located in the commune. The A4 motorway runs through the commune.

RESULTS AND DISCUSSION

In total, 18 thematic layers were selected under environmental and social headings to prepare maps with suitable (Fig. 2 – dark-green colour) and unsuitable areas (Fig. 3). The dark-green colour covers 37% of the commune's area. The white spots in Figure 2 depict places where MSWCPs cannot be established.

Table 2. Pairwise comparisons of additional location criteria and significance weights of those criteria

No.	Criterion	1	2	3	4	5	Weight
1.	plot area	1	1/7	1/3	1/5	1/5	0.045
2.	use in local spatial development plan	7	1	4	2	2	0.397
3.	distance from the village centre	3	¼	1	1/3	1/3	0.096
4.	distance from the commune centre	5	½	3	1	1	0.231
5.	population density	5	½	3	1	1	0.231
λ_{max} = 5.06, *CI* = 0.016, *CR* = 0.014							

Explanations: *CI* = concordance index, *CR* = inconsistency index.
Source: own elaboration.

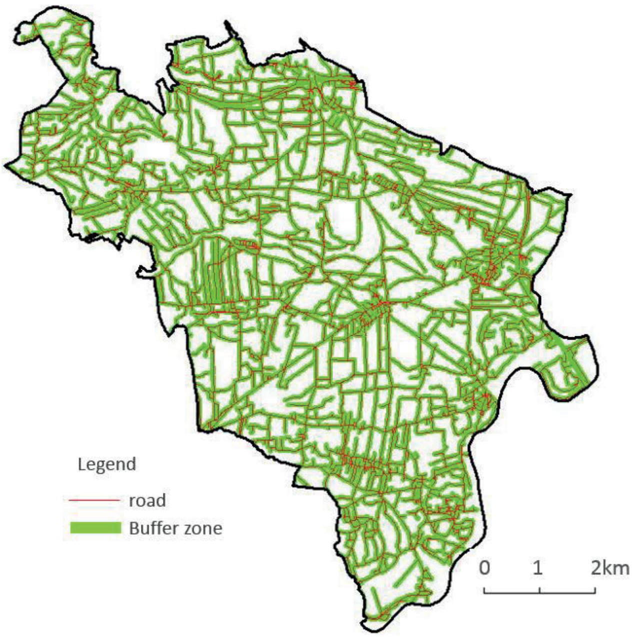

Fig. 2. MSWCP suitable areas (road networks expanded with buffer zones); source: own study

Figure 3 shows areas (light-green colour) that are unsuitable for the location of MSWCPs in the rural commune of Liszki. Those areas were divided into three variants, in accordance with the guidelines presented in Table 1. Unsuitable sites covered 76, 78 and 83% of the commune's area for variants 1, 2 and 3 respectively. The white spots in Figure 3 depict places where MSWCPs could theoretically be established. These places were juxtaposed with the suitable areas (paved roads with a 100-meter buffer zone). The common part, presented in Figure 4, is the final result of the GIS analysis.

Tables 3 and 4 present detailed information on the designated plots. Table 3 presents information on all plots designated in the spatial analysis, while Table 4 only incudes plots larger than 0.2 ha.

With the increase in the width of the buffer zone for the inhabited area, the number of selected plots decreased, but their areas were larger (Tabs. 3, 4). The significant number of designated plots indicated the need to apply additional criteria (AHP method). The ArcView GIS program took into consideration plot area (m^2), distance (m) from the centre of the commune and village, designation in the local spatial development plan (0 when the designation does not include municipal services and waste management, 1 otherwise or if the masterplan has not been

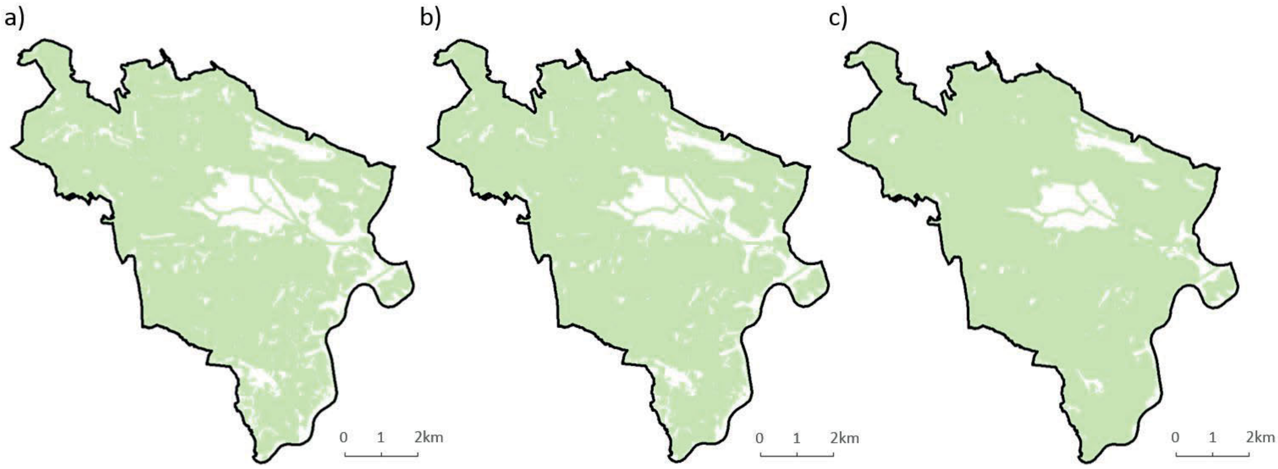

Fig. 3. MSWCP unsuitable areas: a) variant no. 1, b) variant no. 2, c) variant no. 3; source: own study

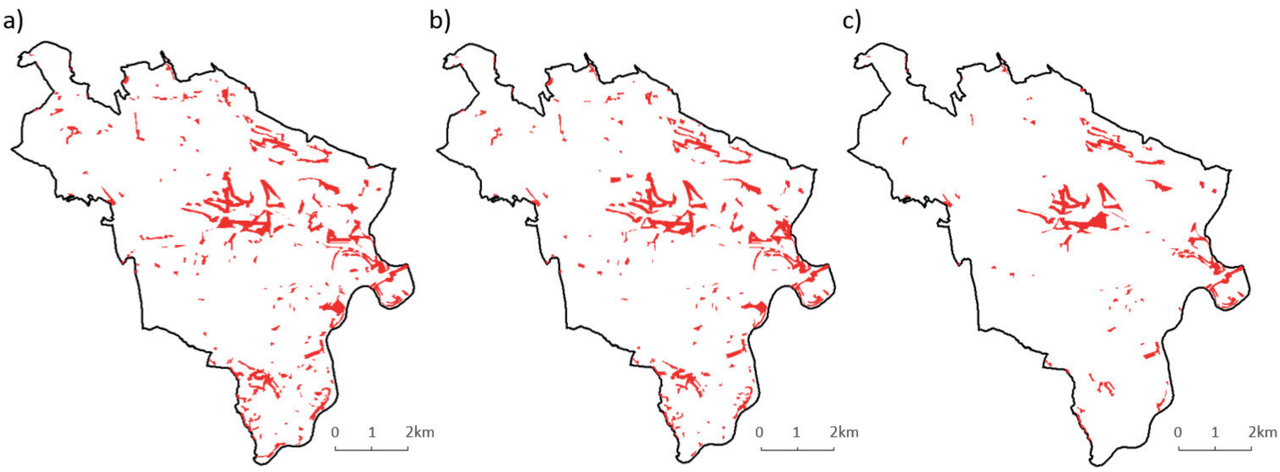

Fig. 4. MSWCP potential locations in the analysed area: a) variant no. 1, b) variant no. 2, c) variant no. 3; source: own study

Table 3. Number and areas of all potential MSWCPs (plots)

Criterion	Variant no. 1	Variant no. 2	Variant no. 3
Number of selected locations	368	281	149
Average area of selected plots (ha)	1.41	1.64	1.88
Total area of selected locations (ha)	524.6	460.8	280.6

Source: own study.

Table 4. Number and area of selected plots with area more than 0.2 ha

Criterion	Variant no. 1	Variant no. 2	Variant no. 3
Number of selected locations	247	167	88
Average area of selected plots (ha)	2.08	2.71	3.15
Total area of selected locations (ha)	514.9	452.7	272.2

Source: own study.

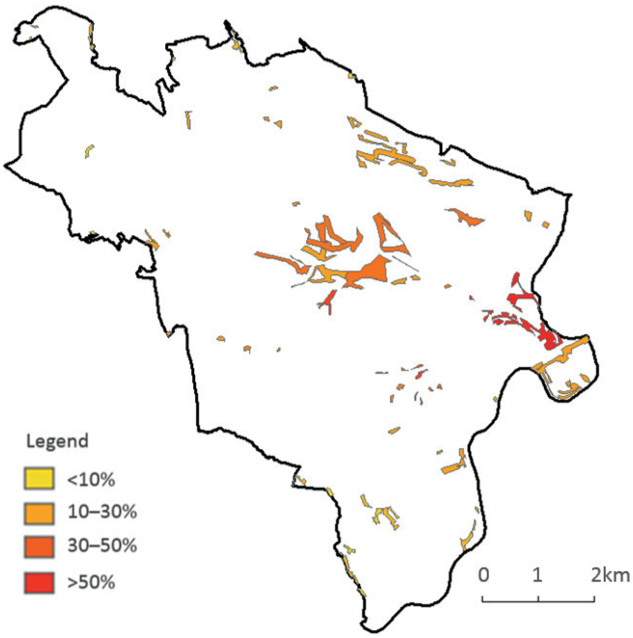

Fig. 5. Analytical hierarchy process (AHP) evaluation of potential MSWCP locations of over 0.2 ha in variant no. 3 together with the results of the AHP assessment; source: own study

adopted), and the population density for each of the designated plots. For each of the criteria, all values were subjected to null unitization so that their range remained between 0 and 1 to take into account whether a given criterion is a catalyst or an inhibitor [Jędrzejczyk *et al.* 2014]. The values were multiplied by the weights of individual criteria set out in Table 2 in order to establish the final rating for each potential location.

Figure 5 shows the location of potential MSWCPs selected in variant no. 3 with an area of 0.2 ha. The use of the AHP method allowed to designate the best locations (highly suitable for MSWCP) to be arranged in accordance with the adopted criteria. Plots marked red received the highest score in the AHP method. Thus, the most advantageous locations were determined for MSWCPs in the rural commune of Liszki. The AHP analysis produced the highest weights (over 50%) for 12 locations in variant no. 3, two of which had an area over 3 ha (Fig. 5). The most suitable location had a weight of 0.598 and a plot area of 3.241 ha. In each of the variants, the highest scores were given to the locations in the eastern part of the Liszki commune, mainly because of the high population density and small distance from the commune centre.

The basic (GIS) and additional (AHP) criteria allowed for the identification of quasi-optimal solutions. This shows that the criteria applied in the study are generally sufficient to determine the location of a MSWCP in a rural commune. The accuracy of the approach used to determine the location of MSWCPs was below 10% (*C.R.* < 0.1) in all analysed variants. The map can be employed in a preliminary site assessment for investors or officials. By increasing the number of criteria (as assessed by AHP), it is possible to provide a more precise definition of suitable investment areas. The created method may facilitate MSWCP feasibility study and provide an argument for resolving social conflicts when locating this type of a waste collection facility.

Compared to studies on determining the location of technical facilities that potentially affect the environment, the location criteria adopted in this study (widths of buffer zones) should be considered liberal, e.g. compared to the work of Artun [2020] or Malinowski *et al* [2018b]. MSWCPs have a low impact on the environment, provided that soil, water and air are adequately protected (e.g. protection against odour emission). Therefore, according to the authors, locating MSWCPs in rural areas does not require the creation of a very wide buffer zone to provide additional protection of individual elements of the environment, as described by Malinowski and Religa [2016]. Therefore, the analysis designated a large number of potential MSWCP locations.

CONCLUSIONS

The process of selecting sites for Municipal solid Waste Collection Points (MSWCPs) in Poland (especially in rural areas) is important and difficult. The task involves a high complexity and the need to reach a compromise between environmental and social points of view. Formal location criteria for this type of a facility have not been established yet. The article lists basic and detailed criteria for locating MSWCPs in rural areas with the use of the GIS spatial analysis and the analytical hierarchy process (AHP). The method was successfully verified (accuracy of the approach: <10%) in the rural commune of Liszki. Depending on the adopted option and distance from residential areas, the analyses designated 88 to 247 potential locations of MSWCPs with a minimum area of 0.2 ha. The GIS-based method was used to determine the location of MSWCPs and the AHP was employed to evaluate their suitability. This led to the identification of quasi-optimal solutions. The procedure can be used to select potential locations for MSWCPs in rural areas. The number and quality of criteria can be changed to adjust them to the specific nature of a prospective MSWCP site. Moreover, weights of particular criteria in the AHP assessment may change as well.

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