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Algorithm for Evaluating the Difficulty of Land Consolidation Using Cadastral Data

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Abstract: Optimum planning and effective land consolidation, widely discussed by contemporary authors, is a response to the perceivable need to modernise global agriculture to ensure the community's food security and create steady, sustainable development in rural areas. Adequate leveraging of agricultural policy instruments requires setting a correct strategic direction, including allocating available funds and considering the technical feasibility of the adopted assumptions. The selection of relevant methods to ensure the efficient and complete accomplishment of the anticipated results should follow a rational analysis of the actual work complexity. This paper presents an innovative, proprietary method for evaluating the difficulty of potential land consolidation using a standardised cadastral data set. The designed tool, which relies on automated algorithms applied in a GIS environment, provides accurate data describing the expected land consolidation complexity at individual stages of the procedure. Detailed and current information on land ownership, use, and farm geometry processed using efficient spatial and statistical analysis methods provides transparent and unambiguous results. The proposed solution was used in developing the difficulty assessment of land consolidation in 58 villages of the Strzyżów district in southeastern Poland.

Keywords: land consolidation; rural land use; algorithm; GIS; cadastre

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1. Introduction

Several issues related to the efficiency of contemporary agriculture, such as the global economic pillar and determining the population's general existence, involve the spatial structure of rural areas as an agricultural production space. A rational division of land based on the optimum utilisation of agricultural areas and ensuring convenient land management conditions translates into real crop production growth, which is relevant in the context of global food requirements [1].

Land consolidation is a strategic tool for realistic spatial governance of rural areas, following sustainable development policy, perceived as areas of economic activity, living space, and ecosystem elements [2–5]. Worldwide, researchers have analysed the monitoring of the domestic land consolidation process and evaluated the implemented solutions. Jin et al. evaluated the results of a long-term land consolidation plan implemented in China. They point to the positive effect of land consolidation on domestic agricultural productivity, underlining that the observed results do not fully reflect the programme's assumptions [6]. Bizoza (2021) describes specific studies of the various aspects of land consolidation schemes in Rwanda. Comparing the outcomes of different analyses conducted over the past decade, he highlights the predominance of conclusions pointing to a relationship between land consolidation and, among other effects, increased crop yield, improved living conditions, and indirectly, the observed economic growth [7]. Similar analyses have been conducted in China [8], India [9], and Turkey [10–12] and many countries of Central and Eastern

Europe, including Czechia [13], Poland [14], Slovakia [15–18], Slovenia [19], Estonia [20], Lithuania [21], Finland [22], Albania [23], Croatia [24], and Serbia [25].

The efficiency of land consolidation measures is determined by a variety of specific factors, including imposing a defined work strategy on team staffing and developing an internal schedule of tasks statutorily completed by Polish regional governments supported by state regional organisational units—land surveying and agricultural area offices and their divisions [26,27]. Rational employment of resources and correct work organisation translate into the rate and quality of individual measures and, consequently, the maximum benefits of the land consolidation process [28]. Hence, land consolidation planning based on the description of the consolidated site should be considered an essential technical component of the broadly defined land consolidation procedure [29].

Many researchers have raised the necessity of designing evaluation criteria for consolidated land in view of potential work complexity. There are numerous approaches to formulating such expert evaluations. The world literature documents the processing of various source data into measurable indicators, which constitute the difficulty evaluation criteria of individual work stages. Among the proposed solutions, experts have suggested aerial image analysis [30] and examination of changes in land cover and land abandonment specificity [31–33].

The primary source analysed under the broadly defined evaluation of consolidated land is a cadastral data set representing the direct objects of land consolidation. Common indicators include criteria such as parcel shape and size [34], ownership structure [35], land fragmentation and scattering [36], and other characteristics of agricultural holdings [30]. These factors can simultaneously be indicators of land consolidation needs [36] and tools for evaluating the consolidation measures undertaken [37].

An extension to the customarily practiced methods of analysing cadastral data in the land consolidation context can be supplementary research involving factors calculated using geomatic tools, including GIS technology [25,38,39]. The georeferenced graphic part of the cadastral database can provide information on the characteristics of building development [40], the spatial diversity of agricultural holdings, and specific land uses [41]. These indicators, which directly refer to real space, can be regarded as particularly relevant to reliable land evaluation for potential difficulties in consolidation.

This study proposes an in-depth statistical geospatial analysis of selected quantitative and qualitative characteristics of the cadastral database, reflected in the difficulty of potential land consolidation. The proposed solution, designed as a model of algorithms activated by QGIS 3.34 software, ensures the automated calculation of parameters, such as cadastral parcel geometry, specific land uses, and the number of potential consolidation participants and their agricultural holdings. The tool was tested and implemented to evaluate the difficulty of land consolidation by the Subcarpathian Office of Land Surveying and Agricultural Areas in Rzeszów, as an alternative to former professional evaluations conducted by a committee. The Methods section contains a detailed description of the algorithm and its application.

A self-designed calculation method for the experimental analysis of difficulties in potential land consolidation in the rural areas of the Strzyżów district (Subcarpathian voivodeship). Figure 1 shows the location of the study area.

The study area was located in southeastern Poland, within the administrative limits of the Subcarpathian voivodeship. The Strzyżów district is situated at the boundary of two physico-geographical mesoregions. Its eastern part is located in the Strzyżów Foothills, whereas the western one extends into the Dynów Foothills. The region incorporates the Carpathian Flysch Belt. A characteristic feature of the area is the presence of hill ranges reaching up to 500 m above sea level, with the Wisłok River flowing in between them. The hills are covered with mosaic-like fields and forests [42,43].

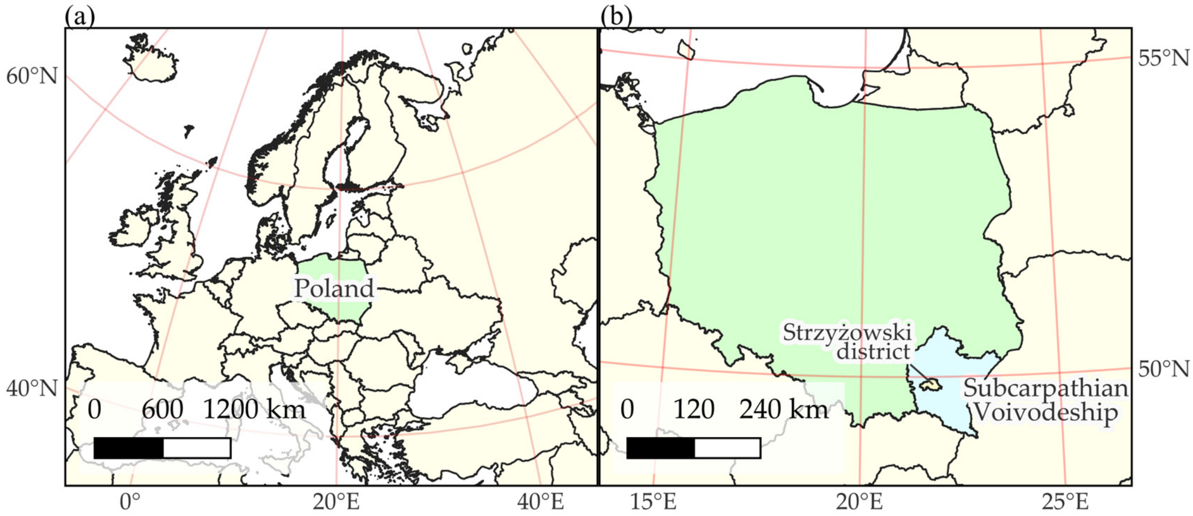

Figure 1. Map location of the study area in Europe (**a**) and Poland (**b**). Source: own elaboration.

According to Statistics Poland (GUS), in 2022, the overall area of the district was 503 km^2, consisting of four rural communes and one urban-rural commune. However, owing to the nature of the study, the analysis did not cover the town of Strzyżów. Excluding urban areas, the study area extends over 489 km^2. The survey covered 58 villages with a total population of about 51,000 [44].

2. Materials and Methods

The objective of this study was to develop a practical survey tool for evaluating the difficulty of potential land consolidation based on cadastral data using the following criteria:

- ensuring reliable results of analyses
- maintaining accessibility to service
- optimising working time, and
- access to input data.

The above postulates, owing to the practical nature of the undertaking, were the main drivers for the adopted solutions and the general criteria for evaluating the final product.

2.1. Acquisition and Selection of Inputs

In the Republic of Poland, the legal standard for exchanging geodetic and cartographic information since 1 January 2023 is solely the Geography Markup Language (GML) [45]. Such files preserve the standardised database structure of the land and building register used as a cadastral resource [46]. However, the software used by bodies keeping the land and buildings register, which form part of district offices and town halls, also provides the possibility of making all or a selected part of the graphical and descriptive data available in alternative formats, including SWDE (for graphical and descriptive data), KCD, DWG, DXF, DGN, SHP (for graphical data), XML, and XLS (for descriptive data).

Given the diversity of available data transfer forms, the tool was designed to support a wide range of existing formats, limiting the data selection criteria mainly to issues related to the content to be analysed. Based on the data availability criterion, four required source data modules were specified with a spatial range covering the precincts (localities) to be analysed:

- vector, polygon layers representing cadastral parcels, land uses, soil class contours, and buildings (contained in a database file or transferred as separate files)
- a list of land parcels linked by a relationship to cadastral units, entities (owners or users), and land and mortgage register numbers (in the form of a database structure, table, or array of tables linking the IDs of individual objects).

The required scope and structure of data are shown in a simplified, illustrative diagram (Figure 2).

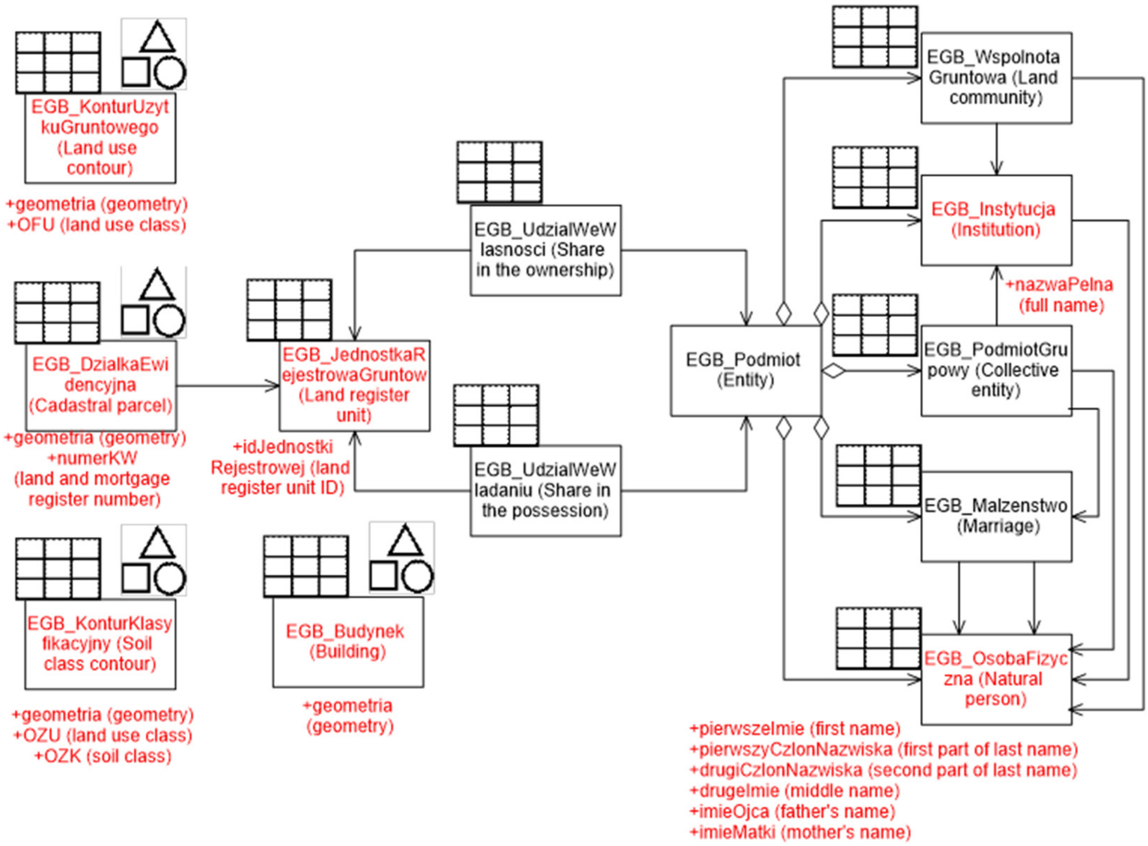

Figure 2. Simplified cadastral data acquisition structure. Source: Regulation, 2021a; own elaboration.

The required input data set, as described above, forms part of the land and building register (EGiB) database, which is made available from time to time, among other purposes, for land and building register modernisation and for land consolidation and exchange, which is the background for this research. Red denotes objects and their attributes used in the analysis. The table symbol or geometric figure next to the object name indicates the nature of the data set. To ensure legibility and transparency, some elements of the database structure, such as relationship cardinality, were not included. A complete Unified Modelling Language (UML) scheme representing the land and buildings register database is laid down in the Regulation of the Minister of Economic Development, Labour and Technology of 27 July 2021 concerning the Land and Buildings Register [46].

The analysed objects form part of a relational database structure. Where the available input data are unrelated vector layers and tables, the data should be concatenated according to relevant legislation [46], followed by the export of the desired summaries, as described later in this section. If a complete database is provided by the records keeper in the relevant GML format [45] or alternative database formats, the necessary source information can be selected using SQL queries, among other methods.

2.2. Analyses

Based on the experience documented in the world literature, expertise, and methods defined in the existing work standards of the Subcarpathian Office of Land Surveying and Agricultural Areas in Rzeszów [47], we specified the categories of potential analyses in terms of technical difficulties related to consolidated sites that could be conducted using available cadastral data. Table 1 presents a general summary of the indicator values for different survey categories, their applications in the assessment of land consolidation sites, and the range of source data used.

Table 1. List of work difficulty analyses referring to individual land consolidation stages and information on the data used. Source: [47]; own elaboration.

Indicator	Examined Value	EGiB Database Objects Used	Reference to Land Consolidation Stage
W_A	Number of soil class contours per 1 ha of the consolidated land	EGB_KonturKlasyfikacyjny EGB_DzialkaEwidencyjna	Soil classification control
W_B	Building land, forests and wooded areas share of the total consolidated land	EGB_KonturUzytkuGruntowego EGB_DzialkaEwidencyjna	Measurement of invariable land components Land appraisal Development of a pre-consolidation register
W_C	Number of land consolidation project participants per 1 ha of the consolidated land	EGB_OsobaFizyczna EGB_Instytucja EGB_DzialkaEwidencyjna EGB_UdzialWeWlasnosci EGB_UdzialWeWladaniu EGB_Podmiot EGB_WspolnotaGruntowa EGB_PodmiotGrupowy EGB_Malzenstwo	Recording the wishes of land consolidation project participants on the desirable location of equivalent land and releasing the pre-consolidation register Land consolidation project presentation, gathering and reviewing objections and concerns Making changes, preparing data for land consolidation project approval and developing terms and conditions for takeover
W_D	Number of agricultural parcels per 1 ha of the consolidated land	EGB_DzialkaEwidencyjna	Recording the wishes of land consolidation project participants on the desirable location of equivalent land and releasing the pre-consolidation register Preparing and consulting a preliminary layout of parcels Developing a detailed project and post-consolidation register Land consolidation project presentation, gathering and reviewing objections and concerns Making changes, preparing data for land consolidation project approval and developing terms and conditions for takeover
W_E	Number of cadastral units per 1 ha of the consolidated land	EGB_JednostkaRejestrowaGruntow EGB_DzialkaEwidencyjna	Recording the wishes of land consolidation project participants on the desirable location of equivalent land and releasing the pre-consolidation register; Preparing and consulting a preliminary layout of parcels
W_F	Parcel shape and elongation	EGB_DzialkaEwidencyjna	Preparing and consulting a preliminary layout of parcels, developing a detailed project and post-consolidation register

Eight elementary analyses (research modules), using a total of 13 objects of the land and register database, were foreseen for the detailed assessment of the difficulties in land consolidation based on cadastral data. Red denotes key objects understood as components subject to direct spatial and database analysis. Black denotes auxiliary objects used to recreate the relationship between key objects.

Given the diverse nature of the research, stemming from a wide range of potential applications, the achievement of the study's main objective was divided into stages corresponding to elementary analyses. For each analysis in the table, a separate algorithm for computing the sub-results independently of the other analyses was developed. Each designed algorithm is simultaneously an integral module of an algorithm aggregating the indicators by considering their weights (a detailed tool specification is presented later in this section). Moving away from the concept of data integration and the development of a unified computational model implies the presence of redundant operations, which contributes to increasing the consumption of computational resources. However, the adopted approach makes it possible to efficiently modify the computational scheme and the range of examined factors in case of changes to the database structure standards, the introduction of new land consolidation procedure methodologies, or the need for non-standard analyses tailored to the specific features of the study area [48]. Based on empirically determined value ranges, the results of each elementary analysis were standardised with reference to a scale corresponding to the coefficients used in the practice of the entity in charge of land consolidation [47].

2.2.1. Quantitative Analysis of Selected Cadastral Objects (Indicators W_A, W_C, W_D, W_E)

Some analyses proposed relate to simple quantitative characteristics computed for land and building register database objects. The number of existing parcels, which translates into the complexity of the steps involved in establishing the boundaries of existing properties and designing post-consolidation boundaries, may add significantly to the potential difficulty of land consolidation. Another relevant indicator is the number of existing soil classification contours, which reflects the area diversity in terms of soil type and quality [49,50], determining the difficulty of developing a current land classification. Interrelated socio-legal factors, such as the number of cadastral units and all land consolidation participants, are also of key significance in planning and implementing land consolidation projects. The first factor reflects, to some extent, the total number of agricultural holdings with land within the projected consolidation area, constituting the basic units determining land appurtenance. Another factor, the number of land consolidation participants, provides indirect information on the possible intensity of difficulties communicating with landowners, including difficulty notifying the parties and establishing titles to land and potential objections and concerns regarding the land consolidation project.

However, it should be noted that the characteristics pertaining to social factors are only indicative and refer to the existing land consolidation experience. Actual problems in communication with land consolidation participants depend on several variables, for which detailed anticipation at the task planning stage may not be satisfactorily effective.

The quantitative characteristics, defined by computational modules "W_A", "W_C", "W_D", and "W_E" (cf. Table 1), to simplify the design tasks and target tool operation were based on a shared conceptual scheme underpinning the designed model algorithms. In each case examined, tabular data were used for individual sites that were sufficient for this type of analysis. The only data source with a graphical representation was the parcel necessary to calculate the exact surface area covered by the study. Figure 3 shows a graphical representation of the simplified data-processing idea.

Converting absolute data in the form of the number of surveyed sites into a value referring to the surface area makes it possible to subsequently compare the specific characteristics of surveyed sites of various sizes and develop an aggregate description of land consolidation difficulties, constituting a factor adjusting the nominal surface area or a synthetic index facilitating comparisons between surveyed objects.

Sections Density of Soil Class Contours Per 1 ha of the Consolidated Land (Indicator W_A)–Number of Cadastral Units Per 1 ha of the Consolidated Land (Indicator W_E) contain detailed descriptions of the respective computational modules.

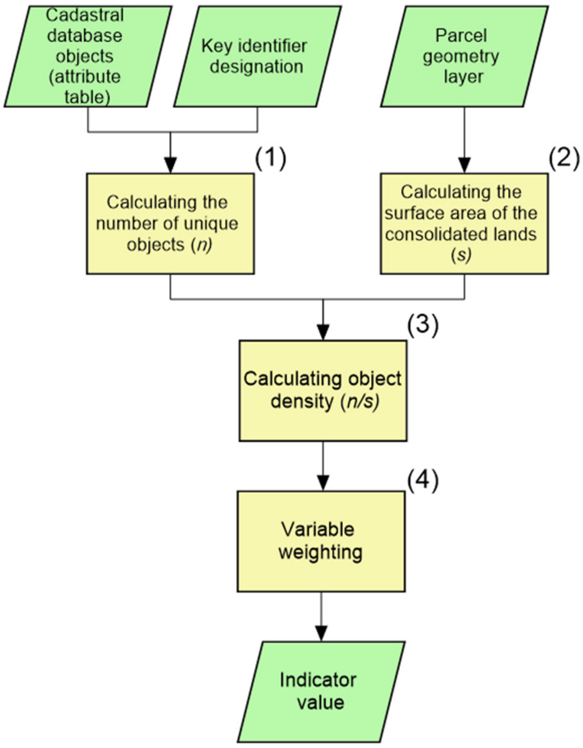

Figure 3. General flow chart of the procedure for determining quantitative characteristics for modules "W_A", "W_C", "W_D", "W_E" Source: own elaboration.

Density of Soil Class Contours per 1 ha of the Consolidated Land (Indicator W_A)

The verification and updates of the soil classification of land during land consolidation and exchange activities imply significant changes in the real estate cadastre and affect the conditions of agricultural land management. The value of the assigned OZU (land use designation) and OZK (soil class designation) attributes, defining land use and soil class of land, respectively, is used in the valuation of farms and determines the possibility and conditions for excluding land from agricultural production [51]. The special significance of land classification necessitates the performance of tasks involving several time-consuming field and desk studies in a reliable and detailed manner. The complexity of this activity significantly increases when there is a great diversity of soils in terms of structure and quality class.

The adopted elementary measure denoted by W_A is calculated according to the following formula:

$$W_A = \frac{n_K}{S}$$

where:

n_K—number of cadastral contours within the consolidated site

S—surface area of the consolidated site

Density of Land Consolidation Project Participants per 1 ha of the Consolidated Land (Indicator W_C)

The underlying condition for correct land consolidation is the development and implementation of optimal solutions for each participant in the project, who are understood as owners of land within the consolidated area. The number of entities involved in a consolidation project (individuals, marriages, and institutions) significantly affects the complexity of land consolidation. The large number of people with different preferences for, among other things, the location and shape of their holdings contribute to increasing the difficulty in designing land consolidation projects and the risk of conflicts of interest between the concerned individuals. The number of land consolidation participants also affects the time needed to carry out any activities that require direct communication with landowners.

Determining the number of potential land consolidation participants requires compiling a list of landowners for each surveyed locality. As the data on the land and its owners are stored in a relational database that maintains unique identifiers for each object, retrieving the desired information is possible using a dedicated SQL query. Next, indicator W_C was calculated using the following formula:

$$W_C = \frac{n_U}{S}$$

where:

n_U—number of potential land consolidation participants (individuals, marriages, and institutions) per consolidated site

S—surface area of the consolidated object

Number of Agricultural Parcels per 1 ha of the Consolidated Land (Indicator W_D)

Eliminating the adverse phenomenon of land fragmentation within agricultural holdings [52], understood as a reduction in the number of parcels forming individual farms while increasing their surface area, is a fundamental objective of the land consolidation procedure. The existing number of agricultural parcels per unit area attests to the land fragmentation level and allows the forecast workload associated with the reorganisation of the spatial structure of the consolidated area to be determined.

The development of an effective index requires the proper selection of the surveyed land, a prerequisite for which is the adoption of an appropriate definition of an agricultural parcel and a correct selection of criteria for filtering the set of registered parcels available in the resources of the real estate cadastre.

Polish legislation includes the concept of "agricultural parcel" [53,54], which is currently used to delimit areas for subsidy payments under the Common Agricultural Policy (CAP) for 2023–2027. According to Regulation (EU) 2021/2116 of the European Parliament and of the Council of 2 December 2021 on the financing, management, and monitoring of the common agricultural policy and repealing Regulation (EU) No 1306/2013, an agricultural parcel is a "unit, defined by Member States, of agricultural area" [55].

According to the Act of 8 February 2023 on the Strategic Plan for the Common Agricultural Policy for 2023–2027, an agricultural parcel is "a compact area of land that is agricultural land comprising no more than one group of crops, except that a short-rotation coppice constitutes a separate agricultural parcel" [56]. This definition differs significantly from the definition of the "cadastral parcel", which is the basic unit of area in the real estate cadastre, defined in the Regulation of the Minister of Development, Labour and Technology of 27 July 2021, concerning the land and buildings register (EGiB) as "a continuous area of land, located within the boundaries of a single cadastral precinct, homogeneous in legal terms, delimited by the boundaries of cadastral parcels" [46].

The lack of an unambiguous spatial relationship between the existing models of "agricultural parcel" and "cadastral parcel", leading to potential complications in the interpretation of laws [57–59], necessitates the development of an alternative, working definition of "agricultural parcel" corresponding to the specific features of the land consolidation procedure. Because of the need to keep the applied solutions in line with the structure of the land and building register database, we assumed that the spatial range of the agricultural parcel was identical to that of the corresponding cadastral parcel. On the basis of this assumption, a set of agricultural parcels was delimited from a set of cadastral parcels. Therefore, a selection criterion for agricultural parcels was designed based on the percentage of agricultural land in the total cadastral parcel area. To meet the requirements of this task, an additional technical computing module was developed with the option of adjusting the minimum share of agricultural land that qualifies a parcel of land as an agricultural parcel. Our analysis assumed that an agricultural parcel was any cadastral parcel of land for which at least 50% of the area comprises total agricultural land within the meaning of the Regulation of the Minister of Economic Development, Labour and Technology on 27 July 2021 concerning the land and buildings register [46], excluding ditches.

The number of agricultural parcels per unit area, denoted by W_D, was calculated according to the following formula:

$$W_D = \frac{n_D}{S}$$

where:

n_D—number of agricultural parcels within the consolidated site

S—surface area of the consolidated site

Number of Cadastral Units per 1 ha of the Consolidated Land (Indicator W_E)

A preliminary analysis of the number of cadastral units made it possible to estimate the number and size of agricultural holdings within a potential land consolidation site. This information is a key factor in determining the duration and technical complexity of designing the optimised spatial structure of the consolidated locality. A distinctively large number of agricultural holdings per unit area may be related to the lack of the technical possibility of making significant changes to their layout.

The indicator describing the number of cadastral units per unit area, denoted by W_E, was calculated according to the following formula:

$$W_E = \frac{n_J}{S}$$

where:

n_J—number of cadastral units within the consolidated site

S—surface area of the consolidated site.

2.2.2. Building Land, Forests and Wooded Areas Share of the Total Consolidated Land (Indicator W_B)

An essential aspect of assessing the difficulty of land consolidation is the potential duration of fieldwork, which includes the geodetic measurement of so-called non-relocatable terrain invariants. To assess the complexity of this stage, an algorithm was designed to compute the share of the area covered by invariable elements in the total consolidated land. The tool relies on a geometric-tabular dataset representing land use, as defined by the class EGB_UzytkiGruntowe. The land use information required by the algorithm was extracted based on the attribute denoted as OFU in the database application schema. However, to ensure the compatibility of the tool with non-standard data, the possibility of indicating the correct land use designation field is left to the user. Figure 4 presents a flowchart of the computational module operation.

This indicator, denoted by W_B, is calculated according to the following formula:

$$W_B = \frac{1}{S} \times \left(S_B + S_{Ba} + S_{Bi} + S_{Bp} + S_{Br} + S_{Bz} + S_{Ls} + S_{Lz} + S_{Lzr}\right)$$

where:

S—surface area of the consolidated site.

S_B—surface area of land use "B" (housing area) within the consolidated site

S_{Ba}—surface area of land use "Ba" (industrial area) within the consolidated site

S_{Bi}—surface area of land use "Bi" (other built-up land) within the consolidated site

S_{Bp}—surface area of land use "Bp" (urbanised land without buildings or under building development) within the consolidated site

S_{Br}—surface area of land use "Br" (built-up agricultural land) within the consolidated site

S_{Bz}—surface area of land use "Bz" (leisure areas) within the consolidated site

S_{Ls}—surface area of Ls" (forests) within the consolidated site

S_{Lz}—surface area of land use "Lz" (wooded areas) within the consolidated site

S_{Lzr}—surface area of land use "Lzr" (wooded areas within agricultural land) within the consolidated site

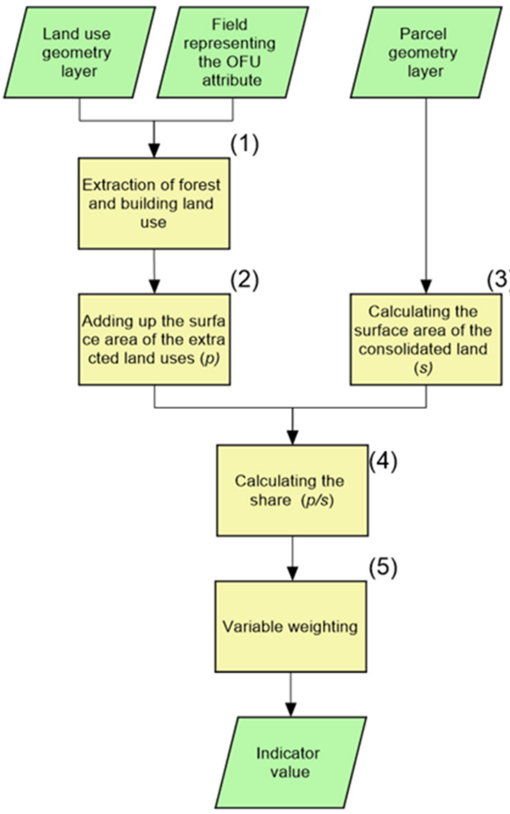

Figure 4. Flow chart of the algorithm for computing the forest and wooded area share of the total consolidated land. Source: own elaboration.

2.2.3. Parcel Shape and Elongation (Indicator W_F)

The presence of cadastral parcels of particularly unfavourable shapes, including excessively elongated and irregular polygons, is a key factor indicating the legitimacy of adjusting the spatial structure of agricultural holdings in the course of the land consolidation procedure. Simultaneously, highly complex parcel layouts increase the difficulty in designing optimal solutions for land exchange between agricultural holdings.

To provide a comprehensive and reliable tool for assessing parcel geometry, the internationally recognised Parcel Shape Index (PSI) method, as proposed by Demetriou [34], was used. The synthetic index is the result of an analysis based on six elementary factors, calculated using formulas based on expert judgement:

- parcel boundary length (f_1):

$$f_1 = 0.99 + 1.49 \times \left(10^{-2} \times {x_1}^{1.5}\right) - 0.46 \times \left({x_1}^{0.5}\right)$$

where x_1—boundaries with length < 25 m.

- acute angles (f_2):

$$f_2 = \left(1 + 6.05 \times x_2 + 2.71 \times {x_2}^2\right)^{-1}$$

where x_2—acute angles $\leq 80^\circ$.

- re-entrants (f_3):

$$f_3 = \left(1 + 6.05 \times x_3 + 2.71 \times {x_3}^2\right)^{-1}$$

where x_3—re-entrants (215°; 360°).

- number of boundary points (f_4):

$$f_4 = 14.45 - 407.76 \times {x_4}^{-1} + 4280.97 \times {x_4}^{-2} - 20,959.323 \times {x_4}^{-3} + 49,414.25 \times {x_4}^{-4} - 45,677.80 \times {x_4}^{-5}$$

where x_4—number of boundary points.

- shape density (f_5):

$$f_5 = 1,467,298,744.97 \times {x_5}^6 + 4,133,386,014.178 \times {x_5}^5 - 45,406,553.82 \times {x_5}^4 + 2,435,303.92 \times {x_5}^3 - 65,445.193 \times {x_5}^2 + 831.98 \times x_5 - 3.91$$

where x_5—density indicator;

$$x_5 = \frac{S}{L^2}$$

where:
S—area
L—perimeter (total length of the outline)

- shape regularity (f_6).

For an indicator of parcel shape regularity, the author does not specify an explicit calculation formula but cites the accepted definition of a regular-shaped polygon as a figure with rotational symmetry and characterised by equal edge lengths and equal measures of internal angles [34]. However, based on this assumption, the regularity of parcel shapes can only be defined as a binary variable. Given the need for the factor to be realistically measurable, a self-designed formula was created based on the above definition.

The modified index is based on an analysis of the standard deviation of the distance between the vertices of a polygon and its geometric centre. This approach provides a relatively reliable assessment of the shape's regularity. Exceptions are vertices situated on a straight line traced by adjacent points, or at a negligible distance from this straight line. Such vertices are of minimal relevance to parcel shape characteristics; however, they affect the index value. To solve this problem, vertices were excluded from the analysis (rejected) if the corresponding interior angles of the polygon had measures in the range of 170° to 190°. A case example is shown in Figure 5.

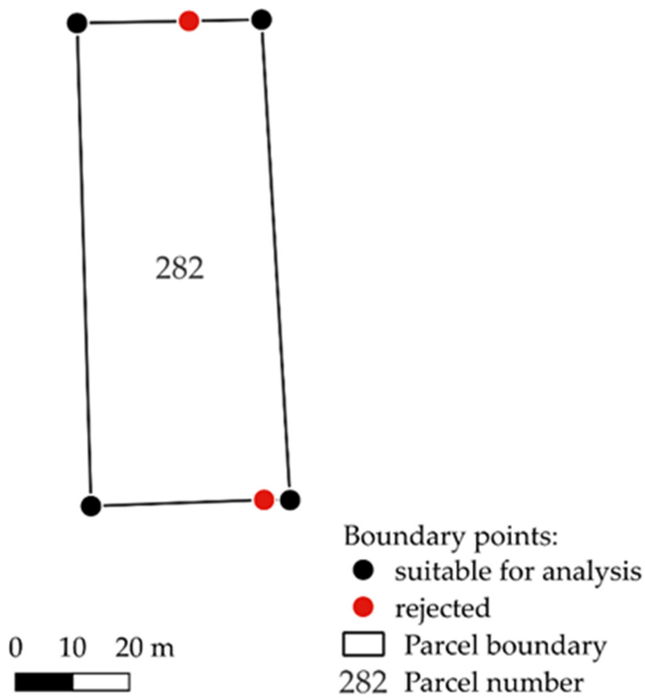

Figure 5. Example of rejected boundary points (red colour). Source: own elaboration.

The indicator values were calculated using the following formula:

$$x_6 = \frac{\sum_{i=1}^{n_j} \left(\sqrt{\left(X_{P_i} - X_D\right)^2 + \left(Y_{P_i} - Y_D\right)^2} - \sum_{i=1}^{n_j} \frac{\sqrt{\left(X_{P_i} - X_D\right)^2 + \left(Y_{P_i} - Y_D\right)^2}}{n} \right)^2}{n}$$

where:

x_6—shape regularity index for the parcel
n—number of vertices of the parcel (except the rejected vertices)
X_{P_i}—X coordinate of the i-th vertex of the parcel
Y_{P_i}—Y coordinate of the i-th vertex of the parcel
X_D—X coordinate of the geometric centre of the parcel
Y_D—Y coordinate of the geometric centre of the parcel

In the case of polygons with regular shapes, for which the measured distances are identical, the indicator takes the value of 0. By contrast, high index values were observed for shapes with a varied distribution of vertices, indicating a lack of regularity.

The overall value of the parcel shape index for the surveyed precinct takes the following form:

$$x = \frac{\sum_{j=1}^{m} \left(\frac{\sum_{i=1}^{6} x_{j_i}}{6} \times S_j \right)}{\sum_{j=1}^{m} S_j}$$

where:

x—aggregated parcel shape index value for the surveyed precinct
x_{j_i}—value of the i-th elementary indicator for the j-th parcel
i—elementary index: $i\epsilon\{1, 2, \ldots, 6\}$
j—cadastral parcel index: $j\epsilon\{1, 2, \ldots, m\}$
m—number of parcels in the surveyed precinct
S_j—surface area of the j-th parcel

2.2.4. Elementary Indicators Synthesis and Ranking Calculation Using the TOPSIS Method

The computed values of the elementary indicators W_A—W_F were expressed in different units and fell into different ranges. For the proper interpretation of the results, it was necessary to ensure that it was technically possible to compare the values of the individual variables and develop a synthetic evaluation of the surveyed sites.

The multiple-criteria decision-making method TOPSIS (Technique for Order Preference by Similarity to Ideal Solution), proposed by Hwang and Yoon [60], was used for the synthesis of the resulting characteristics.

According to the adopted method, the values of the elementary variables were first normalised using the following formula:

$$z_{ij} = \frac{x_{ij}}{\sqrt{\sum_{i=1}^{n} x_{ij}^2}},$$

where:

z_{ij}—normalised value of the j-th variable for the i-th object
x_{ij}—value of the j-th variable for the i-th object.

Next, the coordinates (benchmark values of the individual variables) were determined for ideal and anti-ideal benchmarks. For the ideal benchmark, the following formula is used to determine the coordinates:

$$z_{0j}^{+} = \begin{cases} \max\limits_{i}\{z_{ij}\}, if\ W_j \in LTB \\ \min\limits_{i}\{z_{ij}\}, if\ W_j \in STB \end{cases}$$

where:

z_{0j}^{+}—ideal benchmark coordinates

z_{ij}—normalised value of the j-th variable for the i-th object

W_j—examined variable with j index

STB—set of smaller-the-better variables (stimulants)

LTB—set of larger-the-better variables (destimulants).

The coordinates of the anti-ideal benchmark (counter-benchmark) were determined using the following formula:

$$z_{0j}^{-} = \begin{cases} \min_{i}\{z_{ij}\}, if W_j \in LTB \\ \max_{i}\{z_{ij}\}, if W_j \in STB \end{cases}$$

where:

z_{0j}^{-}—anti-ideal (counter) benchmark coordinates

z_{ij}—normalised value of the j-th variable for the i-th object

W_j—examined variable with j index

STB—set of smaller-the-better variables (stimulants)

LTB—set of larger-the-better variables (destimulants).

The Euclidean distances from the ideal benchmark and anti-ideal benchmark were then determined for each object. The distance from the ideal benchmark was calculated using the following formula:

$$d_{i0}^{+} = \sqrt{\sum_{j=1}^{m}\left(z_{ij} - z_{0j}^{+}\right)^2}$$

where:

d_{i0}^{+}—distance of the i-th object from the ideal benchmark

z_{ij}—normalised value of the j-th variable for the i-th object

z_{0j}^{+}—ideal benchmark coordinate for the j-th variable

In contrast, the distance from the anti-ideal benchmark was determined using the following formula:

$$d_{i0}^{-} = \sqrt{\sum_{j=1}^{m}\left(z_{ij} - z_{0j}^{-}\right)^2}$$

where:

d_{i0}^{-}—distance of the i-th object from the anti-ideal benchmark

z_{ij}—normalised value of the j-th variable for the i-th object

z_{0j}^{-}—ideal benchmark coordinate for the j-th variable

The final calculation step involves computing the value of the synthetic variable in the form of a ranking coefficient:

$$q_i = \frac{d_{i0}^{-}}{d_{i0}^{+} + d_{i0}^{-}}$$

where:

q_i—ranking coefficient for the i-th object

d_{i0}^{-}—distance of the i-th object from the anti-ideal benchmark

d_{i0}^{+}—distance of the i-th object from the ideal benchmark.

The calculations assumed that the "ideal benchmark" is a potential site of maximum difficulty in land consolidation. Therefore, the set of stimulants of the examined feature includes variables whose higher values increase the synthetic score of land consolidation difficulty. Table 2 presents the division of the examined variables into stimulants and destimulants.

Table 2. Division of study variables into stimulants and destimulants. Source: own elaboration.

Stimulants	Destimulants
W_A, W_B, W_C, W_D, W_E	W_F

The values of the factor describing the difficulty of the soil classification verification and updating procedure, obtained using the computational module "A", are summarised in Table 2.

3. Results

Based on calculations using a self-designed algorithm, a ranking of the surveyed villages was developed according to land consolidation difficulty. Table A1 in Appendix A summarises the computed values of the elementary indicators (W_A–W_F) and synthetic indicator values (q) and contains a potential land consolidation difficulty ranking, created using the TOPSIS method.

A detailed description of the results per analytical module, together with cartographic figures, is presented in Sections 3.1–3.6. The results of the synthesis of the values of the elementary variables and developed ranking are described in Section 3.7. Village name designations used in the figures below are explained in Table A1 (Appendix A).

3.1. Number of Soil Class Contours per 1 ha of the Consolidated Land (Indicator W_A)

Indicator W_A, describing the density of soil class contours within the cadastral precinct, assumed values between 1.34 and 4.15, with a mean value of 2.45. Figure 6 shows the spatial distribution of the indicator values.

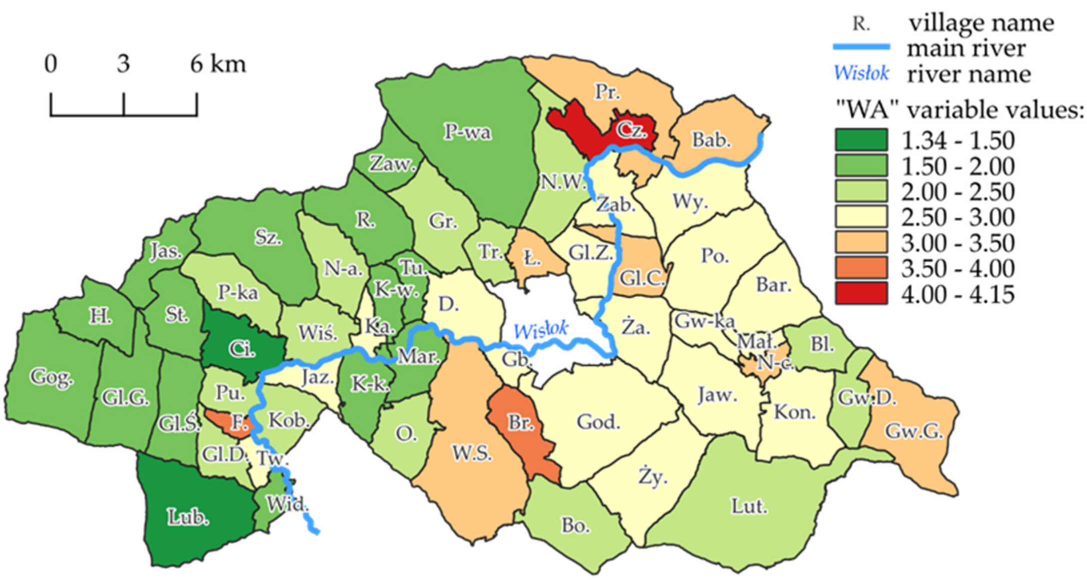

Figure 6. Spatial distribution of W_A (number of soil class contours per 1 ha of consolidated land). Source: own elaboration.

The calculated density of soil class contours takes on considerably higher values in the eastern parts of the Strzyżów district. An increased indicator value implies a potentially higher difficulty in carrying out activities related to verifying and updating the soil classification of land because of the distinctively high diversity of soil types and their usable value. A notably high score was recorded for the village of Czudec, the seat of a rural commune with the same name, located in the north-eastern part of the district.

3.2. Building Land, Forests and Wooded Area Share of the Total Consolidated Land (Indicator W_B)

The computed values of the indicator W_B, which describes the ratio of the area of building land and forests and wooded areas to the total area of all land uses in a given village, ranged from 0.10 to 0.80. The mean value was 0.45. Figure 7 shows the spatial distribution of the values of this variable.

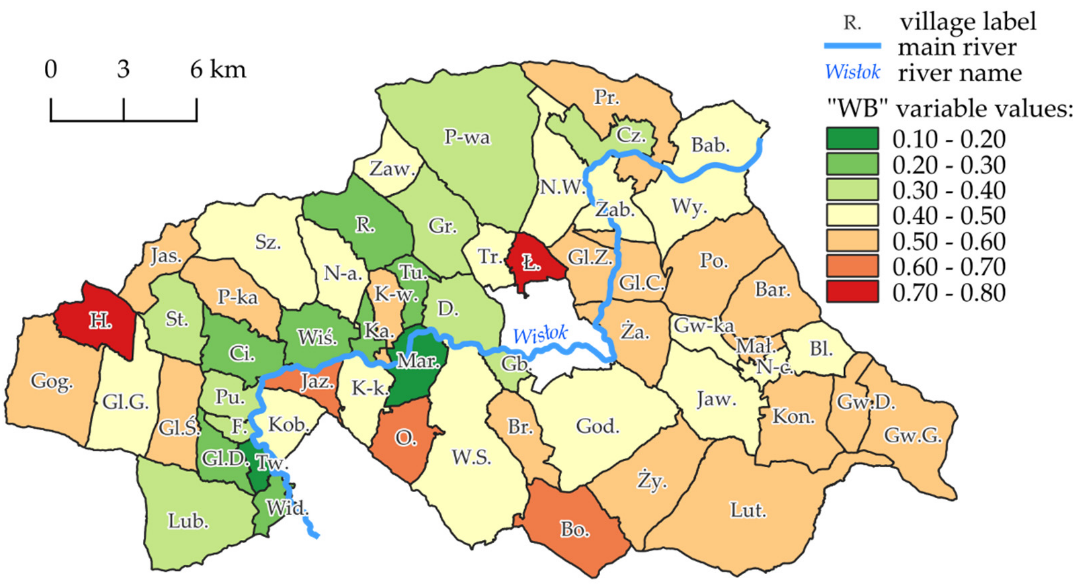

Figure 7. Spatial distribution of W_B (building land, forest, and wooded area share of the total consolidated land). Source: own elaboration.

The eastern part of the Strzyżów district features an increased proportion of total building land and of forests and wooded areas. The high forest cover in the area should be identified as an important reason for the observed phenomenon. Areas covered with high-rise vegetation and built-up land present terrain obstacles that make transportation difficult. These areas were also subject to land surveying as so-called terrain invariables. The abundance of built-up, forested, and wooded areas can significantly reduce the possibilities for designing agricultural holdings, and thus decrease land consolidation efficiency in a locality while increasing the effort and time required to complete the task.

3.3. Number of Land Consolidation Project Participants per 1 ha of the Consolidated Land (Indicator W_C)

In the analysed area, the indicator W_C, which describes the number of land consolidation participants (total number of individuals and institutions) referring to the potential land consolidation area, assumed different values ranging from 0.29 to 5.50, with a mean value of 1.26. Figure 8 shows a cartographic visualisation of the computed indicator values.

The area of Strzyżów district is predominantly characterised by a relatively low number of potential land consolidation participants, corresponding to the low population density in the rural areas of the district. The small number of landowners with a significant area of their agricultural holdings may be a circumstance fostering the design of efficient changes in the spatial structure of agricultural land.

Higher values above 1.1 land consolidation participants per 1 ha of consolidated land were recorded almost exclusively in the villages of the Wisłok River valley, featuring a higher density of settlements than the other areas. A distinctively high score was recorded for the densely populated village of Frysztak in the south-western part of the district.

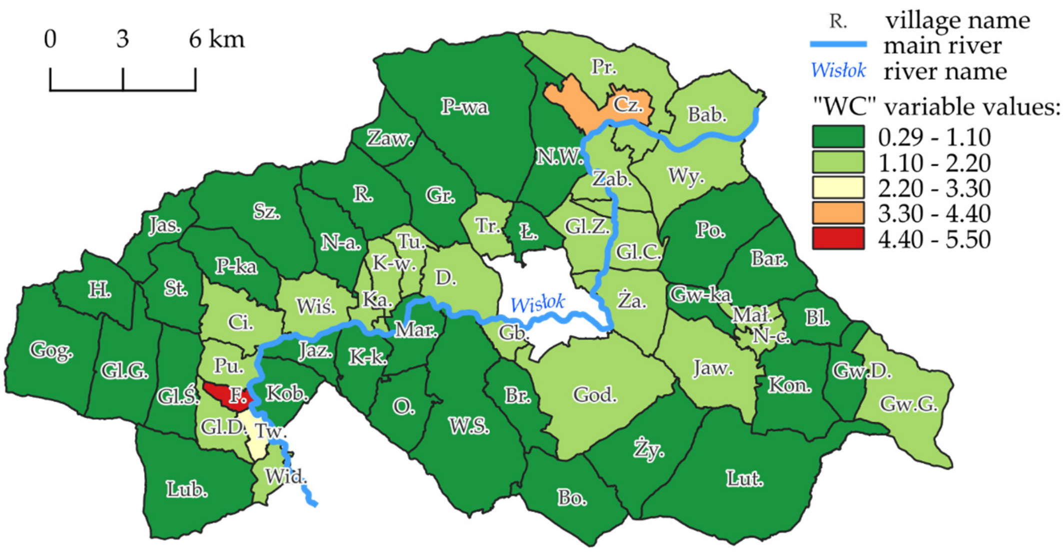

Figure 8. Spatial distribution of W_C (number of land consolidation participants per 1 ha of consolidated land). Source: own elaboration.

3.4. Number of Agricultural Parcels per 1 ha of the Consolidated Land (Indicator W_D)

The indicator W_D, representing the number of so-called agricultural parcels per unit of area, took on values ranging from 0.32 to 3.29. The mean value is 1.77. Figure 9 shows the spatial distribution of the indicator values.

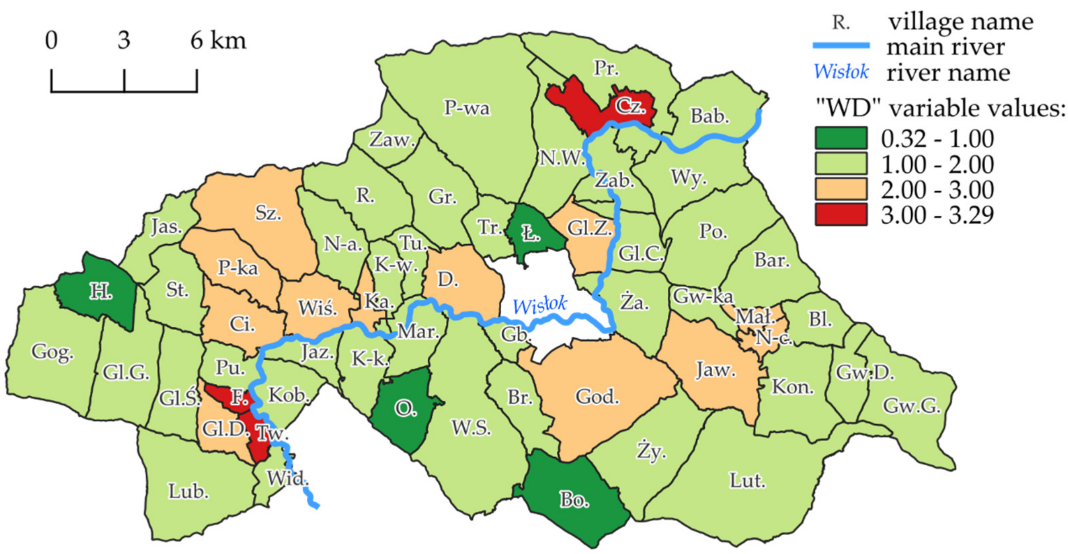

Figure 9. Spatial distribution of W_D (number of agricultural parcels per 1 ha of consolidated land). Source: own elaboration.

The values of the variable imply a similar density of agricultural parcels across almost the entire district. Only for the cadastral precincts of Frysztak, Twierdza, and Czudec do the indicators exceed three parcels per 1 ha of agricultural land. The high density of cadastral parcels, which also implies their small size, points to intense land fragmentation, which determines the rationale for land consolidation work. Concurrently, the division of holdings into a significant number of small parcels increases the complexity of the project work.

3.5. Number of Cadastral Units per 1 ha of the Consolidated Land (Indicator W_E)

The cadastral unit density index values (W_E) ranged from 0.21 to 3.64, with a mean value of 0.96. Figure 10 illustrates the spatial distribution of the computed results.

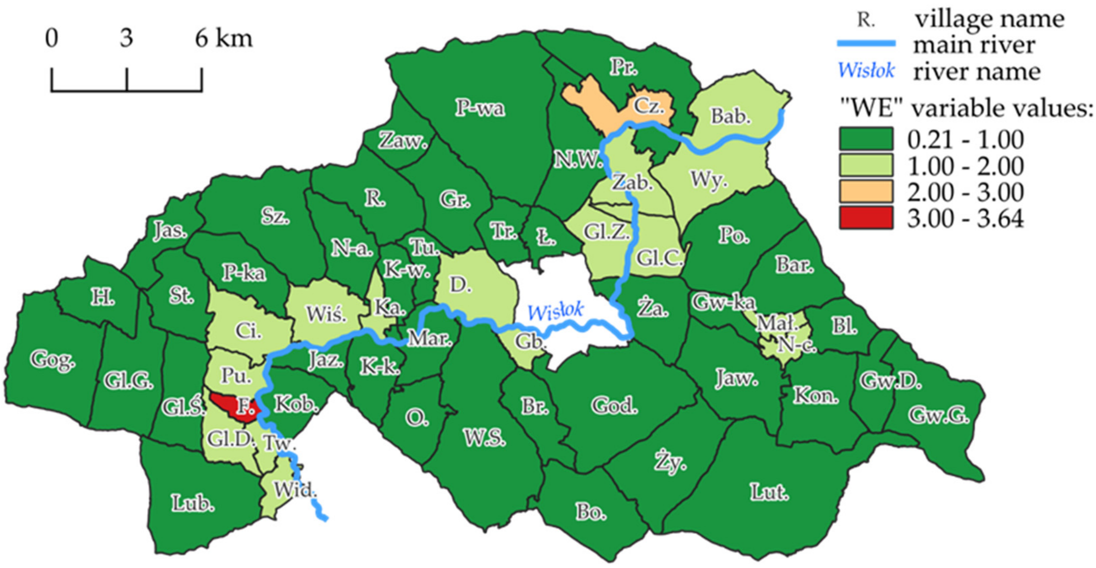

Figure 10. Spatial distribution of W_E (number of cadastral units per 1 ha of the consolidated land). Source: own elaboration.

The distribution of the density index values of cadastral units shows significant similarity to the distribution of the values of the variable W_C (density of land consolidation participants). This phenomenon should be interpreted as a strong linear relationship between the study variables (the computed correlation coefficient for the variables W_C and W_E was 0.996). A disruption to this relationship would result in variations in the spatial presence of cadastral units with a distinctively high number of entities. Since the elimination of joint ownership hindering real estate management is a procedure carried out during land consolidation, the presence of such joint ownership would provide particular information on land consolidation validity and the increased complexity of potential measures.

3.6. Parcel Shape and Elongation (Indicator W_F)

The synthetic index W_F for assessing cadastral parcel geometry took values ranging from 0.19 to 0.48, with a mean value of 0.40. Figure 11 shows the spatial distribution of the analysis results.

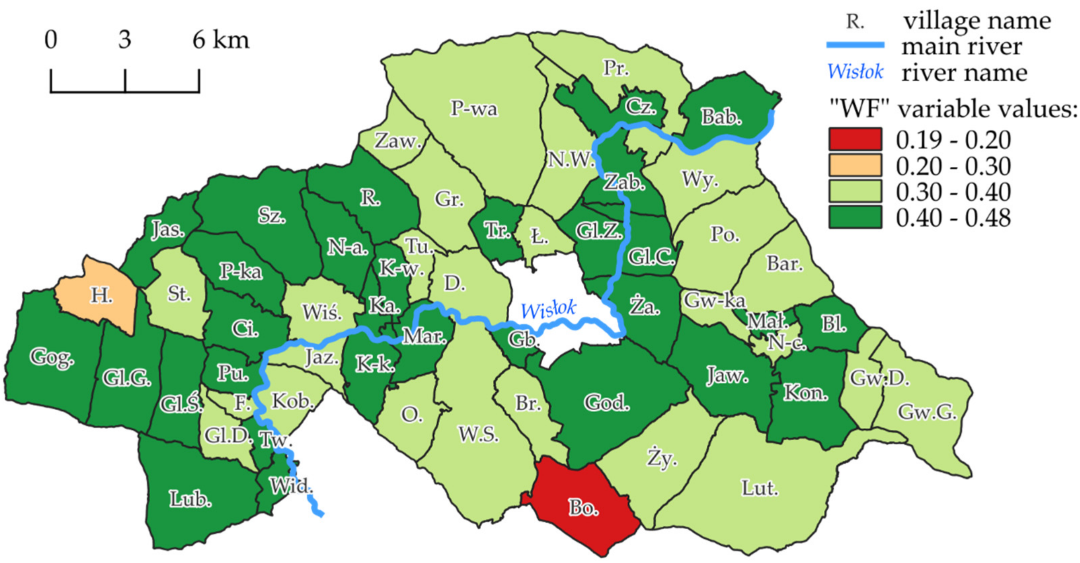

Figure 11. Spatial distribution of W_F (parcel shape and elongation). Source: own elaboration.

The recorded parcel shape and elongation indicator values in the predominant area of the Strzyżów district imply a relatively favourable parcel geometry compared with the general specificity of agricultural land in the area of the Subcarpathian voivodeship. Most surveyed villages featured a significant proportion of parcels with near-rectangular shapes. A partial disruption of the parcel geometry regularity, which affects the final value of the indicator, may be due to undulating hilly terrain. Minimum values of less than 0.30 were observed only in the cadastral precincts of Huta Głogowska (Frysztak commune) and Bonarówka (Strzyżów municipality).

3.7. Synthesis and Interpretation of Results

The values of the variables W_A—W_F were normalised, and then, using the multiple-criteria decision-making method TOPSIS, the value of the synthetic index q, characterising the potential difficulty of land consolidation in each of the surveyed localities and constituting the basic parameter of the developed ranking, was calculated. Table A1 in Appendix A summarises the precise values of the indicator q and lists the ranking positions. The spatial distribution of the results obtained in the analysed villages of the Strzyżów district by commune is shown in Figure 12.

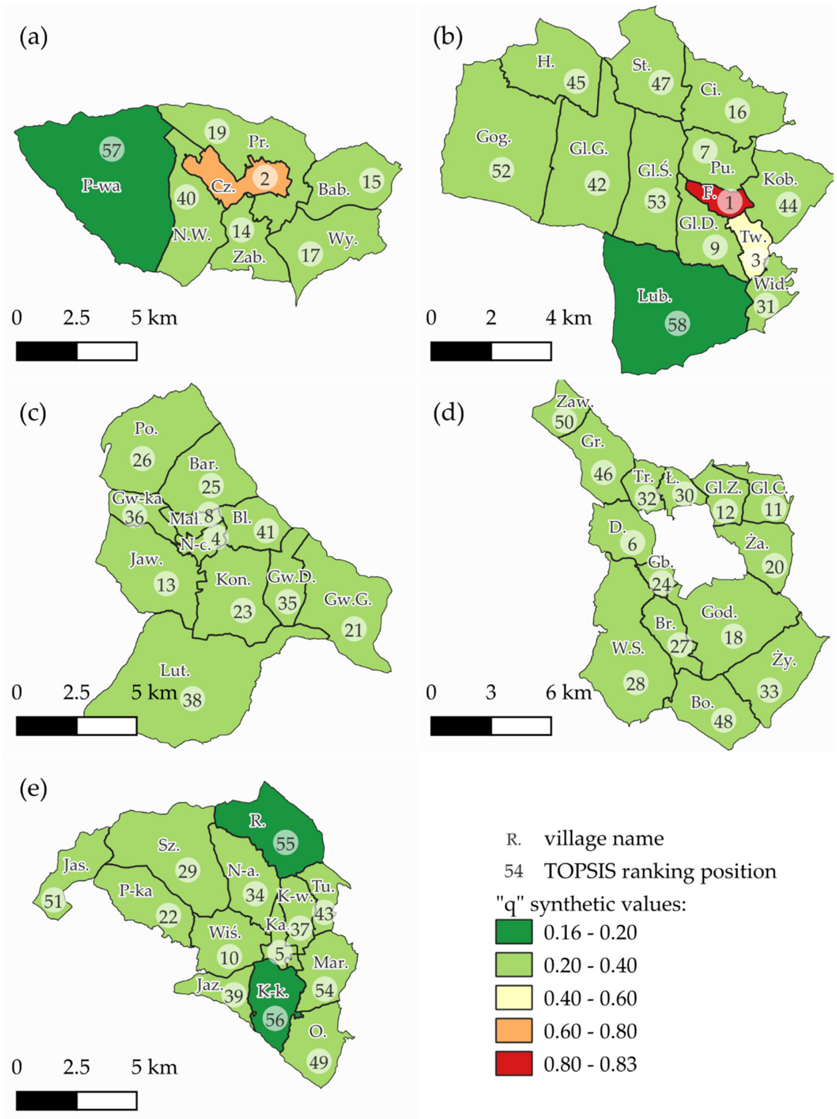

Figure 12. Values of the synthetic indicator q and ranking positions of villages in the Strzyżów district: (**a**) Czudec commune; (**b**) Frysztak commune; (**c**) Niebylec commune; (**d**) Strzyżów municipality; (**e**) Wiśniowa commune. Source: own elaboration.

The analysis of the results showed a noticeable variation in the level of land consolidation difficulty between the surveyed communes. The highest value of the synthetic index, which stands out among the other results, was recorded for the village of Frysztak, which is the seat of a commune of the same name. The village of Twierdza (ranked 3rd) and the village of Lubla with the lowest observed difficulty (ranked 58th) are also located within the boundaries of the Frysztak commune (a). An analogy was also noted in the commune of Czudec, comprising the second and second-to-last ranked villages assigned to Czudec and Pstrągowa, respectively. It is also noteworthy that eight of the ten highest-rated sites were situated on the left bank of the Wisłok River. The relationship between the surface area of the village and potential land consolidation difficulties was also examined in detail. The Pearson correlation coefficient calculated for these two variables was −0.31, indicating a weak negative relationship.

4. Discussion

The analysis of potential land consolidation difficulty is a crucial tool to support planning and implementing rural management procedures to maximise work efficiency by selecting appropriate measures and strategies. Distinctively high values for factors determining work complexity and reducing the efficiency of activities may imply a need to verify the desirability of undertaking activities in the chosen locality. However, it should be noted that the main factor determining the legitimacy of land consolidation projects remains the assessment of consolidation needs, considering various aspects of the spatial structure of agricultural land [48]. Doroż et al. also point out that due to the high cost of land consolidation activities, the projects should be implemented, in particular, in areas where the maximum benefits are expected [61]. Because of the coincidence of a considerable number of factors determining land consolidation urgency with their difficulty determinants, it should be assumed that rural management practices undertaken in areas with high nuisance parameters, in many cases, may translate into a real benefit of local agriculture restructuring and stimulation of the economic development of villages. Modern methods for automated spatial data processing [62] and design techniques based on artificial intelligence algorithms provide efficient solutions to high-complexity problems [63].

The applied research methods, designed as automated computational algorithms, have enabled efficient and detailed analyses of the ownership structure, land use, and topography for any region of Poland. It is also possible to develop alternative solutions tailored to the specific features of cadastral systems in other countries of the European Community and the world. In our opinion, a reliable and precise assessment of the complexity of potential rural management procedures should be the next level of the decision-making process, following the delimitation of localities with the highest land consolidation needs and maximum expected benefits of the projected consolidation. Adding the difficulty aspect to the rural management strategy will enable a realistic assessment of available resources, contributing to the efficient planning of measures at the level of regional and national administrations and their implementation by authorised bodies.

5. Conclusions

Proper planning and effective land consolidation project implementation are key instruments for agricultural policy. Measures to reorganise deficient spatial structures in rural areas allow for a stable increase in the productivity of local agriculture and ensure optimal living and economic conditions for rural residents. The rational management of space according to sustainable development policy also leads to an improvement in the conditions of the natural environment and landscape values.

The significance and permanence of changes introduced by land consolidation require precise planning of activities and proper disposal of available resources. The identification of land consolidation needs and delimitation of potential land consolidation objects, which are issues present in the world scientific literature, is a response to the growing need for urgent restructuring of the agricultural sector to stabilise national and global food security and adapt the agricultural production space to contemporary work methods and market requirements. This proprietary concept of assessing the potential land consolidation difficulty based on standardised cadastral data significantly contributes to the multi-criteria-based decision-making process in programming tasks and selecting their implementation methods. Detailed knowledge based on current data and advanced data processing and interpretation mechanisms is an integral factor that determines the success of the measures.

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Appendix A

Table A1. Elementary indicators and synthetic index values and ranking position for the villages of the Strzyżów district Source: authors' elaboration.

Name of Locality	Designation	Area	W_A	W_B	W_C	W_D	W_E	W_F	q	Rank
Frysztak	*F.*	150.34	3.68	0.39	5.50	3.29	3.64	0.40	0.83	1
Czudec	*Cz.*	561.53	4.15	0.31	3.39	3.18	2.34	0.45	0.61	2
Twierdza	*Tw.*	191.54	2.69	0.15	2.62	3.06	1.85	0.44	0.47	3
Niebylec	*N-c.*	198.72	3.21	0.46	2.04	2.02	1.41	0.31	0.40	4
Kalembina	*Ka.*	204.42	2.84	0.29	1.89	2.31	1.37	0.46	0.36	5
Dobrzechów	*D.*	787.82	2.92	0.31	1.77	2.48	1.32	0.40	0.36	6
Pułanki	*Pu.*	394.13	2.37	0.35	1.86	1.99	1.37	0.43	0.35	7
Małówka	*Mał.*	186.41	2.55	0.51	1.53	2.41	1.21	0.46	0.34	8
Glinik Dolny	*Gl.D.*	430.60	2.29	0.25	1.80	2.26	1.34	0.37	0.34	9
Wiśniowa	*Wiś.*	677.62	2.30	0.22	1.76	2.22	1.26	0.34	0.33	10
Glinik Charzewski	*Gl.C.*	578.93	3.17	0.51	1.44	1.77	1.16	0.41	0.32	11
Glinik Zaborowski	*Gl.Z.*	549.71	2.63	0.54	1.42	2.10	1.12	0.48	0.32	12
Jawornik	*Jaw.*	1214.61	2.64	0.47	1.13	2.79	0.94	0.45	0.31	13
Zaborów	*Zab.*	650.19	2.99	0.49	1.50	1.74	1.06	0.45	0.31	14
Babica	*Bab.*	869.82	3.01	0.49	1.42	1.80	1.07	0.41	0.31	15
Cieszyna	*Ci.*	710.28	1.34	0.30	1.56	2.39	1.21	0.42	0.31	16
Wyżne	*Wy.*	1035.88	2.92	0.49	1.38	1.72	1.05	0.39	0.30	17
Godowa	*God.*	2019.74	2.64	0.48	1.20	2.41	0.95	0.47	0.30	18
Przedmieście Czudeckie	*Pr.*	1395.54	3.22	0.53	1.37	1.48	0.96	0.38	0.30	19
Żarnowa	*Ża.*	847.22	2.66	0.58	1.29	1.71	0.98	0.42	0.30	20
Gwoźnica Górna	*Gw.G.*	1306.13	3.01	0.53	1.18	1.88	0.91	0.36	0.29	21
Pstragówka	*P-ka*	770.97	2.20	0.51	0.94	2.75	0.79	0.41	0.29	22

Table A1. *Cont.*

Name of Locality	Designation	Area	W_A	W_B	W_C	W_D	W_E	W_F	q	Rank
Konieczkowa	*Kon.*	1097.70	2.52	0.57	1.07	1.99	0.89	0.44	0.28	23
Gbiska	*Gb.*	221.60	2.89	0.40	1.40	1.50	1.03	0.41	0.28	24
Baryczka	*Bar.*	927.35	2.93	0.56	1.10	1.49	0.87	0.39	0.27	25
Połomia	*Po.*	1361.44	2.88	0.54	1.10	1.51	0.87	0.38	0.27	26
Brzeżanka	*Br.*	609.07	3.83	0.59	0.83	1.20	0.66	0.36	0.27	27
Wysoka Strzyżowska	*W.S.*	2384.54	3.08	0.49	0.87	1.92	0.78	0.40	0.26	28
Szufnarowa	*Sz.*	1494.00	1.98	0.45	1.04	2.17	0.88	0.41	0.26	29
Łętownia	*Ł.*	348.63	3.48	0.80	0.42	0.59	0.33	0.37	0.26	30
Widacz	*Wid.*	260.57	2.00	0.28	1.31	1.92	1.04	0.42	0.26	31
Tropie	*Tr.*	412.93	2.48	0.44	1.14	1.77	0.91	0.46	0.26	32
Żyznów	*Ży.*	1332.04	2.58	0.58	0.73	1.96	0.62	0.40	0.26	33
Niewodna	*N-a.*	712.20	2.16	0.47	1.03	1.95	0.85	0.43	0.26	34
Gwoźnica Dolna	*Gw.D.*	502.69	2.21	0.56	1.05	1.32	0.82	0.38	0.25	35
Gwoździanka	*Gw-ka*	345.18	2.83	0.43	0.93	1.90	0.74	0.39	0.25	36
Kożuchów	*K-w.*	394.36	1.54	0.53	1.16	1.44	0.90	0.48	0.25	37
Lutcza	*Lut.*	2815.83	2.36	0.51	0.77	1.89	0.63	0.39	0.24	38
Jazowa	*Jaz.*	380.74	2.69	0.62	0.75	1.23	0.57	0.39	0.24	39
Nowa Wieś	*N.W.*	1007.14	2.26	0.50	1.04	1.30	0.79	0.36	0.24	40
Blizianka	*Bl.*	486.97	2.49	0.41	0.93	1.84	0.77	0.43	0.24	41
Glinik Górny	*Gl.G.*	1122.25	1.54	0.44	1.02	1.74	0.81	0.42	0.23	42
Tułkowice	*Tu.*	315.05	1.92	0.30	1.24	1.48	0.96	0.39	0.23	43
Kobyle	*Kob.*	592.93	2.05	0.50	1.01	1.20	0.76	0.32	0.23	44
Huta Gogołowska	*H.*	667.92	1.53	0.71	0.54	0.60	0.44	0.28	0.23	45
Grodzisko	*Gr.*	968.88	2.25	0.32	1.01	1.82	0.81	0.40	0.23	46
Stępina	*St.*	715.70	1.87	0.36	1.08	1.59	0.89	0.40	0.22	47
Bonarówka	*Bo.*	1096.47	2.06	0.69	0.29	0.32	0.21	0.19	0.22	48
Oparówka	*O.*	647.43	2.29	0.62	0.64	1.00	0.46	0.33	0.22	49
Zawadka	*Zaw.*	485.65	1.90	0.43	0.93	1.53	0.79	0.37	0.22	50
Jaszczurowa	*Jas.*	554.66	1.88	0.55	0.91	1.14	0.69	0.41	0.22	51
Gogołów	*Gog.*	1481.81	1.55	0.51	0.81	1.58	0.66	0.45	0.21	52
Glinik Średni	*Gl.Ś.*	787.91	1.75	0.53	0.88	1.23	0.69	0.41	0.21	53
Markuszowa	*Mar.*	592.03	1.90	0.10	1.10	1.84	0.81	0.46	0.21	54
Różanka	*R.*	986.03	1.83	0.30	1.07	1.41	0.82	0.41	0.20	55
Kozłówek	*K-k.*	609.24	1.88	0.43	0.62	1.24	0.52	0.44	0.17	56
Pstrągowa	*P-wa*	2949.76	1.73	0.37	0.69	1.17	0.56	0.35	0.16	57
Lubla	*Lub.*	1556.83	1.35	0.33	0.85	1.20	0.68	0.43	0.16	58
	Unit:	[ha]	[1/ha]	[-]	[1/ha]	[1/ha]	[1/ha]	[-]	[-]	
	Minimum:		1.34	0.10	0.29	0.32	0.21	0.19	0.16	
	Maximum:		4.15	0.80	5.50	3.29	3.64	0.48	0.83	

Table A1. *Cont.*

Name of Locality	Designation	Area	W_A	W_B	W_C	W_D	W_E	W_F	q	Rank
	Mean:		2.45	0.45	1.26	1.77	0.96	0.40	0.28	
	Median:		2.43	0.49	1.09	1.77	0.88	0.41	0.26	
	Standard deviation:		0.62	0.13	0.75	0.59	0.49	0.05	0.10	

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