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Exploring Unconventional 3D Geovisualization Methods for Land Suitability Assessment: A Case Study of Jihlava City

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Abstract

Effective management of urban development requires robust decision-support tools, including land suitability analysis and its visual communication. This study introduces and evaluates seven 3D geovisualization methods—Horizontal Planes, Point Cloud, 3D Surface, Vertical Planes, 3D Graduated Symbols, Prism Map, and Voxels—for visualizing land suitability for residential development in Jihlava, Czechia. Using five raster-based data layers derived from a multi-criteria evaluation (Urban Planner methodology) across three time horizons (2023, 2028, 2033), the visualizations were implemented in ArcGIS Online and assessed by 19 domain experts via a structured questionnaire. The evaluation focused on clarity, usability, and accuracy in interpreting land suitability values, with the methods being rated on a five-point scale. Results show that the Horizontal Planes method was rated highest in terms of interpretability and user satisfaction, while 3D Surface and Vertical Planes were considered the least effective. The study demonstrates that visualization methods employing visual variables (e.g., color and transparency) are better suited for land suitability communication. The methodological contribution lies in systematically comparing 3D visualization techniques for thematic spatial data, providing guidance for their application in planning practice. The results are primarily intended for urban planners, designers, and local government representatives as supportive tools for efficient planning of future built-up area development.

Keywords: land suitability; 3D; geovisualization; Jihlava; urban planner

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1. Introduction

The development of settlements has always been a significant phenomenon accompanying the evolution of human society. In today's world, with a continuously growing population, it is essential to pay increased attention to this process. Therefore, urban planners and designers must ensure effective management of spatial development through strategic planning, preventing issues such as urban sprawl, the uncontrolled expansion of urban areas.

One approach to addressing this challenge is the Urban Planner methodology [1–4], which utilizes multicriteria analysis and Saaty's method (Analytic Hierarchy Process for pairwise comparison of criteria) [5,6] to assess land suitability for specific thematic categories, such as housing, recreation, or industry. Land suitability is defined as the capacity of a given area to offer various opportunities and conditions for different uses, ultimately aiming to meet human needs [7]. Yang et al. [8] highlight the importance of land suitability analysis as a valuable GIS application in the field of planning and management, supporting data-driven decision-making for sustainable spatial development.

Academic studies on land suitability generally follow two main directions. The majority focus on the practical application of land suitability (e.g., [9–13]), aiming to identify suitable areas for specific uses such as residential development, wind farms, and others. The second approach is theory-oriented (e.g., [14–17]), addressing methodological frameworks, the evaluation of specific methods, and their comparative analysis. Some studies combine these perspectives, exploring the usability of particular methods and their practical implementation. A common outcome of all studies analyzing land suitability, as well as methodologies such as Urban Planner, is the map visualization of results [1–3].

Map outputs supporting decision-making in land development and spatial planning are produced in the form of either analog or digital maps (e.g., [1,17–20]). Almost all of these outputs are visualized in a 2D format, which is suitable for both analog and digital equivalents. However, the focus of this article is to identify, present, and evaluate 3D geovisualization methods that can effectively depict land suitability in a digital environment.

Three-dimensional visualizations effectively present large amounts of complex information to a wide range of users, making them suitable even for users who have little or no experience with mapping or GIS [21]. Three-dimensional display techniques are, in the most general way, of high importance for cartography. Not only for an optimized perception of the georelief, but they are also essential for the visualization of other spatial information [22]. The advantages and disadvantages of 3D geovisualization include additional display space, the ability to display additional variables, or solving the problem of overlapping symbols. Disadvantages include variable scale across 3D scenes, perspective distortion, or problems with transparency and cast shadows [23]. The transfer of existing, proven cartographic principles to modern media and imaging technologies, and the development of new cartographic methods are key challenges for current and future research [24].

There are many ways and methods to represent spatial data in three dimensions; however, methods for 3D geovisualization of thematic data have not yet been clearly defined in the literature. Some methods are more suitable for topographic and elevation data, while others are more suitable for thematic data. Examples include the use of horizontal and vertical planes and point clouds for visualizing climate data [25], voxels for representing population [26], or 3D graduated symbols for visualizing earthquakes [27].

2. Related Works

The integration of 3D geovisualization into geographic context has become increasingly prevalent due to its capacity to convey intricate spatial phenomena with enhanced clarity, interactivity, and analytical depth. Whether in digital or analog formats—such as 3D building models or digital terrain models—these visualizations provide an intuitive framework for spatial cognition and decision-making. According to Žejdlík and Voženílek [28], the efficacy of 3D geovisualization lies in its ability to present spatial data with high fidelity while fostering user engagement and comprehension. Similarly, Thöny et al. [29] highlight its role in facilitating cognitive immersion and spatial understanding.

The application of 3D geovisualization has been extensively explored in the context of narrative-driven spatial communication, or storytelling, which serves as an effective method for knowledge dissemination [29]. Döllner and Hinrichs [30] investigated the methodological integration of 3D visualization into GIS environments, addressing the challenge of incorporating dynamic spatial representations into analytical workflows. A related inquiry was conducted by Dell'Unto et al. [31], who examined the utilization of 3D geovisualization for archeological documentation in Pompeii. Their research emphasized the dual function of 3D integration—not only as a visualization tool but also as a mechanism for conducting spatial analyses.

Further advancements in 3D geovisualization include its intersection with temporal analytics, as explored by Thakur and Hanson [32], who examined methods for visualizing spatiotemporal phenomena within interactive 3D environments. Ware and Plumlee [33] contributed to the theoretical discourse by analyzing perceptual and cognitive aspects of 3D visualization, while Wang et al. [34] investigated geospatial data representation through 3D graphs, assessing their utility in spatial data interpretation and decision support systems. These studies collectively underscore the evolving role of 3D geovisualization as an indispensable component of contemporary geographic research, enabling more comprehensive spatial analyses and facilitating interdisciplinary applications.

The use of 3D geovisualizations in urban space and planning is becoming increasingly common, providing a more realistic perspective on spatial problem solving. Three-dimensional city models, which visualize not only buildings but also engineering networks, public infrastructure, and environmental elements, have become valuable decision-making tools. In such environments, advanced 3D analyses can be conducted, yielding new insights necessary for efficient planning and development. The potential applications of 3D urban visualizations in spatial planning were examined in a study by Miranda et al. [35], while the current trend of integrating virtual reality with 3D modeling to enhance spatial planning was addressed by Cao and Chen [36]. The use of 3D methods in Czech urban planning is explored by Rucký and Janečka [37], who state that, unlike traditional 2D visualization methods, 3D elements allow for a more perspective-driven view of issues, offering a broader context. This topic is also being applied in practice; 3D city visualizations are used by institutions such as The Prague Institute of Planning and Development [38] and the city of Brno [39]. On a global scale, 3D visualizations in urban planning are increasingly explored in professional research, with growing implementation within information systems and spatial analyses for planning purposes. Billen et al. [40] provided a summary of the experiences with the use of 3D city models, identifying key challenges that will need to be addressed. They note that 3D city models, enriched with data and integrated into information systems, can serve as a robust platform to support sustainable development and more efficient urban management. The integration of 3D models in urban planning was also examined by Sun et al. [41], who focused on their use within BIM and GIS for 3D cadastral purposes. An additional benefit for 3D geovisualization comes from freely available data, such as that from OpenStreetMap (OSM) and the Shuttle Radar Topography Mission (SRTM). These data have applications not only in land-use planning but also extend into transportation, ecology, and culture [42].

3. Main Objectives

Three-dimensional geovisualizations combined with land suitability analyses are not commonly used. A total of seven methods (Horizontal Planes, Point Cloud, 3D Surface, Vertical Planes, 3D Graduated Symbols, Prism Map, and Voxels) were tested for 3D visualization, which were evaluated in terms of their complexity of implementation as well as their practical applicability in land-use planning. The foundation of the research on 3D geovisualization of land suitability is a study that focuses on calculating land suitability using the Urban Planner methodology [1]. For the purposes of this study, only the land suitability layers for residential use were selected, which were visualized in 3D form within a web map application.

Two main objectives were defined for the purposes of this study. The first is to demonstrate new ways of visualizing land suitability using 3D methods. The second objective is based on the evaluation of these 3D geovisualization methods based on the knowledge gained from users of land suitability maps. The main research question of the article is to find out which of the seven presented 3D geovisualization methods are considered useful by users and which ones are difficult to work with. The results of this study should reveal which methods are most suitable and which are least suitable for visualizing land suitability. Feedback from users will help to understand the role of 3D in the context of land suitability visualization. Methods that are identified as suitable can be tested in more detail in the future.

4. Data and Methods

The main research questions of the study focused on the design and subsequent evaluation of 3D geovisualization of land suitability. For this purpose, seven different methods of 3D visualization were selected and applied to housing suitability data within one of the cadastral areas of the city of Jihlava. The resulting visualizations were published through an interactive ArcGIS Online web-based map application, available at https://experience.arcgis.com/experience/2f05485ccaaf4d56ad7690bbc5db3864 (accessed on 6 July 2025). The Esri solution (ArcGIS Online) was chosen because respondents are used to viewing land suitability data using this technology. Following the creation of the visualizations, a questionnaire survey was conducted to assess the usability and comprehensibility of the various forms of 3D geovisualization of land suitability. The methodology of the study is graphically illustrated in Figure 1.

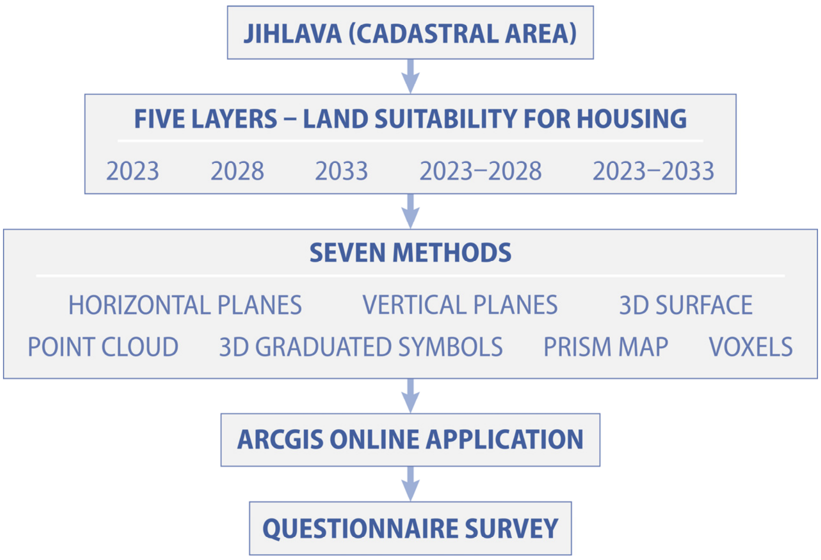

Figure 1. Methodology for visualizing land suitability using seven methods and subsequent evaluation using a questionnaire survey.

4.1. Study Area

As the study area for the 3D visualization of land suitability, the cadastral area of Jihlava was selected, situated in the central part of the city of the same name. While the original study considered the entire city of Jihlava, the visualization was conducted within a single cadastral unit to meet the specific research objectives. The primary reason for narrowing the study area was the high computational demands and rendering speed constraints associated with data processing on the ArcGIS Online platform.

Jihlava is located in the central part of the Czech Republic, at the historical border between Moravia and Bohemia (Figure 2). It serves as a key regional center and an important transportation hub. The city covers an area of 87.87 km^2 and has a population of 53,986 [43]. The selected cadastral area of Jihlava, designated as the study area, spans 13 km^2 and is home to nearly 40,000 residents.

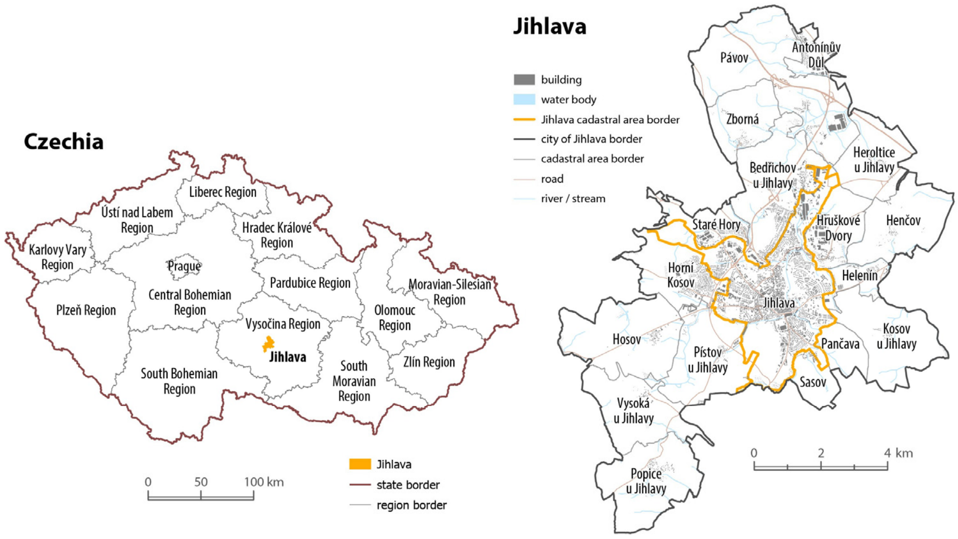

Figure 2. Study area—the Jihlava cadastral area.

4.2. Urban Planner Methodology

The calculation of land suitability was carried out using the Urban Planner methodology, which was originally developed as an analytical tool for assessing land suitability within the ArcGIS for Desktop environment [2,3]. Through continuous development, the original analytical tool evolved into a comprehensive and structured methodology.

The core of the Urban Planner is a multicriteria analysis, in which individual evaluation criteria are assigned weights that reflect their relative importance in the assessment of land suitability. The weights of the criteria were calculated using the Saaty method, based on the opinions of spatial planning experts. In this study, a total of six experts were involved in this calculation. Each weight indicates the relative importance of a criterion in the assessment of land suitability, with the total weight for a specific type of land suitability equaling 100%. In the subsequent step, the final land suitability layers are calculated by multiplying the individual criterion layers by their respective weights, followed by summing the results. The outcome of the multicriteria analysis is a set of spatial layers representing land suitability, indicating the degree to which different areas are appropriate for a given functional objective (e.g., residential development). These outputs allow for the identification of areas with the highest land suitability and serve as a valuable basis for strategic decision-making in urban and regional planning.

The Urban Planner methodology has already been implemented multiple times in practical projects in both the Czech Republic and Slovakia. At the same time, it has attracted academic interest, particularly in relation to the technical aspects of its application, the optimization of the weighting process, and the evaluation of its effectiveness in real-world scenarios [44–48].

4.3. Case Study Jihlava

The primary objective of applying the Urban Planner methodology in the case study of Jihlava [1] was to calculate land suitability across three time horizons—2023, 2028, and 2033—for two thematic areas:

- Housing—identification of areas suitable for the development of single-family and multi-family residential buildings,

- Industry and logistics—delineation of areas appropriate for light industrial production and warehousing.

To simulate future spatial conditions for the years 2028 and 2033, a data-driven modeling approach was employed. This approach was based on data derived from real urban studies and actual investment plans, allowing for a realistic configuration of future development scenarios.

The results of the analysis revealed that, on a city-wide scale, land suitability increased only slightly over the observed period, contrary to initial expectations. However, a key insight for decision-making emerged in the form of land suitability values within so-called development zones. These areas had been previously designated by the City of Jihlava as priorities for future growth. Through the application of the Urban Planner methodology, it was possible to identify specific locations where strategic investments should be focused, thereby supporting the city's effective and sustainable development.

4.4. Data

Visualized data layers representing land suitability and their temporal differences were produced as part of the Jihlava case study, conducted by Bittner a Burian [1]. In this study, the Urban Planner methodology was implemented within the administrative area of the city of Jihlava. A total of 32 evaluation criteria were applied to assess land suitability for housing and industry and logistics across three time horizons: 2023, 2028, and 2033. The criterion layers and the resulting layers of the land suitability analysis were created at a spatial resolution of 1×1 m. The data sources used in the analysis included open access datasets (e.g., OpenStreetMap), data provided by the City of Jihlava, as well as urban studies and investment plans. Data representing the state of the territory in 2028 and 2033 were largely generated through data modeling. This type of modeling took into account actual land-use studies and investment plans

For the purposes of this article, the main objective of which is to show the various possibilities of visualizing land suitability in 3D, five layers were chosen:

- Land suitability for housing in 2023;
- Land suitability for housing in 2028;
- Land suitability for housing in 2033;
- Change in land suitability for housing between 2023 and 2028;
- Change in land suitability for housing between 2023 and 2033.

4.5. Visualization Methods

These five layers of land suitability for housing were visualized using seven methods of 3D geovisualization: Horizontal Planes, Point Cloud, 3D Surface, Vertical Planes, 3D Graduated Symbols, Prism Map, and Voxels. These methods were chosen because they are suitable for creating visualizations from raster data, such as land suitability data. These methods are increasingly used in scientific publications but have not yet been used for land suitability visualization.

Horizontal Planes are a way of displaying continuous spatial data where the entire dataset has a constant elevation (Z) coordinate and differs only in the way it is displayed, such as the color of the cell [49]. This is the simplest method and the only one that shows the original land suitability data in the case of this article. The other methods require adjustments to the data using different tools. The elevation was set to 5 m above the surface. The transparency was set to 50% to make the buildings and basemap visible.

A Point Cloud is a type of discrete visualization where each point is represented by three coordinates. It can be a 2D point cloud, where all points have a constant Z coordinate, or a 3D point cloud, where the Z coordinate is variable [50]. Cloud points can be distributed randomly or in a regular grid. The method represents land suitability in the form of a regular point cloud, where the points are 7 m apart. The points have a variable height based on the land suitability value. The values are, therefore, expressed by two graphical variables—color and height (the higher the altitude and the darker the color, the higher the value). In this visualization, the density and size of the points must be chosen appropriately.

A 3D surface is a continuous visualization method usually created by interpolating points from a point cloud. Unlike horizontal planes, each cell does not have a constant Z coordinate, but the height of the cells is variable depending on the value of the phenomenon. In the case of this article, the height of the cell corresponds to the land suitability value. The values are, thus, expressed by two graphical variables—color and height (red color and low elevation means low values, green color and high elevation means high values). For the 3D surface, a 30-times elevation (z-factor = 30) was used to better highlight differences in land suitability. For this method, only one layer was visualized (Housing 2023). Due to the technical design of the 3D surface, five separate scenes would need to be created as the 3D scene in ArcGIS Online only allows for one elevation surface. Therefore, the application would have to contain five pages for the different layers displayed by the 3D surface method, which would worsen the user experience.

Vertical planes are usually located in the middle of urban roads and rendered by extruding vertically the linear geometry of the road network. In order to answer possible occlusion issues, transparency can be applied to the vertical planes [51]. The boundaries of the development areas for housing were chosen for the Vertical Planes visualization. These were split at the breakpoints using the Split Line at Point tool and the information was extracted from the lines using the Add Surface Information tool. The land suitability value is represented by the height and color of the plane (the higher the plane and the darker the color, the higher the value).

The 3D Graduated Symbols method is based on 2D graduated symbols method used in thematic maps. Symbols can take many forms, from 3D bars to spheres to pie charts, while the size of these elements depends on the value (e.g., column height, sphere diameter) [52]. This method represents land suitability using 3D Graduated Symbols in the form of columns with variable height and color based on value (the higher the column and the darker the color, the higher the value).

A Prism Map method is a 3D choropleth map with extruded height to encode a numerical attribute. Prism Maps are predominantly used for visual impact, and the unfamiliarity with prism maps hampers their understanding [53]. The Prism Map method displays average land suitability values in area units by varying height and color (the more extruded the polygon and the darker the color, the higher the value). The transparency was set to 50% to make the buildings and basemap visible. When creating a visualization using this method, it is necessary to choose the area units (e.g., administrative) appropriately. In this case, Development Areas for Housing were chosen. The disadvantage is the aggregation of the data into less detailed spatial units, thus losing detail.

In Voxel-based geovisualization, data is represented by blocks with different heights depending on their values. It, therefore, has common elements with the 3D graduated symbols and prism map. However, in contrast to 3D graduated symbols, in the case of voxels the adjacent blocks (columns) are connected to each other, and unlike prism map, all polygons have a constant size [28]. The voxels represent values in a similar way to the Prism Map (the more extruded the polygon and the darker the color, the higher the value). However, unlike Prism Map, a regular continuous square grid with a cell area of 50 square meters is used. The transparency was set to 50% to make the buildings and basemap visible.

The selection and application of 3D geovisualization methods in this study were informed by Jacques Bertin's theory of visual variables as introduced in Sémiologie Graphique (1967) [54]. For example, the Horizontal Planes method primarily utilizes position and color hue to communicate continuous surface values, while 3D Graduated Symbols and Prism Maps incorporate size (in the form of height) along with color intensity to express magnitude. Voxels rely on the volume and uniform grid placement to represent spatial distribution, combining position, color, and size in a volumetric structure. According to Bertin's framework, combining multiple visual variables can enhance perception, but only when the variables are orthogonal and not overloaded. Some methods, such as Point Clouds, may challenge perceptual clarity due to the simultaneous use of too many variables (height, density, and color), making them less suitable for certain types of pattern recognition [28]. The goal of using these seven methods was to find out which methods users work well with and which ones are pointless to use.

4.6. ArcGIS Online Application

Selected methods were integrated into a web application in the ArcGIS Online environment created with ArcGIS Experience Builder. First, the data was processed in ArcGIS Pro. Seven 3D scenes were created in the ArcGIS Online environment for individual methods. The process of preparing data in ArcGIS Pro and visualizing it in ArcGIS Online is shown in Figure 3. Finally, the seven 3D scenes were integrated, and a web map application was created in ArcGIS Experience Builder. In addition to the thematic layers of land suitability, additional layers were also added to the application, namely development areas for housing, 3D buildings, water, and the border of the Jihlava cadastral area. These topographic layers help users to better navigate the 3D scene and derive spatial relationships. The exact land suitability values can be found by clicking on a feature. The terrain elevation was not considered when creating the visualizations, as it would distort some methods (e.g., horizontal planes would not be planes; voxels—height would not represent only the potential value, but also the altitude, etc.).

Figure 3. ArcGIS Pro tools used in data preparation and 3D geovisualization in ArcGIS Online.

The application was created in ArcGIS Experience Builder (Figure 4). It contains eight pages—an introduction and seven pages for each method. In the introduction, the user can learn about the application and the seven methods of 3D geovisualization. The other tabs always contain a visually dominant window with a 3D scene showing the land suitability data using different methods. A sidebar is located on the right. At the top of the sidebar is a legend that changes dynamically based on the active layers. The layers can be switched at the bottom of the sidebar.

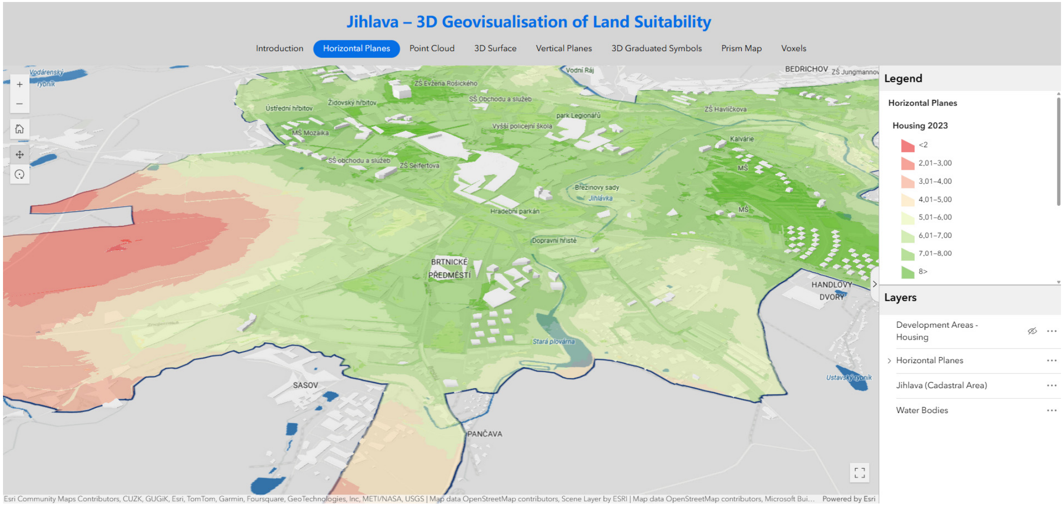

Figure 4. ArcGIS Online application.

4.7. Usability Evaluation of 3D Geovisualization

A questionnaire survey was then conducted with experts in urban planning and GIS from local governments of selected cities in Czechia and Slovakia who have experience with the Urban Planner methodology. To objectively evaluate 3D geovisualization of land suitability using different methods, a questionnaire survey was chosen. The survey was targeted at experts of municipal authorities of selected cities in Czechia and Slovakia who are involved in urban planning and GIS. In these cities, land suitability analysis using Urban Planner methodology has been carried out previously, so the respondents are familiar with this data. The questionnaire was created using ArcGIS Survey123 and is in Czech as it is aimed at Czech and Slovak respondents. The respondents were selected professionals from the field of spatial planning and GIS who have already encountered land suitability maps.

The questionnaire is structured in nine parts. In the introductory part, the respondent is introduced to the research, the specifics of the web map application, and the data used. It also describes recommendations on how to work with the application. The introduction is followed by seven sections for each method. These always include an illustration of the method and questions that are repeated for each method (Figure 5):

- How do you find this method? (Very bad–Bad–Neutral–Good–Very good);
- Does the method properly represent land suitability? (Disagree–Rather disagree–Don't know–Rather agree–Agree);
- Were you able to correctly determine the values of the land suitability? (Disagree–Rather disagree–Don't know–Rather agree–Agree);
- Briefly evaluate this visualization. (open answer).

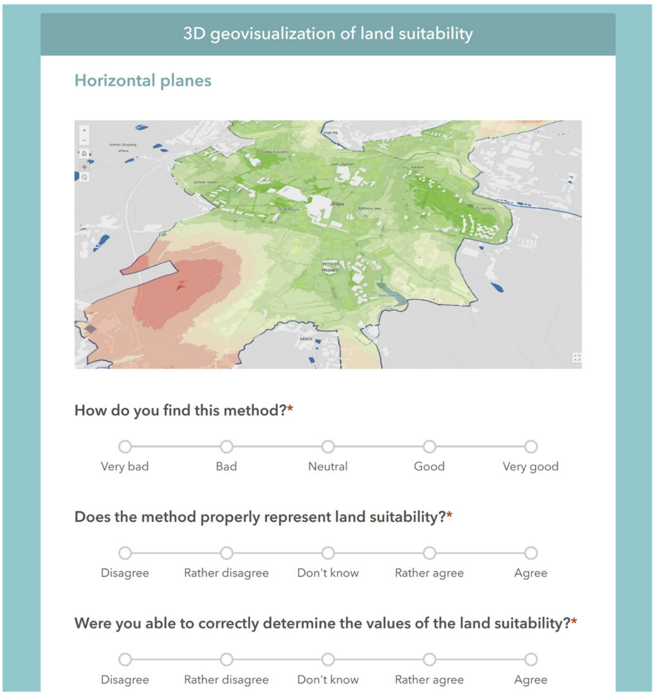

Figure 5. Questionnaire for evaluation of 3D geovisualization of land suitability (example: Horizontal Planes).

The questionnaire concludes with questions for overall assessment and information about the respondent. The questions are as follows:

- Rate each method of 3D geovisualization on a scale from 1 (worst) to 5 (best);
- Do you consider the possibility of visualizing land suitability in 3D to be meaningful? (open answer);
- Do you work with 3D visualizations/models? (yes/no);
- What is your role in spatial planning? (Urbanist, GIS expert, Environmental specialist, Architect, Other).

5. Results

Five layers of land suitability for housing were visualized using seven methods, which provide a different perspective on land suitability geovisualization. The 3D visualization environment for land suitability data exploration is interactive for all methods and allows the user to freely work with the 3D scene and switch layers and visualization methods. Four methods cover the entire territory of the Jihlava Cadastral Area. For three methods (Point Cloud, 3D Graduated Symbols, Voxels), the entire Jihlava Cadastral Area was not covered due to data complexity, as the visualization would take a long time to load, which would worsen the user experience. The symbols are rendered on the Development Areas for Housing and their 40m surroundings defined by a buffer.

5.1. Horizontal Planes

The Horizontal Planes method (Figure 6) was rated by respondents as clear, intuitive, and user-friendly. Its main advantage lies in the straightforward representation of land suitability values, which are easily understandable even for a non-expert audience. Users appreciated its similarity to traditional 2D mapping, the ease of navigating the environment, and the clear interpretation of the color scale, which effectively conveys the spatial distribution of the phenomenon.

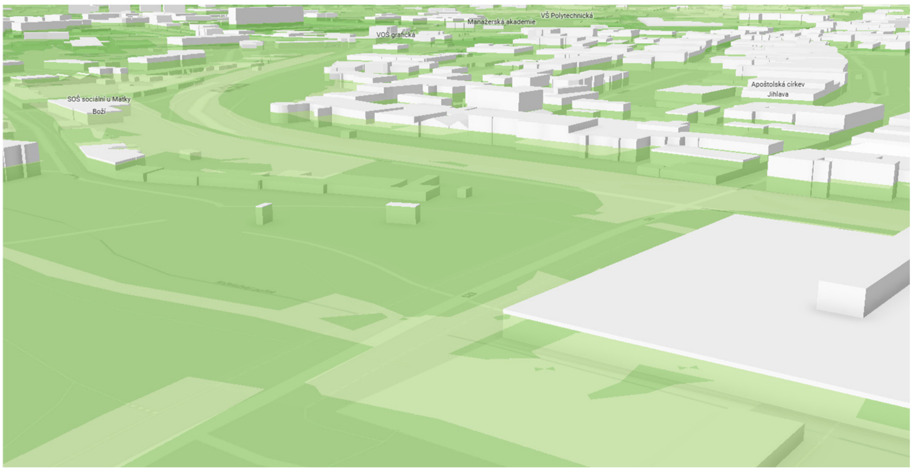

Figure 6. Horizontal Planes—visualization of land suitability at a constant height above the surface.

This method is considered particularly suitable for gaining an overall understanding of a larger area. However, its use in detailed scales faces certain limitations—upon zooming in, the visualized surfaces may break apart, and the combination of the surface layer with 3D building models can create a confusing impression. Additionally, concerns were raised about the placement of the visualization plane above the terrain surface, which hampers spatial orientation and diminishes the potential of the 3D models.

Further criticism focused on the choice of color scale—some categories tended to blend together in the overall view, and the ability to highlight differences or changes within individual areas was insufficiently emphasized. Despite these drawbacks, most respondents considered this visualization to be an effective tool for presenting land suitability, especially when an appropriate level of transparency is maintained and technical display parameters are optimized (e.g., reducing flickering during zooming and rotation).

5.2. Point Cloud

The visualization of land suitability using Point Cloud (Figure 7) was rated quite ambivalently by respondents. Some appreciated the method's ability to better highlight the potential of smaller areas compared to traditional representations using horizontal planes. It was also positively noted that the base map remained readable even without transparency settings, and that only areas with significant potential were included in the visualization.

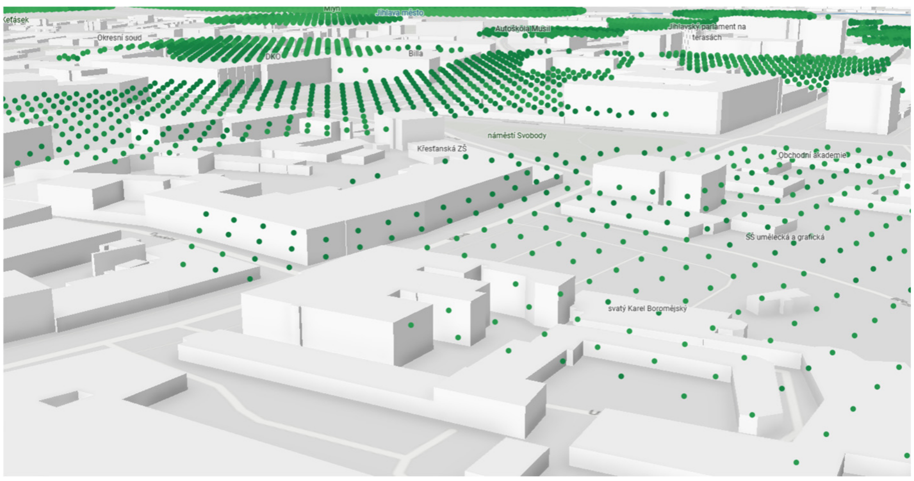

Figure 7. Point Cloud—visualization of land suitability in a regular point cloud with variable height.

On the other hand, criticism predominantly focused on the overall clarity and interpretability of the method. The meaning of individual points—particularly their height, density, and size—was unclear to most respondents. Color was often the only reference point, but due to an unclear color scale and a lack of precise descriptions, the final visualization was perceived as not very informative. Upon zooming in, the display often appeared confusing, and potential values were, according to some users, discernible only through interactive elements (e.g., pop-up windows), not directly from the visualization itself.

Further criticism was directed at the technical performance—in some cases, the visualization loaded slowly, which can be limiting when dealing with larger datasets. Inappropriate color schemes could also cause the points to blend into the background. Spatial occlusion by buildings when tilting the view, along with difficulties in judging point height, further reduced user-friendliness.

Overall, the point cloud method was perceived as less suitable for directly expressing land suitability, mainly due to the difficulty of interpreting values, the unfamiliar form, and the low intuitiveness of the results.

5.3. Three-Dimensional Surface

The visualization of land suitability through a 3D Surface (Figure 8) was evaluated by respondents as visually appealing but difficult to interpret. The method allows for the highlighting of contrasting values, making it more suitable for analyzing smaller areas with highly heterogeneous potential.

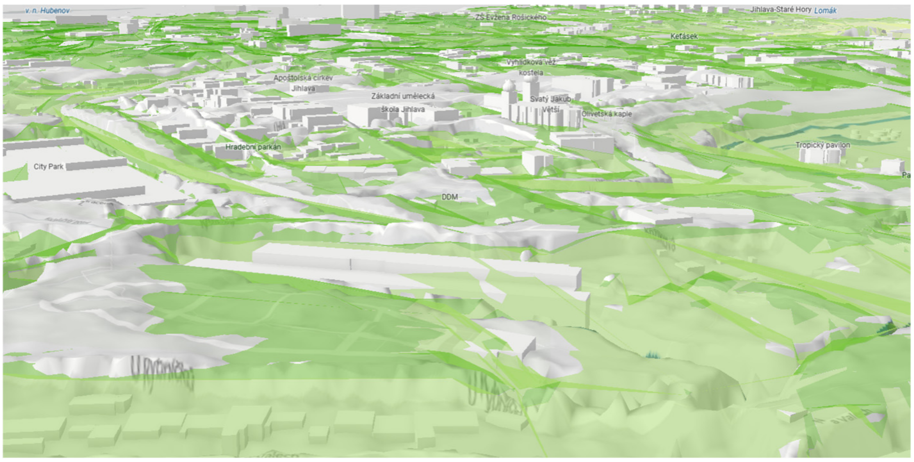

Figure 8. Three-Dimensional Surface—visualization of land suitability with a continuous surface with variable height.

Users repeatedly pointed out reduced readability due to shading, optical distortion, and the uniform elevation of development areas. In some cases, orientation within the territory was considered challenging, even in familiar environments. A significant limitation was also the slower rendering performance and the difficulty of interpreting the color scale on undulating terrain.

Overall, the method was considered unsuitable for presenting land suitability, particularly in built-up areas, where the spatial effect did not offer any added informational value compared to standard 2D visualization.

5.4. Vertical Planes

The visualization method using Vertical Planes (Figure 9) received mixed evaluations. Its main advantage lies in the ability to highlight and compare the level of land suitability along the immediate borders of specific areas. However, this feature also represents a key limitation—the method does not allow for the interpretation of potential within the interior of polygons, which may result in the loss of important information.

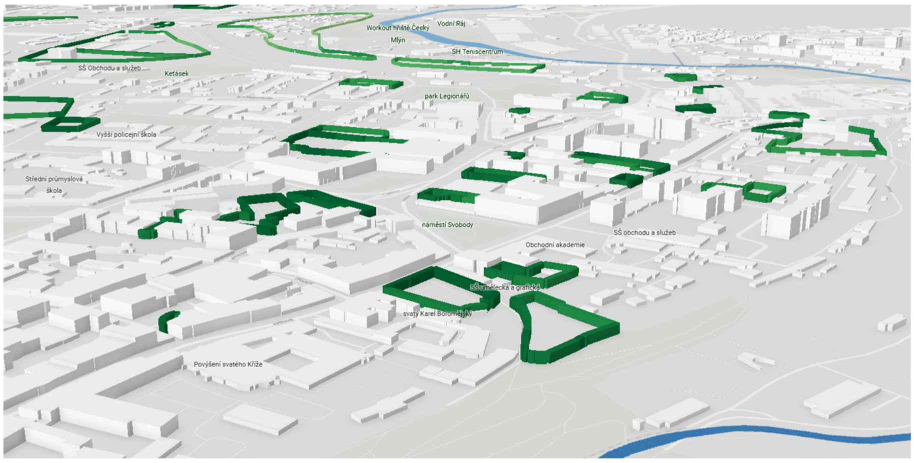

Figure 9. Vertical Planes—visualization of land suitability in vertical planes with variable height.

In terms of clarity and readability, the method was perceived as less intuitive, particularly in more complex spatial structures with nested boundaries. Some users found it confusing, citing insufficient height differentiation and the difficulty of interpreting color gradients. When combined with 3D building models, the visualization often evoked vertical zoning rather than conveying a true spatial representation of land suitability.

Nevertheless, in several cases, the method was considered intuitive and visually engaging, especially in the context of built-up environments. Overall, however, it is better suited for specific purposes—such as comparing boundary values between locations—rather than for comprehensive analysis of land suitability across an entire area.

5.5. Three-Dimensional Graduated Symbols

Respondents noted that the 3D Graduated Symbols method (Figure 10) uses cylinder height to emphasize land suitability, allowing for the visualization of both small and large areas with a clearly visible base map, especially when viewed from an optimal angle. This approach is similar to the point cloud method but provides a visual enhancement through the use of vertical exaggeration.

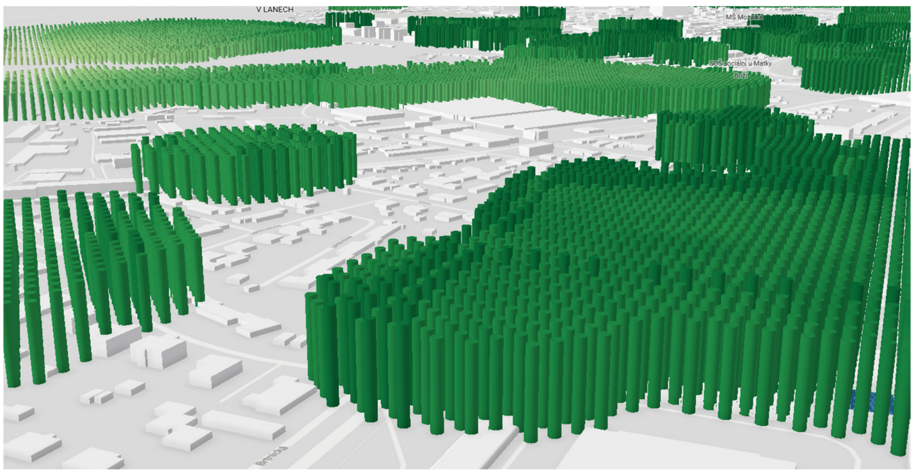

Figure 10. Three-Dimensional Graduated Symbols—visualization of land suitability using columns with variable height.

However, some criticisms focus on the insufficient differentiation in cylinder height, which makes it difficult to interpret the values accurately. Additional concerns include slow loading times and the complexity of determining exact land suitability values. Some users also questioned the necessity of combining height and color to represent the same phenomenon, arguing that it may result in visual distortion.

The method is considered suitable for advanced users, though its added value in a 3D format is not always apparent. To improve its effectiveness, it would be advisable to increase the contrast in both height and color, which would enhance clarity and precision in interpreting land suitability.

5.6. Prism Map

According to respondents, the Prism Map (Figure 11) method focuses on selected locations and uses color and extrusion to represent values, making the visualization easily interpretable. This approach is effective for displaying the average land suitability of specific sites but does not convey the detailed characteristics of the entire area or specific suitability values within it. The method is particularly appropriate when the goal of the map is to present average potential rather than conduct a detailed analysis.

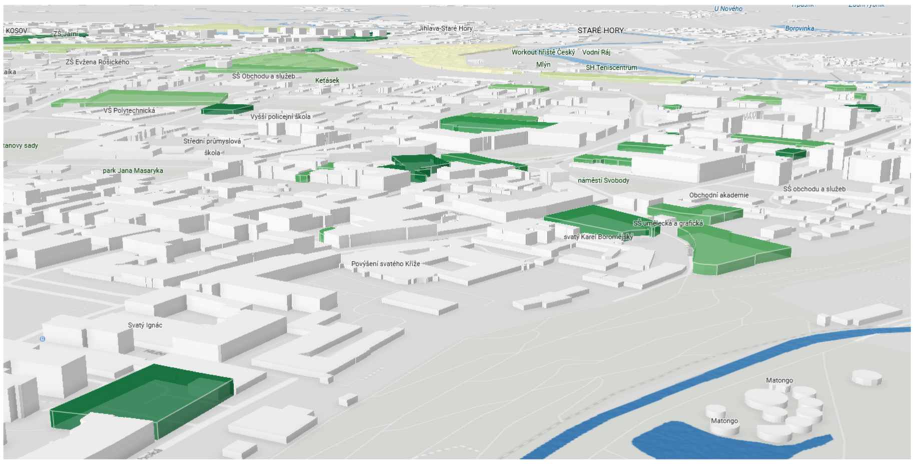

Figure 11. Prism Map—visualization of land suitability using polygons with variable height.

Positive aspects include its intuitive nature and clarity, especially when combined with the display of buildings. However, some users noted a loss of detail over larger areas and the evocation of vertical zoning, which may be less suitable for expressing land suitability. For 3D city models, the method is seen as beneficial, as it allows for better visibility of land suitability within built-up areas. Some concerns were raised about the limited differentiation in extrusion and the use of color, which could result in a degree of visual distortion. Overall, this method is regarded as conservative and well-established, with some suggestions for improvement in the differentiation of height and color to enhance overall clarity.

5.7. Voxels

Based on responses from the questionnaire survey, the Voxels method (Figure 12) can be likened to the use of Prism Map. However, special attention should be paid to the setting of transparency to ensure the visibility of underlying map layers. This was not always successful due to the large extrusion of voxels, which often obscured the visibility of building features. The resulting visualization is strongly influenced by voxel size, which affects the level of detail in the displayed data. Users frequently reported slow loading times and delayed rendering, which complicates the method's usability, especially for larger areas.

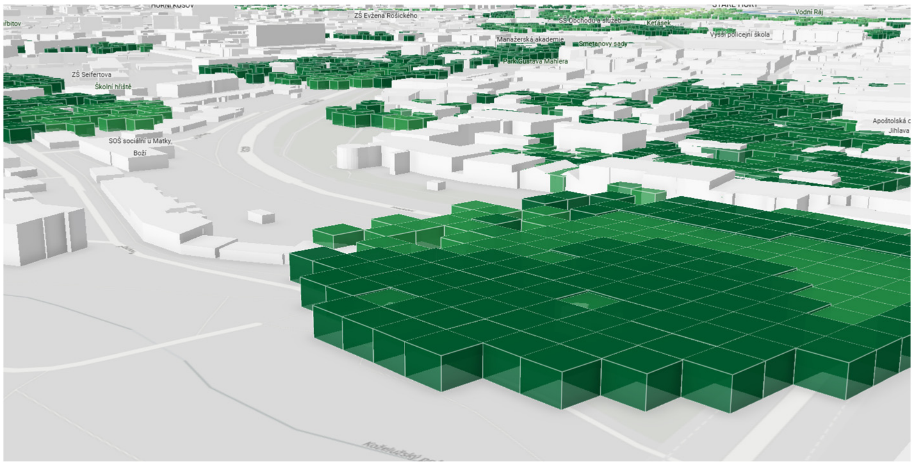

Figure 12. Voxels—visualization of land suitability using equal square polygons with variable height.

This method may be suitable for visualizing land suitability at a large scale, where voxels provide a surface-level representation. However, in the 3D column form, extrusion tends to be too pronounced and does not always accurately reflect the actual land suitability. In built-up areas, voxels may appear distracting and can create the misleading impression of representing specific building proposals, which is not the intended purpose. The discontinuity of voxels, combined with the use of color, often results in poor readability and hampers the ability to distinguish subtle color variations, making analysis more difficult.

Overall, the voxel method is considered challenging to interpret and demanding in terms of computational performance, which limits its broader applicability. Nevertheless, it may offer potential for more detailed analysis in smaller areas, although further evidence would be needed to confirm its effectiveness—provided that rendering performance and the differentiation between individual values are improved.

5.8. Overall Evaluation of Results

The questionnaire survey was completed by 19 respondents, including 10 GIS specialists, 2 urban planners, and 1 architect. The remaining six respondents indicated the option "Other". Fourteen respondents regularly work with 3D visualizations or 3D models (Figure 13).

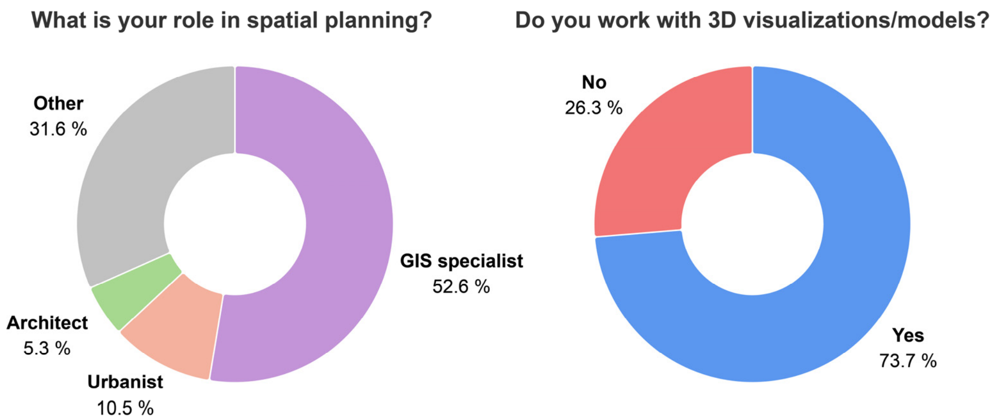

Figure 13. Information about respondents.

For each method, three identical questions were asked, and users were given the option to answer on a scale of "Very bad" to "Very good" and "Disagree" to "Agree". The answers to these questions are graphically represented in Figure 14.

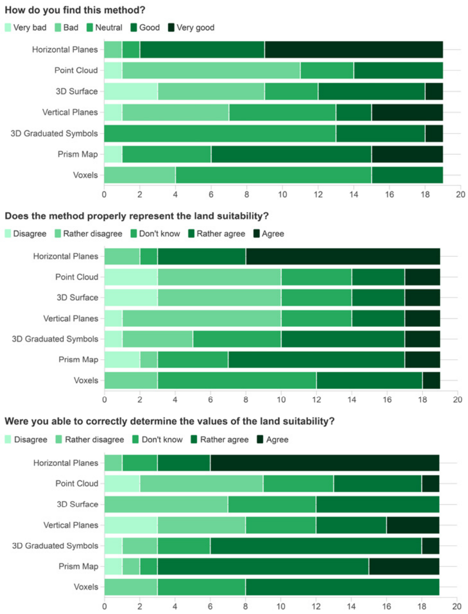

Figure 14. Evaluation of answers to questions for individual methods.

According to the question "How do you find this method?", Horizontal Planes and Prism Map came out as the best, while Point Cloud and 3D Surface had the worst results. Three-Dimensional Graduated Symbols was the only method with no "Bad" or "Very bad" ratings. The Vertical Planes method comes out as the most controversial as it received many positive as well as negative ratings. Voxels came out as the most neutral method, as no one rated it "Very bad", but no one rated it "Very good" either.

Users have chosen Horizontal Planes as the best method to represent land suitability. Other positively rated methods were 3D Graduated Symbols and Prism Map. Three methods (Point Cloud, 3D Surface, Vertical Planes) had very similar results, covering the full range of responses. The Voxels method had the highest proportion of responses in the "Don't know" category.

Users best determined land suitability values using the Horizontal Planes method. The Prism Map, 3D Graduated Symbols and Voxels methods also achieved good results. In the case of Point Cloud, 3D Surface, and Vertical Planes, neutral or negative responses prevailed.

In the overall evaluation, the respondents chose the Horizontal Planes method as the best, which most closely resembles classic 2D visualizations. Other well-rated methods were Prism Map, Voxels, and Point Cloud. On the other hand, 3D Surface and Vertical Planes were voted as the worst by users. However, no method had an average rating of less than 3 points (Figure 15).

Overall, according to respondents, the use of 3D visualization for representing land suitability can be meaningful in certain cases, though it is not always essential. Three-Dimensional visualization can reveal details that might be difficult to perceive in 2D and offers a new perspective on the data, which may aid spatial understanding and imagination. However, effective use of this technology requires prior experience with similar visualizations, as some methods can be complex and unintuitive. For the average user without expert knowledge, navigating 3D visualizations can be challenging and time consuming.

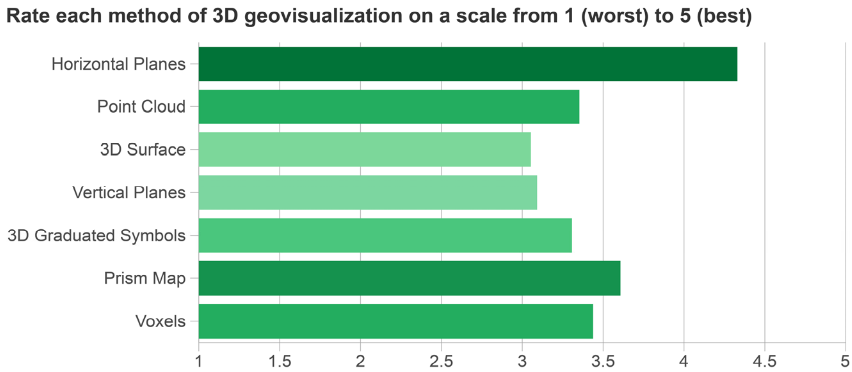

Figure 15. Average rating of 3D geovisualization methods on a five-point scale.

The results of the user evaluation also highlight how 3D visualization methods compare with traditional 2D land suitability representations, which served as the implicit baseline for many respondents. In particular, the high ratings for the Horizontal Planes method can be attributed to its visual similarity to standard 2D maps, preserving established conventions such as consistent color scales and planar layout. This suggests that methods that build upon familiar 2D paradigms—while offering some spatial depth—are more accessible and interpretable to urban planning professionals. Conversely, methods that deviated strongly from the 2D logic, such as Vertical Planes or Point Cloud, were rated less favorably, likely due to a steeper learning curve and the lack of established cartographic conventions. The Prism Map, although 3D in form, retains the area-based aggregation familiar from zonal maps and was perceived as both intuitive and informative—underscoring that spatial logic and data granularity may matter more than dimensionality per se. These findings indicate that while 3D methods offer new possibilities for representing land suitability, their added value depends on how they balance visual innovation with cognitive and perceptual usability. Future comparative studies with controlled baseline tasks could further quantify these differences in performance and user preference.

In general, 3D visualization makes sense in specific contexts, such as urban planning or visualizing built-up areas. However, for the representation of land suitability alone, 2D methods—or combinations of horizontal layers or point clouds—are typically recommended, as they tend to be clearer and easier to interpret. In some cases, 3D visualization could still be useful, but it should be applied judiciously and with an appropriate display method, such as color-coded 3D building models based on suitability levels.

Many users point out that if issues such as slow loading times and low data processing performance were resolved, 3D visualization could become more widely applicable. At the same time, they note the absence of a third dimension for land suitability in relation to various spatial functions (e.g., elevation levels for housing potential). If 3D visualization were tailored to display a specific type of potential—such as suitability by elevation—it could become more meaningful.

In summary, while 3D visualization offers certain advantages, its use should be tailored to specific needs and complemented by clear and comprehensible visualization methods.

6. Discussion

While this study provides a focused evaluation of 3D geovisualization methods in a specific urban context (Jihlava, Czech Republic), the findings have broader implications for similar scenarios in other regions. For instance, the high usability of Horizontal Planes and Prism Map methods—rooted in simplicity and familiarity—suggests that these techniques could be successfully applied in other mid-sized Central European cities where land suitability analysis is based on multicriteria models. However, in metropolitan regions with more complex spatial dynamics or vertical urban structures (e.g., high-rise districts), volumetric methods like Voxels may become more relevant despite their lower rating in this study.

Nevertheless, the generalizability of the results is constrained by several factors. The survey, which included 19 respondents—all experts in urban planning and GIS—offers a focused view of user experience and preference. Nonetheless, the limited sample size raises concerns about the representativeness and generalizability of the findings. Although the deliberate targeting of experienced professionals strengthens the internal validity of the results, the small respondent pool restricts the breadth of perspectives, especially regarding more unconventional or less widely adopted visualization methods. Moreover, the relatively low response rate suggests potential selection bias, where only those with a strong interest in the topic may have participated, potentially skewing the feedback. However, this user-centered approach ensures that the study's findings are grounded in practical relevance, thereby enhancing their applicability in real-world urban planning contexts.

One of the biggest weaknesses of the research is the use of only a descriptive questionnaire without real tasks, benchmarks, or objective measurement of respondents' performance (time, accuracy, errors). The absence of performance-based metrics further limits the robustness of the evaluation. The aim of this article was to find out which method users subjectively work better or worse with, and which one is, therefore, appropriate to consider for testing visualizations in the future. Since the questionnaire survey was conducted remotely, it was not possible to treat homogeneous conditions when filling out the questionnaire (time, internet speed, etc.). For this reason, these results may not be comparable. However, in the future, it would be possible to evaluate these visualizations, for example, using an eye-tracking experiment or other methods. A solution would also be to organize a workshop so that all respondents are in one place and uniform conditions are ensured. Integration of objective performance measures could yield deeper insights into cognitive processing and user interaction with different visualization formats.

A further limitation lies in the inherent variability of the visualization methods evaluated. Not all examined techniques are equally suitable for communicating land suitability data. The inclusion of less appropriate or less familiar methods was justified by the study's aim to cover a broad spectrum and stimulate critical expert feedback. However, this approach may have led to interpretive challenges and reduced the comparability of results across methods. In particular, the user's unfamiliarity with novel or experimental techniques likely affected both interpretation accuracy and time required to complete tasks. These factors should be more critically considered when evaluating the practical applicability of such visualizations in time-sensitive decision-making environments.

Moreover, when comparing the results with previous works on 3D visualization of spatial phenomena such as noise [55] or demographic distribution [26], a recurring theme emerges: user performance and preference are strongly influenced by the legibility of visual variables and the level of abstraction. The results align with these findings by confirming that methods that overload visual encodings (e.g., Point Cloud, 3D Surface) tend to perform poorly in user evaluations.

The thematic context of land suitability itself imposes unique visualization demands, which cannot be assumed to generalize to other spatial phenomena. For example, previous studies on visualizing noise pollution and traffic incidents have demonstrated that user performance varies significantly depending on the nature of the data and the chosen visualization paradigm. Different topics may have different specifics in terms of how they should be properly presented. Beran et al. (2022) created 3D noise visualizations using various methods, which were then evaluated through user testing. They used horizontal planes, vertical planes, 3D surface, space–time cube, and 3D graduated symbols for visualization. The results of the study show that user testing was successful in proving the usability of the proposed methods as all tasks had a high percentage of successful completion [55]. Another study focuses on sphere and bar 3D graduated symbols, especially on the influence of guidelines when reading visualizations. According to the results, circles are not as difficult to interpret as expected but 2D and 3D bars yield more accurate results with less variation [52]. Some articles focus on exploring 3D geovisualization methods in virtual reality environments. For example, in the case of the prism map method, the possibility of user interactivity and scene rotation is very important [56].

Technical constraints also posed significant challenges. Some visualization methods (e.g., Point Cloud, 3D Graduated Symbols, Voxels) were computationally intensive, resulting in long loading times and degraded user experience. Moreover, limitations in the ArcGIS Online platform—particularly the inability to apply custom color palettes for quantitative data—compromised the clarity of certain visualizations. Since it is not possible to set a custom color palette for the quantitative color scale, one of the available color scales was used, which, however, does not adequately represent the information being displayed. These shortcomings underscore the importance of evaluating not just the conceptual suitability of a method but also its technical feasibility and usability under real-world conditions.

These findings suggest that method suitability is highly context-dependent, and general claims about effectiveness must be interpreted cautiously given the technical constraints of the ArcGIS Online platform. Future research should, thus, include controlled experiments across diverse urban environments, incorporate objective task-based assessments, and explore other platforms (e.g., CesiumJS, Three.js) offering greater flexibility in 3D symbology.

In summary, while findings of this research are context-specific, they provide a useful comparative foundation for guiding 3D geovisualization choices in urban planning. They also underline the importance of balancing visual expressiveness with interpretability—especially when targeting non-expert audiences. Moreover, further investigation into the integration of real-time data and dynamic modeling within 3D geovisualizations could enhance their utility for urban planners. By incorporating temporal changes and predictive analytics, these tools could offer even more robust support for decision-making processes.

Building on the findings of this study, future research could explore the application of 3D geovisualization techniques in a broader range of urban contexts, including cities with varying sizes, densities, and planning challenges. Comparative studies across different regions could provide deeper insights into the adaptability and effectiveness of these visualization methods in diverse settings. Furthermore, there is significant potential for integrating additional research methodologies, such as eye-tracking experiments, which could provide a deeper understanding of the optimal parameter settings for individual 3D geovisualizations to enhance the clarity and efficiency of map-based communication.

7. Conclusions

This study demonstrates the significant potential of innovative 3D geovisualization techniques to enhance land suitability assessment in urban planning, using the city of Jihlava as a case study. As part of the first objective of this study, seven distinct 3D visualization methods were applied within a web-based GIS platform, providing a comprehensive comparison of their effectiveness in representing multi-temporal land suitability data for residential development. By offering an alternative interactive representation of land suitability, 3D visualizations may support specific decision-making scenarios—particularly when spatial relationships or patterns are difficult to convey in 2D. However, their effectiveness depends on the user's experience, the design of the visualization, and other factors. The ability to convey complex spatial information in an intuitive manner is particularly beneficial for stakeholder engagement, facilitating a clearer understanding of potential development scenarios and their implications.

The second objective was achieved through the use of a questionnaire survey, whose findings reveal that while methods such as Horizontal Planes and Prism Map offer good clarity, interpretability, and usability, others, such as Point Clouds and 3D Surfaces, face challenges related to visual complexity and technical performance. These results answer the research question of the article. In the future, it is proposed to conduct further testing of only those methods that were selected as suitable by the users. These insights underscore the importance of selecting appropriate visualization techniques tailored to user expertise and data characteristics to maximize decision-making support. Ultimately, integrating 3D geovisualization into urban planning processes can offer more realistic and comprehensive spatial insights than traditional 2D maps, thereby improving the quality and transparency of land-use decisions.

To strengthen the conceptual foundation of the evaluation, interpretation of the visualization results was aligned with Bertin's theory of visual variables [54]. Bertin emphasized that effective visual communication depends on the appropriate selection and combination of graphical variables such as size, value, orientation, texture, and position. In this context, user preferences for methods like Horizontal Planes or Prism Maps can be understood as a result of their clear and controlled use of separable variables—mainly color and position/height—enabling intuitive comparison and pattern recognition. Conversely, lower-rated methods such as Point Clouds and 3D Surface might suffer from visual overload or ambiguous encoding due to simultaneous and less clearly differentiated use of variables. These observations support Bertin's notion that redundancy in visual variables must be used carefully to avoid interpretative confusion. Grounding the evaluation in this theoretical framework not only clarifies the observed results but also provides a transferable lens through which future geovisualizations of land suitability—or other thematic data—can be critically designed and assessed.

This study not only demonstrates the relative strengths and weaknesses of various 3D geovisualization methods for land suitability communication but also opens up several promising avenues for future research and practical implementation. Moving forward, objective performance testing—such as measuring interpretation accuracy, task completion time, or user gaze patterns—could complement the current subjective evaluations and deepen the understanding of how users interact with 3D thematic visualizations. Additionally, replicating this study in urban areas with different spatial morphologies, cultural planning practices, and data availability would enhance the generalizability of the findings.

One of the major challenges for future development lies in selecting an appropriate visualization platform and suitable data formats for effective 3D geovisualization. These choices could help mitigate one of the key limitations identified in the evaluated methods—slow rendering performance. The combination of 3D environments with land suitability visualization also presented a disadvantage in some cases, as it represented a novel concept for many users. This unfamiliarity may partly explain the concern expressed by several respondents that less experienced map users might struggle with this type of visualization. For this reason, respondents also indicated that they would prefer traditional visualizations of land suitability in 2D maps.

During the research, some recommendations for future visualizations emerged. In order to speed up the loading speed, it is advisable to optimize the data before creating visualizations (e.g., remove unnecessary attributes). It is also important to set the color scales well with respect to the displayed topic. For methods where extrusion or height plays a significant role (e.g., Voxels, 3D Graduated Symbols), this variable should be clearly visible. Data where there are small differences in values (e.g., only in decimal places) should, therefore, be recalculated to make the differences larger.

While analytical functions and interactivity can also be implemented in 2D environments, 3D geovisualizations offer unique potential for exploring spatial patterns involving elevation, volume, and layered structures—particularly when these aspects are critical to land suitability interpretation. These features can help reveal previously overlooked spatial relationships and patterns within the area of interest. An example could be incorporating 3D visualization of territorial potential into digital twins, for which classic 2D visualization would not be sufficient.

The study underscores the need for continued development of 3D web GIS platforms, including greater control over symbology, improved performance with complex datasets, and better support for combining thematic and topographic layers. Addressing these technical challenges will be key to enabling wider adoption of 3D geovisualization in spatial planning and decision support contexts.

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