Evaluation of 3D geovisualization of volumetric geospatial data in the form of horizontal planes using selected software

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Abstract: *The main motivation of the paper is to provide an overview of 3D geovisualization capabilities of selected software and present selected methods of visualization of 3D geospatial data using horizontal planes. The paper is focused on the evaluation of software and methods for the visualization of thematic geospatial data with an emphasis on visual analysis in 3D. Meteorological data of the ALADIN forecast model were used to create visualizations. The first part focuses on the evaluation of selected software in terms of 3D visualization capabilities. The evaluation encompasses software tools such as geographic information systems, web-based solutions, and 3D computer graphics software. The result is a comparison of these software in terms of suitability for visual analysis in 3D, for example in terms of spatial data support, 3D visualizations, or analytical functions. The second part is focused on the presentation of four methods of 3D data visualization using horizontal planes for visualizing thematic data, including single plane, multiple planes without transparency, multiple planes with transparency, and multiple planes overlay. These methods were evaluated based on graphical variables, both the original ones defined by Jacques Bertin and those added later by other cartographers, to achieve the most optimal visual analysis in 3D. The article concludes by highlighting the advantages and disadvantages of the different visualization methods, and their specifics in terms of graphical variables. The importance of interactive visualization environments for fully utilizing the potential of these methods is emphasized.*

Keywords: *3D geovisualization, visual analysis, graphical variables, meteorological data*

Introduction

The need to present 3D cartographic content on computer monitors is growing, and the possibilities of these presentations are expanding. However, these visualizations should be comprehensible even for users without cartographic education (Popelka and Brychtova 2013). Nevertheless, visualizing 3D geospatial information raises the question of how to effectively represent this information. The ongoing shift from static media to various interactive display technologies has a huge impact on the design, creation, and use of digital maps and spatial visualizations. As Semmo et al. (2015) appeals, the application of widely used cartographic principles to advanced imaging technologies and the development of new cartographic methods are therefore key challenges for current and future research. With 3D geovisualizations, visual analysis brings more efficiency. From the cartographic perspective, visual analysis is understood as the analysis of a map product, or products, only by the visual perception of information on a map. An example is a visual comparison of two maps showing the same area but at different times. Thus, the user can derive phenomena values, spatial relationships, spatial distribution, and other findings based solely on his own observations, without the need for quantification, statistical evaluation, or special analytical tools. However, visual analysis can also be applied to 3D spatial data in addition to maps. When exploring 3D data using visual analysis, questions may arise that aren't answered in the current visualization. Therefore, for visual analysis, it is necessary to be able to display additional variables in the visualization

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or remove those that are no longer needed. Other frequent, important, and effective methods used in visual analysis are, for example, comparing, filtering, aggregating, highlighting, or zooming and panning (Few 2009). When designing interactive visual analytics tools, multiple factors need to be considered with respect to their target users, such as displaying aggregated data at the desired geographic scales, designing appropriate visualizations, logically organizing visualizations, and using effective interactions (Zuo et al. 2022).

Although the visualization of thematic spatial data in a 3D environment is currently very popular, no methods have yet been defined for the visualization of 3D thematic data in the form of horizontal planes. For the purposes of the study, meteorological data was used to create visualizations. The joint visualization of simulated meteorological data with urban models allows to support the validation of meteorological models by comparing the simulation results with morphological indicators used as simulation input, for example by appropriate visual analysis of the relationships between urban heat islands and the urban environment (Gautier et al. 2020a). Studying urban climate on a larger scale means considering the spatial and geometric structure of meteorological data to visualize them together in the same graphical interface, augmented by interaction options for their manipulation and exploration (Christophe et al. 2022). Visualization of meteorological data is mostly used to verify and communicate the results of simulations, especially air temperature profiles, dynamic wind display or possible wind corridors, with the expectation of verification of input/output data and model characteristics. Many types of representation are used, most commonly as vertical and horizontal cross-sections (Gautier et al. 2020a). Representation using horizontal planes consists of representing 3D data through a series of 2D sections corresponding to one height level at a time, and representing each of these 2D sections using a 2D horizontal plane that consists of a series of horizontal 2D planes placed on top of each other. Rendering 3D data using a series of horizontal 2D planes introduces the problem of overlapping between planes. Thus, there is the possibility of using transparency to be able to display different data values (Gautier et al. 2020b).

When choosing optimal visualization methods in the form of horizontal planes, visual (graphic) variables can play a crucial role. These were originally described by the French cartographer Jacques Bertin (1918-2010) in his book Semiologie Graphique (Semiology of Graphics) in the original edition of 1967. Graphical variables are the properties of cartographic characters that can be modified independently of each other. Bertin proposed seven basic variables – position, size, color (value and hue), orientation, shape, and texture. Except for location, these variables have been labeled as retinal, that is, as those to which the user automatically and subconsciously responds. Each of these variables can be used for any value, but some variables are more appropriate for a given data than others (Bertin 1983). Evaluation of graphical variables for different 3D geovisualization methods can help to understand the choice of method for different type of data.

Objectives

The article has two objectives. The first objective of the study is to explore the possibilities of 3D geovisualization of thematic spatial data in selected software. Visualizations were performed in seven software programs from three categories: geographic information systems (ArcGIS Pro, QGIS), web-based solutions (ArcGIS Online, Cesium), 3D computer graphics software (Unity, Unreal Engine, Blender). The goal of testing is to select the software that shows the most benefits for visual analysis. The second objective of the study is to find out the optimal ways to visualize horizontal 2D planes based on the evaluation of graphical variables using the software that was selected in the previous step. Presenting and evaluating different visualization methods will improve the visual analysis of thematic 3D data, i.e. data analysis based only on visual perception. The primary source for 3D visualizations and their evaluation is the dataset of the ALADIN prediction model. The main motivation for the study is to present methods of visualization of 3D data using horizontal planes and then evaluate these methods based on graphical variables to achieve the most optimal visual analysis.

Methodology

In the first phase, seven software from three different categories were selected with the aim of selecting the software that would prove to be the most suitable for 3D visual analysis. Several criteria were tested, such as support for spatial data, support for 3D visualizations or the possibility of creating 3D applications. Desktop and web-based and commercial and non-commercial software were purposefully selected to cover the widest possible spectrum. Subsequently, visualizations in the form of horizontal planes were created in the selected software, using data from the ALADIN weather forecast model. Four methods of 3D data visualization in the form of horizontal planes were selected. The specifics in terms of graphical variables were described for these methods. The paper's methodology illustrating both objectives is shown in figure 1.

Data provided by the Czech Hydrometeorological Institute (CHMI) of the ALADIN prediction forecast model in GRIB format were used for visualization of horizontal planes. ALADIN is a numerical weather model developed in 1991 by the French meteorological service Météo-France in cooperation with other interested countries. The data are related to 2014, cover almost the whole of Europe and contain various meteorological variables (e.g. temperature, humidity, wind speed) at several altitude and pressure levels. GRIB is a raster data format commonly used in meteorology to store historical and forecast weather data.

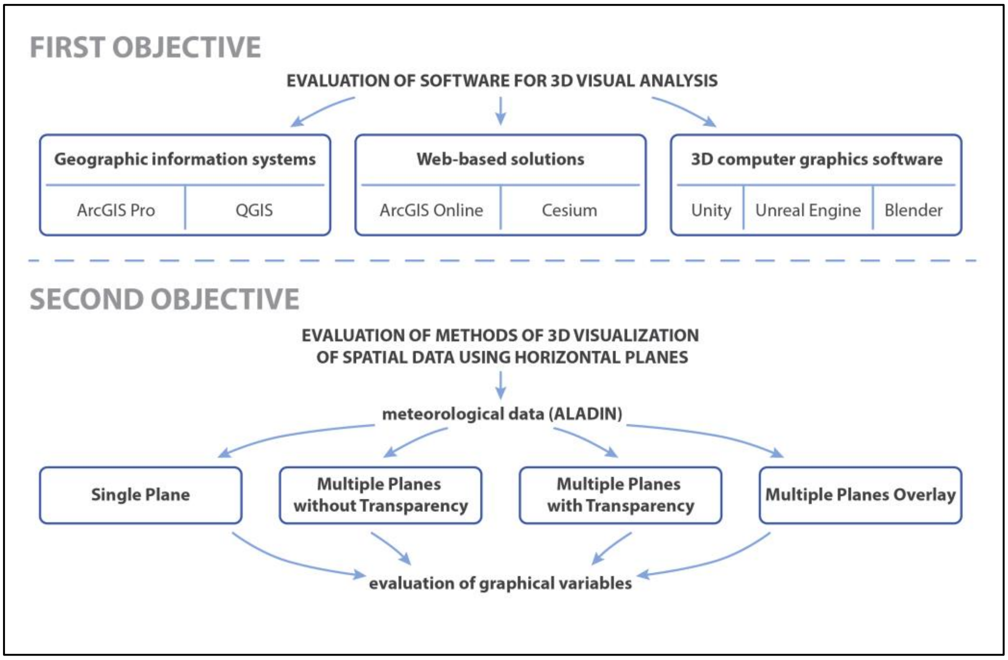

Fig. 1. *Methodology of the article illustrating the two objectives*

Methods of 3D geovisualization using horizontal planes

Horizontal plane is a way of displaying raster 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. Visualization of 2D planes in the form of static outputs is quite limiting, as they overlap when displaying multiple planes at different height levels. For this reason, it is desirable to use this type of visualization in an interactive environment, which is also necessary for visual analysis and data exploration. Ideally, such an environment should be able to e.g. filter data, provide analytic functions, or create animations to enable interactive visual analysis based on user requirements. Furthermore, four methods of visualization of 3D data in the form of horizontal planes are introduced, each of which has its advantages and disadvantages and is suitable for a different type of displayed data. 3D data can be visualized using horizontal planes using the following methods:

- Single Plane
- Multiple Planes without Transparency
- Multiple Planes with Transparency
- Multiple Planes Overlay

Single Plane

The most basic method of visualizing 3D thematic data in the form of horizontal 2D planes is the visualization of only one plane (fig. 2). Planes can be displayed either in parallel using a local scene, or in a global scene considering the curvature of the Earth. When visualizing a single plane, it is also possible to adjust its transparency, which allows for better orientation thanks to the visible topography. However, transparency distorts the visualization method used, which can impair visual analysis. The advantages of visualization in the form of a single plane are its simplicity, visibility of the entire plane, and the possibility of using transparency. The disadvantage is the impossibility of visual analysis of relationships between different meteorological variables, different pressure levels or comparisons at different times. This can be solved by creating animations with different parameters.

Multiple Planes without Transparency

When displaying multiple planes at different elevation levels (fig. 3) the displayed data can be compared. However, the problem is the overlapping of layers, which prevents all data from being visible at the same time. The solution can be a vertical scroll bar (swipe) function, which would allow the data to be displayed only at a certain height, which the user can change dynamically. This type of visualization is suitable for comparing the same meteorological variable, but at different times or altitudes. However, it is necessary to set the optimal spacing between layers, which depends on the scale and the data being displayed. The impossibility of displaying topography on the earth's surface can be solved by using country borders and labels that are always displayed in the topmost layer. The advantage of visualizing multiple planes without transparency is the ability to compare relationships between layers. The disadvantages are overlapping data and invisibility of the topography.

Multiple Planes with Transparency

Transparency can be used to visualize multiple planes at different heights (fig. 4). This partially resolves data overlap and allows spatial relationships to be compared. However, it is necessary to set the optimal transparency value so that the layers are easily distinguishable and do not blend. As with no transparency, it's a good idea to use a scroll bar (swipe) to display the topography on the top layer. With this type of visualization, the same color scale and data range should be used for all layers so that the data can be compared. However, it is difficult to present these results in the form of a static output, as a dynamic environment is needed for the visual analysis of 3D data. The advantages of visualizing multiple planes with transparency are the ability to compare relationships between layers and the partial resolution of overlapping data thanks to transparency. The transparency must be set correctly so that the layers do not distort each other too much.

Multiple Planes Overlay

The fourth option for joint visualization of horizontal 2D layers is to overlay them at the same height level (fig. 5). With the right color settings, new information can be obtained by combining them. This method is suitable for comparing different data at the same time and height, but it is more difficult to interpret than previous ones. This can be solved by using a horizontal scroll bar (swipe) feature that will allow the user to gradually overlap the layers. The visualization is limited to two layers, as correct interpretation would be impossible if multiple layers overlapped.

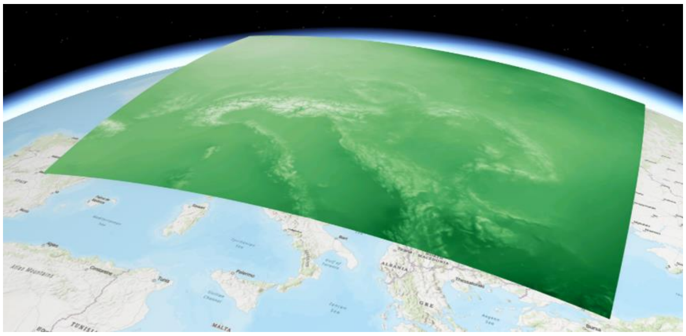

Fig. 2. Visualization of ALADIN model data – Single Plane

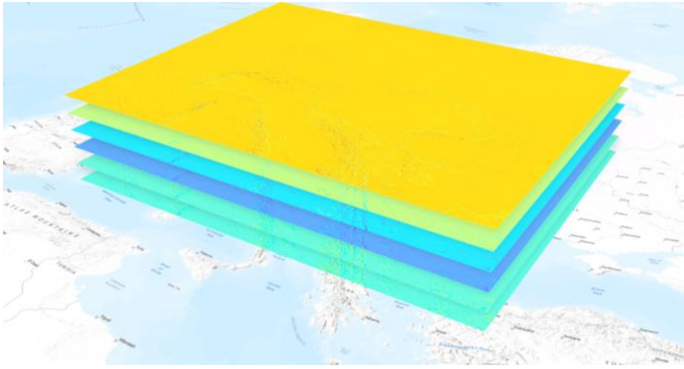

***Fig. 3.** Visualization of ALADIN model data – Multiple Planes without Transparency*

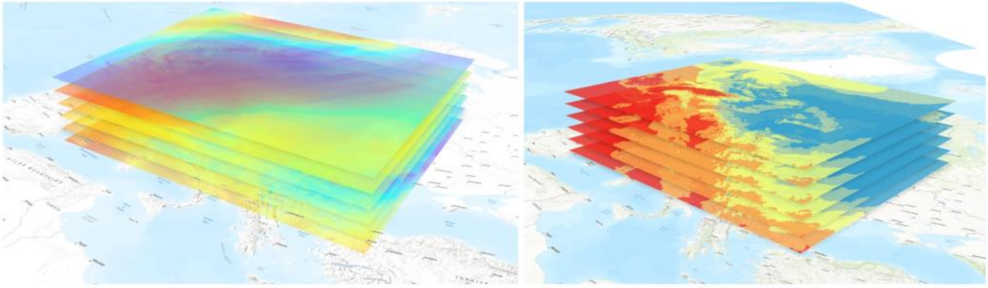

***Fig. 4.** Visualization of ALADIN model data – Multiple Planes with Transparency*

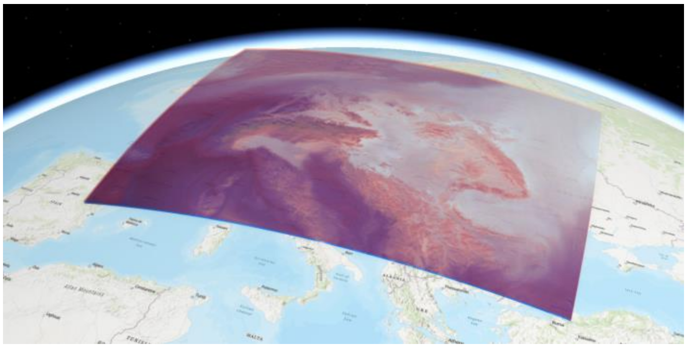

***Fig. 5.** Visualization of ALADIN model data – Multiple Planes Overlay*

Graphical variables

Graphical or visual variables describe the graphical dimensions in which a map or other visualization can be changed to encode information. Visual variables were originally described by French cartographer Jacques Bertin (1918-2010) in his book Semiologie Graphique (Semiology of Graphics) in the original 1967 edition, revised in 1983 (Roth 2017). Graphical variables are differences in map elements as perceived by the human eye. Regardless of the type of map, these are the basic ways of distinguishing graphical symbols (Axis Maps 2023). Garlandini and Fabrikant evaluated the efficiency and effectiveness of visual variables for visualizing geographic information (Garlandini and Fabrikant 2009).

The original so-called "retinal variables" were proposed by Jacques Bertin (Bertin 1983). These are:

- position
- size
- shape
- color value
- color hue
- orientation
- texture/pattern

This list was then successively made by other cartographers (Morrison 1974, MacEachren 2004, Roth 2017) and extended by:

- color saturation
- arrangement
- crispness/fuzziness
- resolution
- transparency

In addition, the 3D environment allows adjustment of other graphical variables, such as height, extrusion, object surface (pattern, shading), light emission (Limberger et al. 2023) or fog (Vetter 2023).

Description of selected software

To choose the software for the next phases of the study, seven software were selected at the beginning, which have the potential to enable visual analysis of 3D data. These are either freely available software (open-source and proprietary), freemium (basic functionality for free, advanced functionality for an additional fee) or commercial software, the license of which is available at the Department of Geoinformatics. Each of them was tested in support for spatial data, support for spatial analytical functions, or possibilities of visualization of 3D spatial data. Software are divided into three categories according to their purpose: geographic information systems, web-based solutions, and software for computer 3D graphics.

Geographic Information Systems

When working with two-dimensional spatial data, geographic information systems are the obvious choice. They enable support for many formats, including their conversion, spatial analytical functions, data management and organization, and advanced methods of geovisualization and mapping. However, when visualizing 3D data, GIS may not always be suitable, as 3D geovisualizations are not yet a standard in GIS, and the vast majority of GIS does not have advanced 3D geovisualization capabilities. But, with some software, such as ArcGIS Pro, work with 3D data is already supported at a very good level, and e.g. analysis and modeling in 3D are possible. Two of the most widely used geographic information systems were selected:

- ArcGIS Pro is a desktop GIS developed by Esri available under a commercial license. It supports a wide range of spatial data formats, such as file formats, databases, or web services, including multidimensional data (e.g. NetCDF). ArcGIS Pro supports data visualization, advanced analytics, and data management in 2D, 3D, and 4D (Esri 2023a).
- QGIS is a desktop GIS that falls into the category of Free and Open-Source Software (QGIS 2023). It is available under the GNU General Public License, which allows it to be used for commercial purposes.

Web-based solutions

Web-based solutions usually do not provide as many capabilities for visualization of spatial data as classic desktop GIS. However, one of the main advantages is the ability to access data and tools from anywhere and at any time via an internet browser. At the same time, web-based solutions allow for easy distribution of geographic data through web maps, applications, and 3D scenes, so users can quickly and efficiently share information with others. The disadvantages of working with spatial data in a web environment are dependence on internet connection, dependence on server availability, limited customization options, and limited possibilities for transferring large data files. Two software products were selected for the "web-based solutions" category:

- ArcGIS Online is a web-based platform developed by Esri that allows users to create, share, and analyze spatial data. Like ArcGIS Pro, it is available under a commercial license. ArcGIS Online provides GIS capabilities in a cloud-based environment, allowing users to access geographic data and tools from anywhere, at any time, while eliminating the need for physical infrastructure for data storage. In the case of ArcGIS Online, all processes are server-side and therefore dependent on an internet connection. Unlike ArcGIS Pro, performance is not dependent on the technical parameters of the computer. Thus, ArcGIS Online is better suited in terms of sharing, collaboration, and teamwork. ArcGIS Online supports a wide range of spatial data formats and 3D models (Esri 2023b).
- Cesium is an open web-based platform for developing 3D geospatial applications. Its goal is to create 3D globes and maps for statistical and time-dynamic content. Cesium is built on a freemium strategy. It is based on an open-source JavaScript library that is freely available for non-commercial purposes. But more advanced features, such as more storage or faster data transfer, need to be paid for (Cesium GS 2023).

3D computer graphics software

3D computer graphics (CGI) software is not yet widely used for geoinformatics tasks, and most users prefer classic GIS. However, in some cases, such as the development of applications for the visualization of 3D data, these software provide far more possibilities. Nevertheless, when working with these software, an advanced knowledge of programming is usually required. In most cases, interoperability is the biggest problem, as 3D computer graphics software do not natively support spatial formats. Yet, there are several extensions and plugins that allow work with spatial data.

Computer 3D graphics are most often used in the creation of films, computer games or animations. However, it is also used in science (physics and mathematics – computer simulations, medicine – 3D imaging of organs and surgical planning, chemistry – visualization of molecules and their interactions). At present, for example, game engines are also being used in geoinformatics, for the creation of realistic simulations of geographical phenomena (e.g. flood simulations), the creation of digital twins, the creation of 3D scenes for virtual reality, and more. Computer aided design (CAD) systems can also be included in 3D computer graphics software, but they are mainly used in architecture and urban planning. Three software products were selected for the "3D computer graphics software" category:

- Unity is an integrated development environment (IDE) and game engine that is widely used in the PC game and interactive visual projects industry. The software allows developers to combine graphics, audio, and programming together, making it easy to create both 2D and 3D games and applications. One of the key features of Unity is its cross-platform support, which means that the resulting projects can be easily distributed across multiple platforms, including computers, mobile devices, gaming consoles, and virtual reality devices. For individuals and students, Unity is free, but in the case of companies, a license needs to be paid for. There is also Unity Pro that provides more advanced functionality (Unity Technologies 2023).
- Unreal Engine is a complex game engine and development framework that has become a key player in the world of professional PC game development and visual projects. Unreal Engine was developed by Epic Games and offers a wide range of tools for developers, from advanced graphics capabilities and physical modeling to extensive C++ script programming. One of the key features of Unreal Engine is its real-time rendering, which allows developers to see the results of their work immediately. The engine also offers an extensive library of pre-built assets and effects, making it easy for developers to create detailed and authentic environments. Unreal Engine supports a wide range of platforms, including PC, consoles, mobile devices, and virtual reality. Like Unity, the standard Unreal Engine license is free for individuals and students, in the case of larger teams, you need to pay for the license (Epic Games 2023).
- Blender is a comprehensive and powerful 3D graphics software that offers a wide range of features for modeling, texturing, animation, and rendering. It is an open-source application with an active community of developers.

Evaluation of selected software in terms of 3D geovisualization capabilities

3D data enable more accurate and realistic visualization of geographic objects and phenomena than in plane representation. In addition, 3D visualizations of thematic data can be enriched, for example, with buildings or terrain. 3D geovisualization allows users to understand geographic relationships more easily and they are often more attractive than traditional 2D maps. At the same time, they can be interactive, so the user can change scene settings, switch layers, change visualization methods, and adjust other parameters according to their preferences. 3D geovisualizations can also be processed in virtual reality. The disadvantages of 3D geovisualization usually include more complex data processing, greater demands on computing power, limited availability of 3D data, or interoperability difficulties.

Visualization in the form of horizontal planes is used in most cases for demonstrations of the 3D environment of individual software, however, horizontal planes are only used for demonstration, and the 3D capabilities of the software are evaluated comprehensively. For all software, four criteria were rated on a scale of 1 to 5, with 1 being the worst result and 5 the best. The average value of these four criteria indicates the overall 3D visual analysis suitability. The description of each criterion is as follows:

- spatial data support: Does the software support spatial data formats that allow 3D geovisualization?
- 3D geovisualizations support: Does the software allow 3D geovisualization? If yes, does it only allow basic visualization or does it offer more advanced features (e.g. realistic symbology, scene lighting, animation)?
- 3D spatial analysis functions support: Does the software offer 3D analytical functions (layer filtering, measurements, horizontal or vertical sliders)?

- possibility to create 3D applications: Is it possible to create a 3D application using the software and then share it?
- 3D visual analysis suitability: Is the software overall suitable for 3D visual analysis? Average value of the four previous criteria.

ArcGIS Pro

- spatial data support – 5: ArcGIS Pro supports a wide range of spatial data formats, such as file formats, databases, or web services, including multidimensional data.
- 3D geovisualizations support – 5, 3D spatial analysis functions support – 5: 3D geovisualization can be performed either in local (planar – fig. 6) or the global scene (curvature of the Earth). In addition to basic navigation functions (pan, zoom, orbit), ArcGIS Pro also has options to add atmospheric effects (e.g. sunrise and sunset, drop shadow) to give 3D visualizations a realistic look. ArcGIS Pro also allows a wide range of advanced features for 3D editing, analysis, and visualization (e.g. 3D visualization of buildings using polygon extrusion, realistic symbology in the form of 3D models, realistic appearance of water, creation of animations, visibility analysis). A great advantage is also the possibility of using so-called sliders, which allow interactive visual filtering of content based on time or space range.
- possibility to create 3D applications – 5: Created 3D scenes can also be shared to ArcGIS Online and then turned into a web map application (e.g. using WebAppBuilder) or StoryMap.
- 3D visual analysis suitability – 5: ArcGIS Pro seems to be very suitable for visual analysis of 3D data, especially due to its advanced support for 3D data, extensive 3D geovisualization capabilities, and user-friendliness. All information about 3D visualization in ArcGIS Pro is documented on the Esri website in the form of user-friendly tutorials and documentation.

QGIS

- spatial data support – 5: QGIS uses the open source GDAL (GDAL/OGR) library to read, write, and convert vector and raster data formats. It allows work with most used spatial data formats.
- 3D geovisualizations support – 3: 3D visualization in QGIS is not yet nearly as good as in ArcGIS Pro, which is of course caused by the different philosophies of both software. 3D visualization is natively supported in QGIS since version 3.0 using the 3D Map View tool (fig. 7). The created 3D scene is linked to the 2D map window – it has the same scope, and the layers have the same symbology settings. An alternative option for 3D visualizations in QGIS is the Qgis2threejs plugin (fig. 7). However, it allows for very similar functionality as 3D Map View.
- 3D spatial analysis functions support – 4: In addition to the basic navigation tools (pan, zoom), there are tools for measuring, creating animations or exporting in the form of an image or 3D object (OBJ format). In the advanced options, terrain (flat, digital terrain model), scene lighting, shadows, camera, and navigation parameters, and more can be set.
- possibility to create 3D applications – 1: QGIS does not allow the creation of 3D applications.
- 3D visual analysis suitability – 3.25: Compared to ArcGIS Pro, QGIS provides only a basic environment for 3D visualization, which is not suitable for advanced visualization of three-dimensional data, so QGIS appears to be unsuitable for visual analysis of 3D data. However, it would probably be possible to create a plugin that would enable the desired functionality.

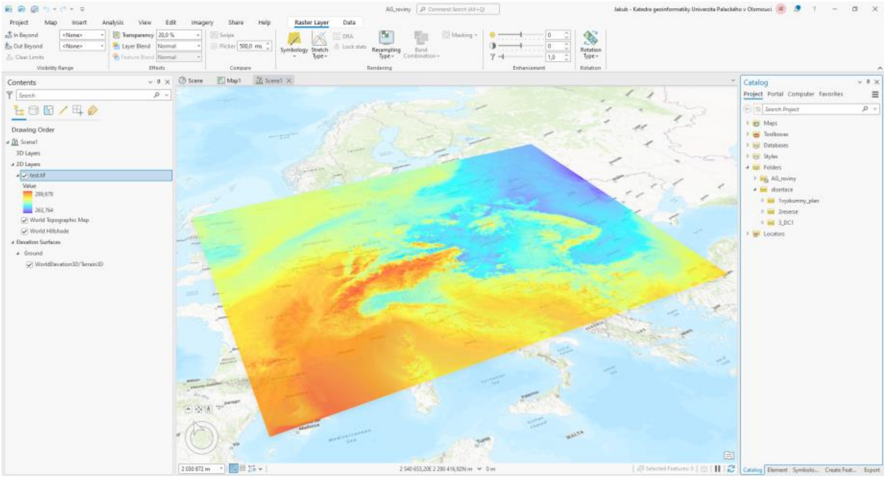

Fig. 6. *Visualization of horizontal plane in ArcGIS Pro*

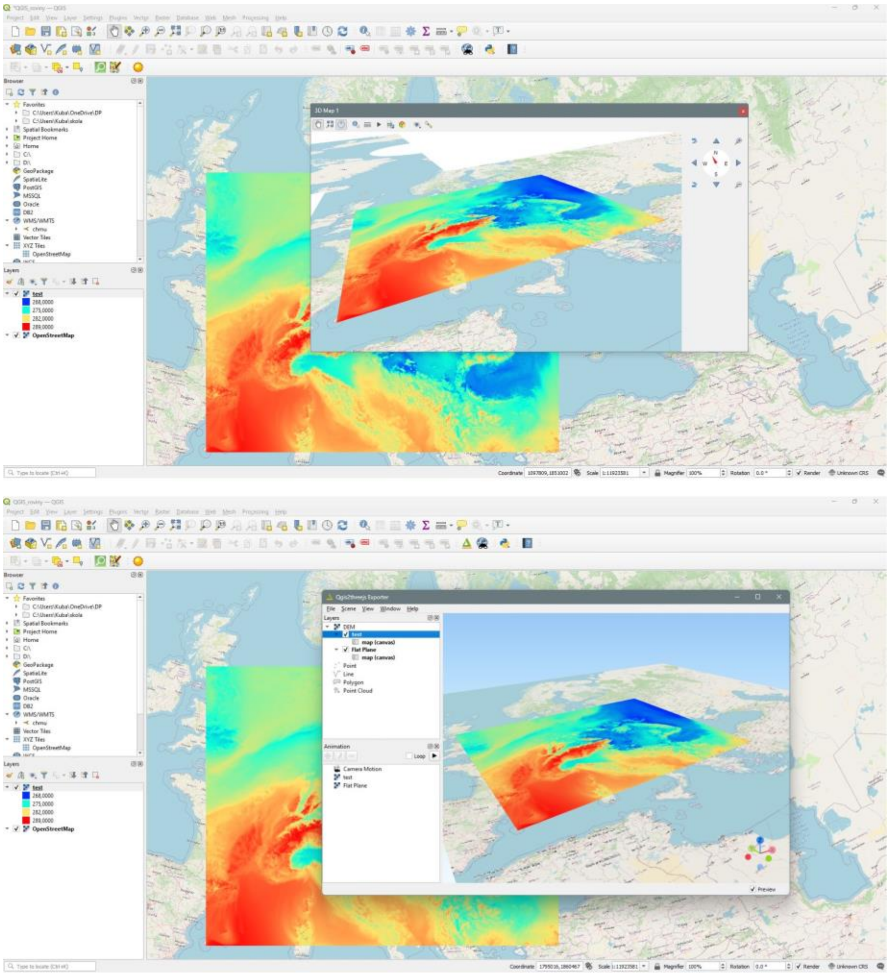

Fig. 7. *Visualization of horizontal plane in QGIS – 3D Map View (top) and Qgis2threejs plugin (bottom)*

ArcGIS Online

- spatial data support – 4: ArcGIS Online supports a wide range of spatial data formats and 3D models. However, there are significantly fewer supported formats than in desktop ArcGIS Pro. There is a problem with raster data support, as ArcGIS Online does not support classic raster data formats, but only raster data published from ArcGIS Pro as a Tile layer. To publish raster data from ArcGIS Pro, the Esri ArcGIS Image for ArcGIS Online extension is required.
- 3D geovisualizations support – 4: There are not as many options for visualization of raster data as in ArcGIS Pro. Working with horizontal planes, for example, is quite problematic (fig. 8).
- 3D spatial analysis functions support – 4: The possibilities of working with 3D data and support for spatial analytical functions are at a comparable level to those of ArcGIS Pro.
- possibility to create 3D applications – 5: 3D scenes can be created directly in ArcGIS Online, or they can be shared from ArcGIS Pro for further work. ArcGIS Online can be used to easily create 3D web map applications from the visualizations created.
- 3D visual analysis suitability – 4.25: ArcGIS Online seems rather unsuitable for 3D visual analysis, but it can be used, for example, to share and present created visualizations.

Cesium

- spatial data support – 4: Cesium supports about twenty data formats.
- 3D geovisualizations support – 4: The basic web application does not provide many 3D geovisualization options, but more advanced functionality can be programmed in JavaScript. When visualizing the horizontal plane, it was not possible to edit the symbology of the uploaded data in the Cesium web environment (fig. 9). At the same time, the application does not allow setting the vertical offset (height) of the layers.
- 3D spatial analysis functions support – 2: Of the analytical functions, only measurement is available.
- possibility to create 3D applications – 4: Cesium makes it relatively easy and quick to create 3D applications, including animations.
- 3D visual analysis suitability – 3.5: In terms of suitability for visual analysis, Cesium is far from reaching the same capabilities as, for example, ArcGIS Pro

Unity

- spatial data support – 5, 3D geovisualizations support – 5, 3D spatial analysis functions support – 5: Thanks to the available API, Unity's functionality can be expanded at will, so there is great potential to support spatial analytical functions and advanced 3D visualizations. ArcGIS Pro and Unity interoperability is enabled by the ArcGIS Maps SDK for Unity plugin (Esri 2023c), which allows data and visualizations from ArcGIS Pro to be exported to Unity to take advantage of game engine features (fig. 10).
- possibility to create 3D applications – 5: Unity widely supports the creation of 3D applications, even for mobile devices or virtual reality.
- 3D visual analysis suitability – 5: Thanks to the very good support of 3D visualizations, the possibility of user extension of the functionality using API and especially the possibility of connecting with ArcGIS Pro, Unity seems to be very suitable for 3D visual analysis.

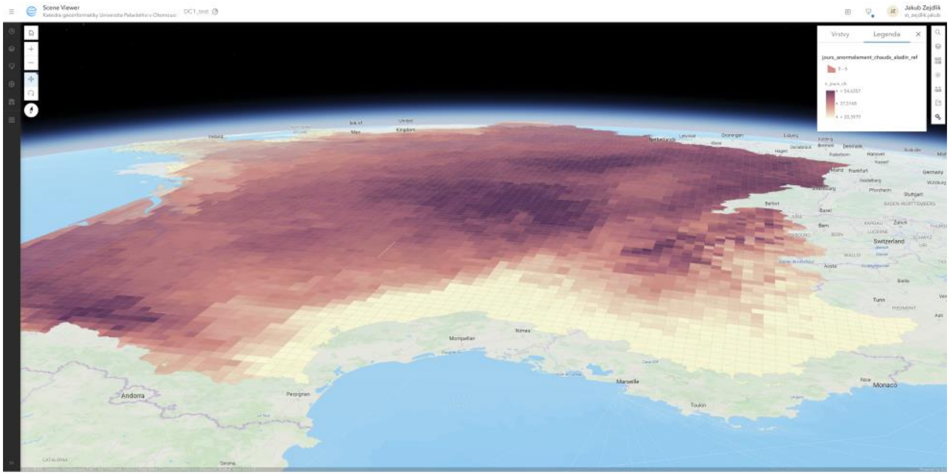

Fig. 8. *Visualization of horizontal plane in ArcGIS Online*

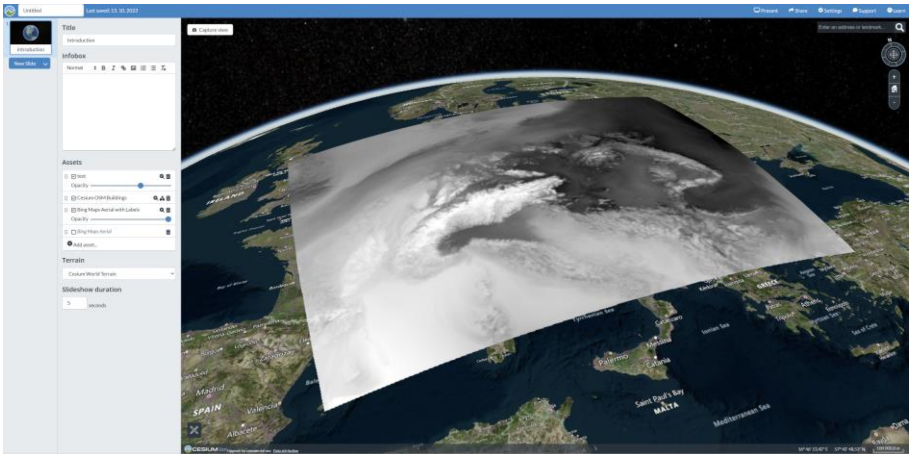

Fig. 9. *Visualization of horizontal plane in Cesium*

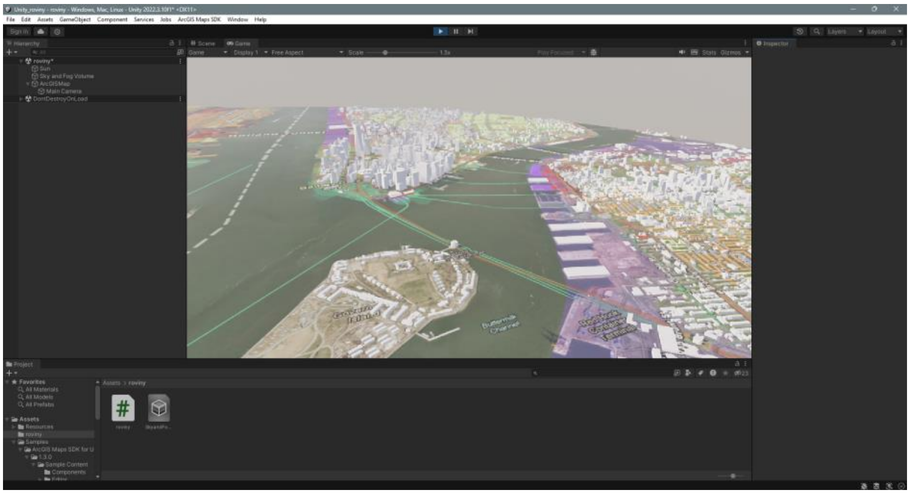

Fig. 10. *3D geovisualization in Unity*

Unreal Engine

- spatial data support – 5: As in the case of Unity, the connection to ArcGIS Pro is enabled by a plugin, specifically the ArcGIS Maps SDK for Unreal Engine (Esri 2023d).
- 3D geovisualizations support – 5, 3D spatial analysis functions support – 5: As with Unity, the available options for 3D visualizations and support for spatial analytics functions are very wide, and the functionality can be extended using the C++ API.
- possibility to create 3D applications – 5: Unreal Engine widely supports the creation of 3D applications, even for mobile devices or virtual reality.
- 3D visual analysis suitability – 5: The Unreal Engine enables very advanced 3D visualizations, extensible functionality, and interoperability with ArcGIS Pro, making it a good fit for 3D visual analysis (fig. 11).

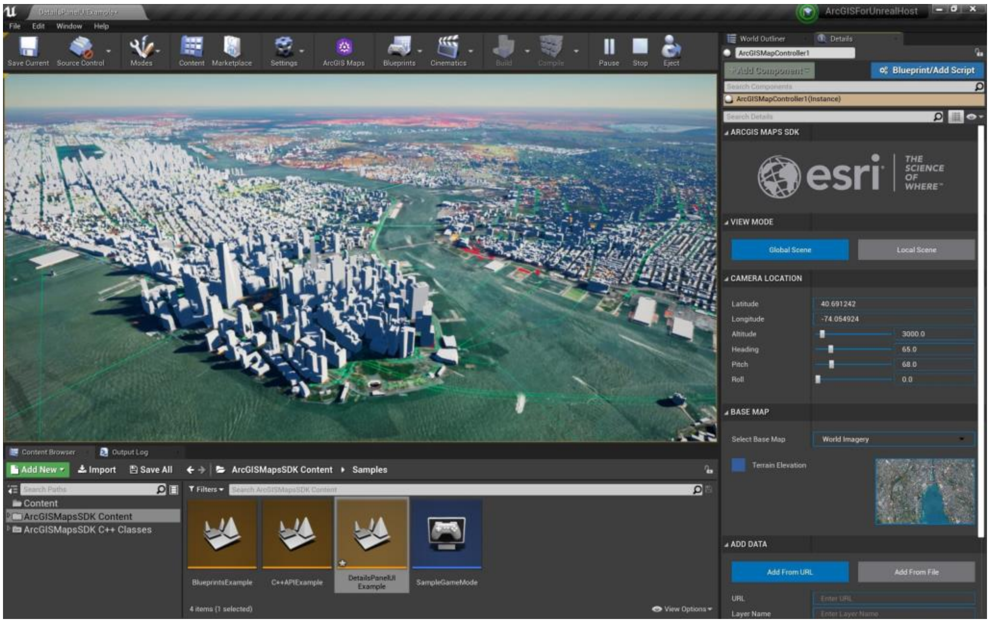

Fig. 11. *3D geovisualization in Unreal Engine; Source: ESRI (2020)*

Blender

- spatial data support – 3: Support for spatial data is enabled by the BlenderGIS add-on, which allows importing the most common GIS formats (e.g. shapefiles, GeoTIFF, OSM). At the same time, it is possible to add selected basemaps (e.g. from Google, Bing, Esri).
- 3D geovisualizations support – 3, 3D spatial analysis functions support – 1: Blender does not support any spatial analysis functions and is only suitable for visualization in the case of spatial data (fig. 12).
- possibility to create 3D applications – 3: Creating 3D applications using Blender requires an advanced knowledge of programming.
- 3D visual analysis suitability – 2.5: Blender is not suitable for 3D visual analysis of spatial data. Although it is possible to import spatial data into its environment, working with them is very limited, also due to the support of only a few formats.

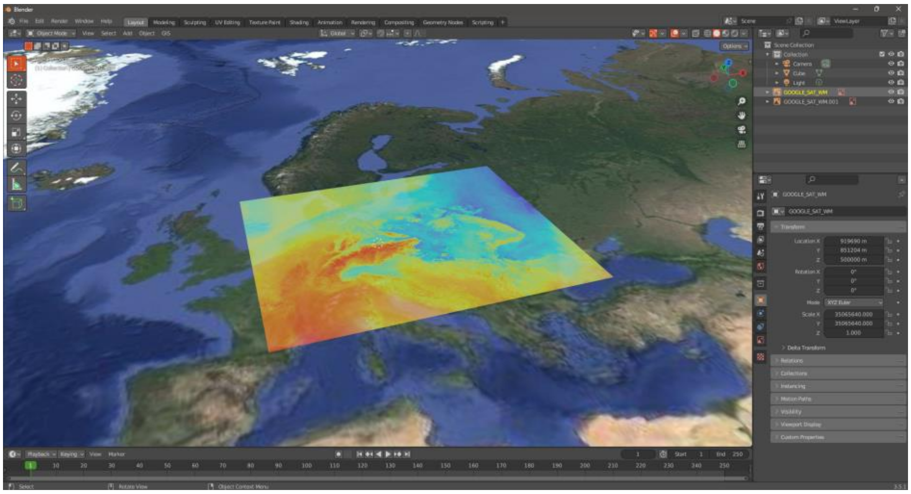

Fig. 12. *Visualization of horizontal plane in Blender*

Software comparison

For each software, four criteria were assessed using a scale from 1 to 5, where 1 represents the lowest rating and 5 the highest. The average score across these criteria reflects the overall suitability for 3D visual analysis (tab. 1 and tab. 2). For 3D visual analysis of thematic data, **ArcGIS Pro** seems to be the most suitable. It offers a wide range of support for 3D data and provides many advanced functions for editing, analysing, and visualising them. Among other things, it allows you to create a realistic character key, create animations or add atmospheric effects. A great advantage is also the high-quality documentation. ArcGIS can also be combined with the **Unity** and **Unreal Engine game engines** to create highly advanced 3D visualizations and interactive applications. The ArcGIS Maps SDK for Unity and ArcGIS Maps SDK for Unreal Engine plug-ins enable ArcGIS to connect with game engines. Both software provide an API that allows users to extend their functionality.

Tab. 1. *Comparison of selected software in terms of suitability for visual analysis in 3D (part 1/2)*

software	type	license	spatial data support	3D visualizations support
ArcGIS Pro	desktop GIS	commercial	5	5
QGIS	desktop GIS	open-source	5	3
ArcGIS Online	Web-based solution	commercial	4	4
Cesium	Web-based solution	freemium	4	4
Unity	3D graphics software	commercial (free for students)	5	5
Unreal Engine	3D graphics software	commercial (basic version for free)	5	5
Blender	3D graphics software	open-source	3	5

Tab. 2. *Comparison of selected software in terms of suitability for visual analysis in 3D (part 2/2)*

software	3D spatial analysis functions support	possibility to create 3D applications	3D visual analysis suitability	note
ArcGIS Pro	5	5	5	advanced 3D visualization options, wide data support
QGIS	4	2	3.25	3D map window, Qgis2threejs plugin, possibility to create plugins and scripts
ArcGIS Online	4	5	4.25	suitable for sharing outputs from ArcGIS Pro, worse possibilities of raster data visualization
Cesium	2	4	3.5	open code – possibility to program own functionality
Unity	5	5	5	ArcGIS Maps SDK for Unity plugin
Unreal Engine	5	5	5	ArcGIS Maps SDK plugin for Unreal Engine
Blender	1	3	2.5	add-on BlenderGIS

Evaluation of horizontal planes in terms of graphical variables

The most significant graphical variables in the case of Single Plane visualization are color and transparency. The hue and brightness of the color must be appropriately selected according to the phenomenon to be displayed and the nature of the data (e.g. divergent scale to represent temperature – blue shades for cold regions, red shades for warm regions). The use of transparency in the case of a single plane allows partial visibility of the topographic background (e.g. state boundaries, cities). However, if set up incorrectly, transparency can distort the visualization due to the blending of the colors of the thematic layer and the basemap. Other visual variables include resolution (pixel size). Resolution affects the graininess of the resulting image – high resolution means more detailed and smoother visualization, but this results in a larger volume of data. When browsing and switching layers interactively, a large volume of data can result in slow loading. It is therefore necessary to optimize the resolution depending on the number of layers, the volume of data, the possibilities of the visualization environment and other parameters.

As in the case of a single plane, the hue and value of the color are the most important for Multiple Planes without Transparency. The color scale should be the same for all planes so that they can be compared with each other. For example, when displaying the average air temperature at different altitudes, the temperature trend depending on the altitude should be obvious immediately. For this reason, it is advisable to display the same meteorological variable in all layers. A combination of different meteorological variables is also possible in this type of visualization, but a larger number of different variables can worsen the user's interpretation. When displaying multiple planes, the height (height spacing of layers) is also very important. The height of the plane, or the vertical distance between the planes, can be either fixed (e.g. 100 km) or it can be variable according to a certain attribute. In the case of ALADIN model data, an example of an altitude attribute can be different pressure levels at which meteorological variables are recorded (e.g. 500 hPa, 700 hPa, 850 hPa). The arrangement of the layers is also related to height. If the data contains information such as altitude, layers should be organized based on this attribute (low values closer to the earth's surface, high values at higher altitudes) to bring the visualization closer to reality.

In the Multiple Planes with Transparency visualization, the same or very similar statements apply to graphical variables as in the visualization of multiple planes without transparency. It is necessary to optimally choose colors, height spacing of the layers and their arrangement. In addition, however, it is necessary to consider the transparency of the graphical variable. This can help solve the overlap problem partially, but it also introduces other problems, such as color blending between layers or with the topographic background. Raster data in the form of horizontal planes can be visualized either continuously or the data can be classified into intervals. The visualization of the classified data does not cause as much color distortion as continuous visualization. The disadvantage of multi-plane visualization is the relatively poor interpretation in the case of static outputs. For this reason, it is advisable to display the visualized data in an interactive 3D visualization environment, which allows the user to freely explore the data (rotate, zoom, filter layers). For visual analysis of multiple planes, the use of animation is also suitable. It can be either uncontrolled (pre-prepared) or controlled, in which the user can, for example, select the layers they are interested in or set a time step. To solve the problem of layer overlap, a vertical swipe can also be used, which will allow the data to be displayed only at a certain height, which the user can change dynamically.

Color value and hue are key for the Multiple Planes Overlay method. When the colors are set correctly, it is possible to obtain new information by combining layers using transparency. For example, when depicting air temperature using red paint and humidity using blue, overlapping them would result in a layer of shades of purple. In this case, the rule would be that the darker the purple color, the higher the values of both variables. The height spacing and arrangement of the layers do not play any role here, as the planes are located at the same or very similar height level. When overlapping multiple planes at the same level, it is suggested to use a horizontal slider (swipe), which would allow the user to gradually overlap the layers. A slider can allow the user to control one or both layers.

Comparison of methods

There are seven graphical variables that are most important in the visualization of horizontal planes - color value, color hue, color saturation, arrangement, resolution, transparency and height (tab. 3). Color (value, hue, saturation) and resolution play an important role in all four methods. Arrangement, transparency and height can be adjusted only for some methods. Only the Multiple Planes with Transparency method allows adjustment of all seven variables. In the case of raster data in the form of horizontal planes, some variables are fixed and cannot be modified in any way. For example, position (location in space), size (data range), shape, or orientation.

Tab. 3. *Comparison of visualization methods using horizontal planes in terms of graphical variables*

graphical variable	Single Plane	Multiple Planes without Transparency	Multiple Planes with Transparency	Multiple Planes Overlay
color value	x	x	x	x
color hue	x	x	x	x
color saturation	x	x	x	x
arrangement		x	x	
resolution	x	x	x	x
transparency	x		x	x
height		x	x	

Discussion

A type of visualization of 3D spatial data in the form of multiple planes can be generally called "multi-layer visualization", i.e. the display of 3D data in the form of horizontal sections at a certain height spacing and a certain arrangement of layers. Planes can display data either in continuous form or in the form of classification into intervals. In continuous visualization, individual raster cells are assigned colors from the selected color spectrum based on their values. However, it is very challenging to read the exact cell values using visual analysis, but it can represent the trend in the data more accurately than in the case of classification. There is also a greater effect of transparency on the distortion of the visualization due to the blending of layers. Visualization in the form of classification into intervals generalizes the displayed information, and it is not possible to read the exact values, but only the values of the interval. However, blending layers does not have the same effect here as it does in continuous visualization. Exploring data in the form of horizontal planes can be improved by using vertical or horizontal scroll bars. The vertical scroll bar (swipe) allows the data to be displayed only at a certain height, which the user can change dynamically. For example, the user can set that they want to display only planes between 500 and 800 hPa. A horizontal scroll bar (swipe) allows the user to gradually overlap layers. For better visibility of the lower layers, it is not necessary to turn off the upper layers directly, but their spatial extent can be changed using the slider.

Commercial software usually performed better than open-source. For example, QGIS has very limited 3D geovisualization capabilities compared to ArcGIS Pro, but it would be possible to program this functionality using Python. 3D computer graphics software generally does not natively support spatial data, however, it is possible to provide interoperability through plugins. Although Blender is an excellent tool for 3D modeling, for example for 3D printing, it is unsuitable for 3D geovisualization and the creation of 3D visualization environments. Software were evaluated only in terms of 3D geovisualization capabilities, e.g. whether it supports spatial data, what are the options for creating applications, whether 3D analytical tools are available. However, technical factors such as rendering speed, limitations on the maximum data size or the maximum size of the rendered region, distortion of the rendered 3D datasets, or rendering resolution were not considered.

Effective visualization of complex 3D spatiotemporal data, such as meteorological data, necessitates the utilization of various methods, including 3D points, isolines, isosurfaces, vertical planes or 3D graduated symbols. These methods offer a more comprehensive depiction of 3D phenomena across various heights compared to relying solely on horizontal planes. Horizontal planes are useful for comparing multiple layers at different height levels within a single visualization. All other visualization methods could be evaluated in a similar manner. By exploring these questions in greater detail, we can provide a more comprehensive understanding of the strengths and limitations of different visualization techniques in capturing the complexities of 3D spatiotemporal data.

Visualization of 3D data in the form of horizontal planes is partly like the Space-Time-Cube method, which displays the map at the base of the cube (axes X and Y) while the Z axis is used to represent time. The spatial and temporal components of a map are shown together, and the relationship between space and time can be revealed. By Space-Time-Cube, any spatio-temporal data can be displayed. Those can be, for example, data recorded by GPS devices, statistical data with location and time component or data acquired with eye-tracking technology. Space-Time-Cube visualization can be applied in a variety of different areas (Popelka and Voženílek 2013). For horizontal planes, however, animations are used to visualize changes over time.

In the case of thematic data, their quality plays a big role, and the uncertainty of the data must be properly represented during visualization. According to Brus et al. (2013) the main and fundamental task in the visualization of uncertainty is to use appropriate visual variables. The reason for using visual variables in visualizing uncertainty consists particularly in natural and strongly developed visual-cognitive abilities of humans. Based on visual symbols, humans are able to understand even very complex problems which can be hardly conveyed only by numbers or text. Visualization of uncertainty in GIS products is essential to communicate uncertainties to decision-makers. This prevents decision makers from being blinded by the quality of the display and makes them aware of the underlying uncertainty of the information (Brus et al. 2013).

For further research, it is advisable to organize user testing that focuses not only on horizontal planes but also on other 3D geovisualization methods (e.g. 3D points, isolines, isosurfaces, 3D graduated symbols). These methods would be compared and validated in terms of suitability for visual analysis, with the expectation that different visualization methods would be suitable for different purposes and data types. For example, respondents would be asked to find the place with the highest temperature near a plain located at an altitude of 50 kilometers. When displaying multiple planes, it is possible to use a description for each plane, which would ensure better orientation in the data. In the case of meteorological data, e.g. a meteorological variable, height, units, or range of values could be indicated for each plane.

Conclusions

The paper provides an overview of 3D geovisualization capabilities of selected software and also presents four selected methods for visualizing raster data using horizontal planes. Both software and methods were evaluated with an emphasis on visual analysis in 3D. The advantages, and disadvantages of seven selected software in terms of 3D geovisualization and suitability for visual analysis are mentioned. The possibilities of 3D geovisualization were tested in the environment of seven software, which were divided into three categories: geographic information systems, web-based solutions, and software for computer 3D graphics. Based on the evaluation of various parameters, the geographic information system ArcGIS Pro seems to be the most suitable for visual analysis in 3D. Its advantages include very good support of spatial data and 3D visualization capabilities, a wide user base and well-prepared documentation. ArcGIS Pro can be connected to Unity or Unreal Engine game engines, thanks to the ArcGIS Maps SDK for Unity and ArcGIS Maps SDK for Unreal Engine. This makes it possible to create very advanced applications for visual analysis of 3D data, but knowledge of the C# or C++ programming languages is required to use the full potential.

Four methods of visualizing 3D data using horizontal planes have been presented: Single Plane, Multiple Planes without Transparency, Multiple Planes with Transparency, and Multiple Planes Overlay. The simplest visualization method is a single plane. This alone does not add anything new and is especially suitable for basic data exploration. It is possible to work with transparency, use animations or add another topic to increase the effectiveness of visualization. Of the graphical variables, color and transparency play a major role. The quality of the visualization also depends on the resolution. When visualizing multiple planes without transparency, the disadvantage is the overlap and thus the inability to effectively view the covered layers. Therefore, it is recommended to use a vertical slider to allow filtering layers by height, or filtering by other parameters. The most important graphical variables are color, height, and layout. Setting the optimal height spacing (Z value) and the arrangement of layers always depends on the nature of the displayed data. The advantage is that thanks to the possibility of distributing layers on the Z axis, it is possible to display more data within one visualization (e.g. different meteorological variables, data at different altitude levels). For multiple planes with transparency, similar statements about graphical variables apply as for the visualization of multiple planes without transparency. In addition, it is necessary to consider the variable transparency, which can partially solve the overlapping of layers, but can cause distortion in the visualization of the overlapped layers. It is necessary to choose both the transparency value and its mode (e.g. multiplication) correctly. The use of supervised or unsupervised animation can also be used. Visual analysis is also affected by whether the visualization is continuous or whether the data is classified into intervals. To overlay two planes at the same level, color and transparency are the most important. With the right color and transparency settings, this method can make it easier to compare two layers by combining them. When using a horizontal scroll bar (swipe), better manipulation and orientation in the visualization can be ensured.

The choice of the optimal visualization method always depends on the nature of the displayed data. If data at different elevation levels are available, it is advisable to visualize them in the form of multiple planes, where transparency can also be used. To visualize the change over time, it is advisable to display the data using a single plane in the form of an animation. To determine the mutual relationship between two meteorological variables, an overlap of two planes at the same level is offered, which allows new information to be discovered. The methods were evaluated only as static outputs, but an interactive visualization environment is needed to fully exploit the potential of these methods. This should be user-oriented and allow, for example, layer filtering, data exploration, animation creation or modification of graphical variables such as color, transparency, height, or layout.

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