VOL 3, NO.2 (2023) 109-128
https://jagst.utm.my

JAGST
Journal of Advanced Geospatial Science & Technology

A Review of Data Sources and Techniques used for Landslide Visualization

Tharshini Murthy, Izham Mohamad Yusoff*, Nik Norliati Fitri Md Nor, Siti Masayu Rosliah Abdul Rashid,
Seyed Milad Bagheri Ghadikolaei, Siti Hamsah Samsudin
Geography Division, School of Distance Education, Universiti Sains Malaysia,
11800 USM Penang, Malaysia
*Corresponding author: izham@usm.my

Abstract – Landslides are slope failure disasters threatening human life and destroying infrastructures. Landslides happen suddenly and cause huge losses. Landslide visualization can provide information and an overview of slope movement and landslides. This study reviews the visualization of landslides by analyzing literature published on this topic from 2018 until February 2023. This study used publications from the 'Web of Science' (WOS) and 'Scopus' in the last five years to get the latest information on this topic. This study has examined trends in the number of publications and sources of publication, study areas, visualization techniques and datasets used, and visualizations produced in either 2D or 3D. The number of publications shows an increasing trend, and the journal that publishes the most articles is 'Remote Sensing'. Areas from China are often chosen as study areas in this topic, followed by Slovenia. There were 19 visualization techniques identified through the article, and Electrical Resistivity Tomography (ERT) was used frequently in 3 publications. Digital Elevation Model (DEM) data is used in most articles (8 articles) compared to the other 10 data, which are Digital Terrain Model (DTM), Knowledge Template, Electromagnetic VLF-R Data, Cloud Data of Discrete Points, Ground-Penetrating Radar (GPR) Data, Electric Resistivity Tomography (ERT) Data, Airborne Lidar, Target Ground Sampling Distance (GSD), Area of Interest, and in situ Data. Landslide visualization in 3D form is produced in most articles compared to 2D. The analysis shows a preference for 3D visualization over 2D, although both techniques are employed due to their unique advantages. The review exercise reveals a rising publication trend, highlighting the prominence of 3D visualization techniques and the popularity of DEM data in landslide visualization studies, while also suggesting the need for more recent and comprehensive research in this field.

Keywords *– Visualization, Landslides, Slope Failure, Techniques, 3D Visualization, 2D Visualization*

Article History: Received 12 July 2023, Accepted 14 August 2023, Published 30 August 2023

How to cite: Murthy, T., Yusoff, I. M., Md Nor, N. N. F., Abdul Rashid, S. M. R., Ghadikolaei, S. M. B. and Samsudin, S. H. (2023). A Study on Techniques and Data Sources Used for Landslide Visualization – A Review. Journal of Advanced Geospatial Science and Technology. 3(2), 109-128.

1.0 Introduction

Landslide refers to the movement of rocks, soil or debris (fine material) down the slope due to gravity and natural factors (melting snow, heavy and prolonged rains and earthquakes) or due to anthropogenic factors (forest logging, earthworks and mining) [1, 2]. Additionally, [3] agrees with [1] and [2] in defining landslides as one of the natural disasters that occur when rocks or soil move downhill. According to him, landslides also happen due to heavy rain threatening people's lives in the surrounding area and causing infrastructure destruction [3]. In his study, [4] also stated that landslides result from gravitational solid force acting on rocks and soil.

Landslide disasters often occur suddenly on a large scale leading to loss of life and significant economic impact on countries. Additionally, landslides cause losses of billions of dollars by destroying infrastructure and endangering thousands of lives worldwide each year. According to [5], landslides cause severe damage globally annually. Between 2004 and 2016, more than 55 000 people lost their lives due to landslides. The estimated yearly infrastructure damage caused by landslides amounts to as much as 20 billion U.S. Dollars [5]. Therefore, landslides are categorized as highly dangerous disasters. Figure 1 displays the 'Global Landslide Catalog' map for 2019, released by NASA.

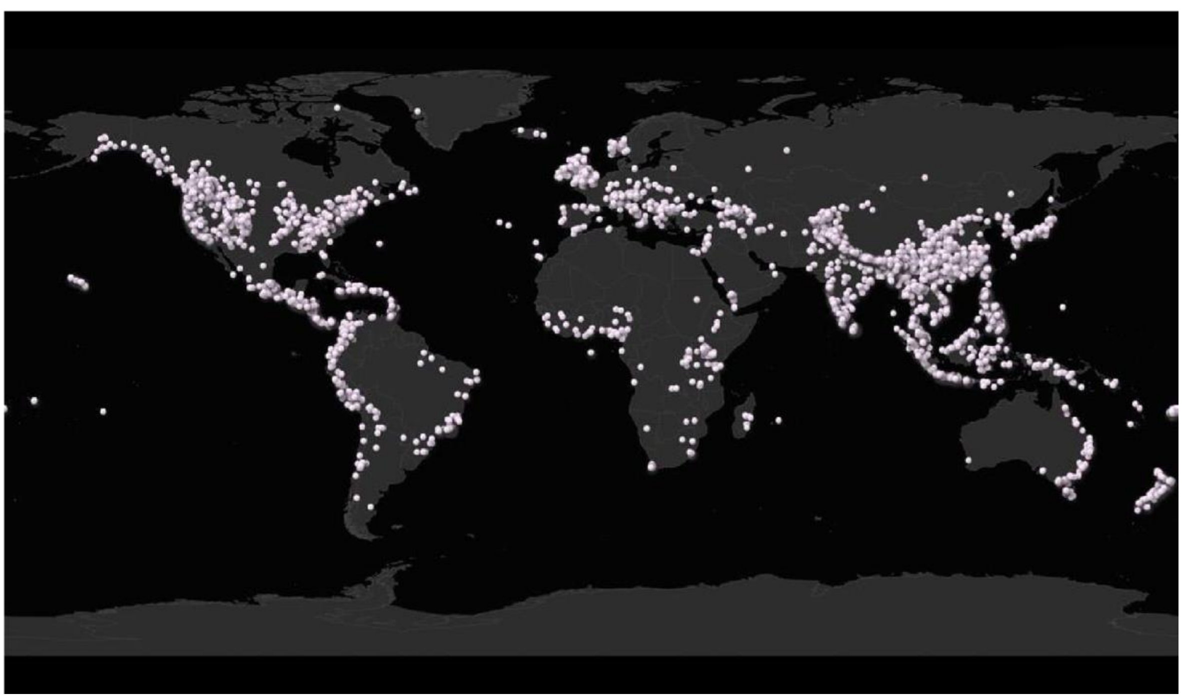

Figure 1. Global Landslide Catalog (GLC) 2019 (NASA). Source: [6]

Almost all the landslide disasters have specific causes. Slope movement occurs when the force acting down the slope, primarily due to gravity, surpasses the length of the earth's material forming the hill. The mentioned causes encompass factors that amplify the downward force of the slope. Landslides can result from various factors, such as rainfall, snowmelt, water level changes, river erosion, groundwater changes, earthquakes, volcanic activity, disturbance by human activity, or any combination of these factors [7]. Additionally, earthquakes and other elements can trigger underwater landslides, known as submarine landslides. Notably, these undersea landslides may sometimes lead to the generation of tsunamis.

There are various studies conducted in this field. For example, [8] and [9] studied landslide susceptibility maps. [10] conducted a study on the early warning system for landslides. Then, [11] conducted a study on landslide prediction using an intelligent approach. Many more studies have been conducted related to landslides. This study will focus on landslide visualization.

Landslide visualization refers to studies that present the research results in a graphical and visual format. In today's era, presenting data or research findings visually is much easier to understand than presenting them solely as numbers or words. Visualization methods are widely used across various fields because they help convey information in a format easily shareable with global audiences [12]. In landslide research, visualization techniques are commonly employed to represent landslide data closely related to geographic information. The results of landslide visualization techniques are often presented in the form of maps or images that accurately depict the topography of the study area [12].

So, the purpose of this study is to review landslide visualization by studying the articles published on this topic. Nowadays, it is crucial to check landslide visualization because it helps researchers, authorities, policymakers, and the public understand the complex processes involved in landslides. Landslide visualization can provide clear visual representations, and the dynamics and triggers of landslides become more accessible and understandable. Moreover, landslide visualization reviews can help policymakers and urban planners understand landslide data, which is crucial when deciding on land use planning and infrastructure development. Then, landslide visualization reviews can also serve as a foundation for future research and innovation. By collating and summarizing existing knowledge, researchers can identify gaps in the current understanding and propose new avenues for investigation.

Therefore, this study will focus on publications trends and sources, study area, trends of visualization techniques/methods, data used for visualization and trends of two-dimensional and three-dimensional visualization produced in articles.

2.0 Methodology

Landslide visualization is a method that represents this disaster through visual graphics, enabling the identification of relevant articles in this field. Three keywords, namely landslide, slope failure, and visualization are used in the selection process, specifically applied to titles, abstracts, and keywords when searching for articles. It is worth noting that landslide and slope failure are two keywords that share the same meaning, and some articles may use either term exclusively. As a result, using these keywords makes it easier to identify accurate and relevant articles related to the topic.

This study utilizes publications from Web of Science (WOS) and Scopus within the five years from 2018 to the beginning of 2023, specifically until February 2023. The selected timeframe examines this field's most current visualization methods and data. Only articles from WOS and Scopus are considered in this study due to their high-quality publications and specific, reliable databases compared to others [13]. Additionally, this study aims to distinguish between landslide visualizations presented in two dimensions (2D) and three dimensions (3D). The selection process resulted in 16 articles and one conference proceeding, with 12 publications chosen from WOS and five from Scopus. Through filtering keywords and publication purposes, 11 articles and one conference proceeding were selected from 33 publications available on the WOS site. A similar approach was taken for the selection of Scopus publications. Notably, all the chosen publications are published in English. Despite the few articles related to landslide visualization for the five years (2018 to early 2023), each selected publication provides valuable insights into landslide disasters and visualization, benefiting researchers and authorities. Figure 2 displays a flow chart illustrating the article selection process.

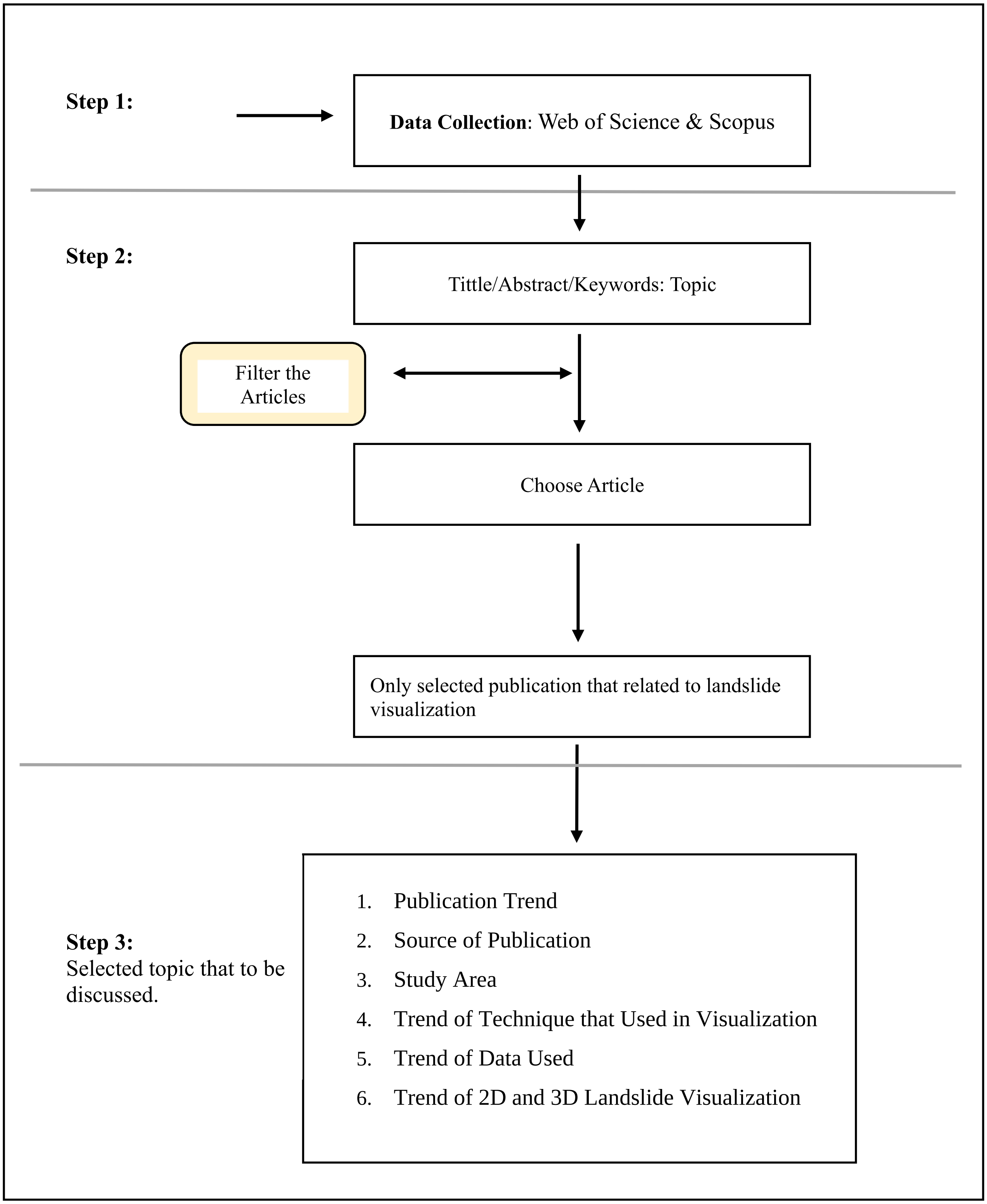

Figure 2. Flow chart of selection of article

3.0 Results and Discussions

3.1 Publication Trends Related to Study Topics

After searching the WOS and Scopus sites, only 17 publications relevant to the topic were selected. Despite the relatively small number of articles studied, they offer valuable and up-to-date information, frequently discussed in the current landscape of the study's topic. Therefore, these 17 publications were carefully considered in conducting this review. Figure 3 illustrates the number of publications from WOS and Scopus between 2018 and the beginning of 2023. The highest number of publications, five articles, was recorded at the beginning of 2023 (until February 2023), while the lowest numbers occurred in 2018 and 2020, with only one article each related to landslide visualization. The publishing trend indicates an improvement over the years, with an increase in the number of publications on this subject.

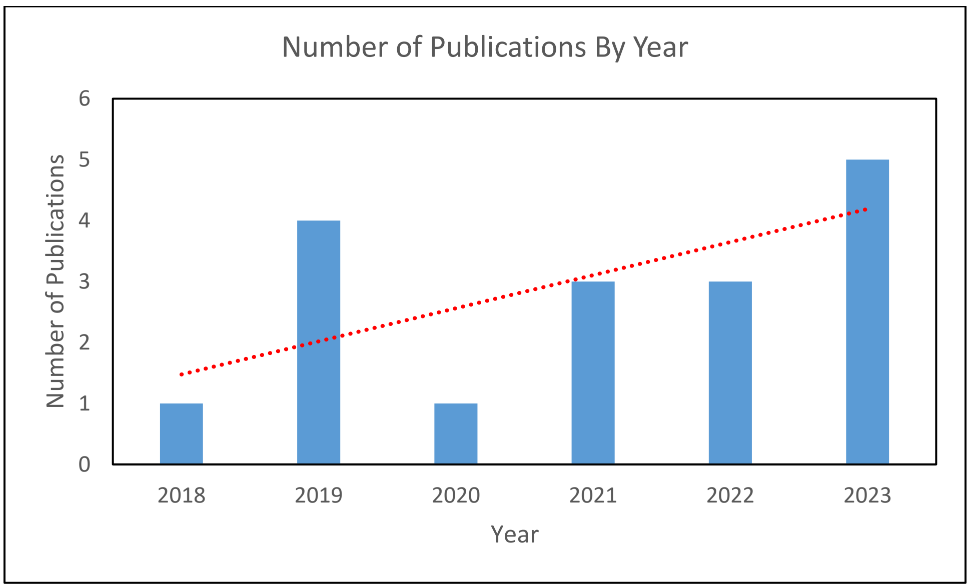

Figure 3. Number of publications by year

The number of publications in 2018 was only one article, which increased to one conference proceeding and three in 2019. However, it decreased to only one article publication in 2020. Nevertheless, the number of publications started to increase again in 2021, with three articles and remained consistent in 2022, with three papers. Based on the current trend, the number of publications in 2023 will continue to increase. Until February 2023, there were five articles, surpassing the number of publications in 2020.

In 2018, an article related to the topic of this study was done by Hu et al. (2018). For 2019, [14, 15, 16, 17] conducted a study on the visualization of landslides. In 2020, only one article was published by [2]. The work of [3, 18, 19] was published in 2021. The exact number of articles was recorded in 2022, which is the result of [20, 21, 22]. The number of publications that related to the topic of the study in 2023 was recorded as many as five publications which are the result of writing [23, 24, 25, 26, 27]. All the publications used in the study did not discuss landslide visualization as a significant topic, but more than half of the articles examined this topic as a major issue.

3.2 Source of Publications

All 17 publications were written in English, indicating that researchers are more inclined to produce their studies in English to gain broader attention from students and researchers worldwide. English is an international language, facilitating a better understanding of the research results among a global audience.

According to Figure 4, 14 journals have recorded publications related to landslide visualization from 2018 until February 2023. These journals include ‘Applied Sciences,’ ‘Drones,’ ‘Elsevier,’ ‘IEEE Computing in Science and Engineering,’ ‘Instrumentation Mesure Metrologie,’ ‘International Journal of Disaster Risk Reduction,’ ‘International Journal of Geo-Information,’ ‘International Journal of Geomate,’ ‘Journal for Taibah University for Science,’ ‘Landslides,’ ‘Remote Sensing,’ ‘Sensors,’ ‘Sixth Geoinformation Science Symposium,’ and ‘Taylor & Francis’.

The journal with the highest publication rate is ‘Remote Sensing,’ accounting for 17.6%, equivalent to 3 publications. The ‘International Journal of Geoinformation’ follows closely with the second-highest publication rate of 11.8%, consisting of 2 articles. All other journals published only one article related to landslide visualization, which accounts for 5.9% each.

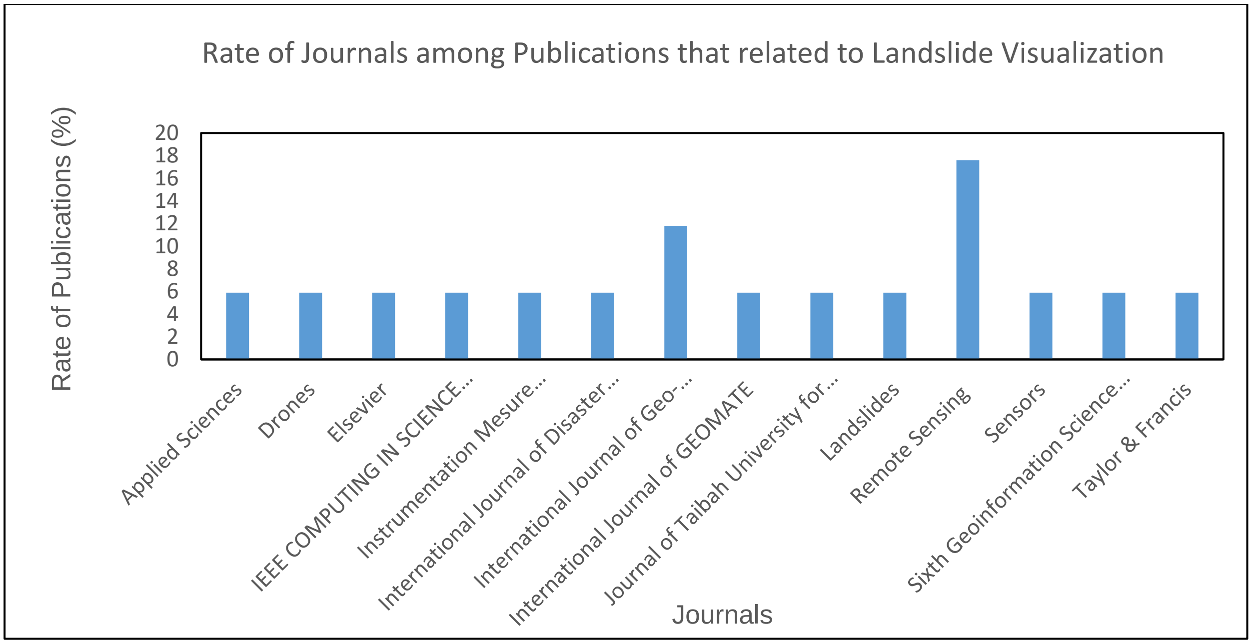

Figure 4. Rate of the journal among publications that related to landslide visualizations

3.3 Study Area of Publications

Landslides occur all over the world, regardless of location and time. These disasters cause billions of dollars in losses as they destroy infrastructure and threaten the lives of thousands of people annually. Consequently, researchers studying landslides select study areas from various countries. In this study, the 17 publications used for research come from study areas in 13 different countries, including California, Central Java (Indonesia), China, France, Indonesia, Northern Italy, Norway, Saudi Arabia, Scotland, Slovenia, Spain, Thailand, and Tibet.

According to Table 1, China is the most frequently selected study area, appearing in 4 publications, which are the results of studies conducted by [17, 23, 26, 28]. This trend can be attributed to China's dense population and frequent landslides. As stated by [29], China has a vast mountainous area, covering 69% of its land, with half of its cities located in mountainous regions. Consequently, nearly 50% of the country's population resides in these areas. Since the 1980s, landslide disasters in China have risen due to construction activities and climate change [29]. These findings align with [30], which also emphasizes China's high rate of mountainous regions, leading to frequent occurrences of landslides, almost becoming a norm. Despite this, the impact of such disasters still results in significant losses in terms of both human lives and economic resources [30]. Hence, it is understandable why China is prominently chosen as a study area in most publications.

Table 1. Frequency of study areas used in publications

Study Area	***Number of Publications***
California	1
Central Java, Indonesia	1
China	4
France	1
Indonesia	1
Northern Italy	1
Norway	1
Saudi Arabia	1
Scotland	1
Slovenia	2
Spain	1
Thailand	1
Tibet	1

Slovenia was selected as a study area in 2 publications by [16] and [19]. As [31] highlights, Slovenia faces various disasters, including earthquakes, landslides, and groundwater pollution. Among these, landslides are a prominent concern due to the tectonic and morphological conditions of the hillside, leading to infrastructure damage and fatalities in the Slovenian territory. Given the frequent occurrences of landslides and their significant impact, Slovenia became the second choice as a study area for researching landslide disasters. Other countries such as California, Central Java (Indonesia), France, Indonesia, Northern Italy, Norway, Saudi Arabia, Scotland, Spain, Thailand and Tibet were only selected in one publication between 2018 and February 2023.

3.4 Trends in Landslide Visualization Techniques/Methods

Various techniques have been developed and employed in landslide studies worldwide. However, the lack of historical landslide records in certain areas and limited information about triggering factors pose challenges for researchers and authorities in predicting landslide occurrences. Nevertheless, mapping landslide areas can provide valuable information about their occurrence. Visualization methods also play a crucial role in depicting landslide areas with graphic effects, presenting a more realistic view to authorities and researchers, facilitating further actions, and easing the research process.

Figure 5 shows 19 techniques used to produce visualizations of landslides identified from the publications used in this study. Among them are ‘Virtual Reality,’ ‘Light detection and ranging (LiDAR),’ ‘Particle image velocimetry (PIV) algorithms,’ ‘Visualization for Archaeological Topography (VAT),’ ‘Unmanned aerial vehicles (UAVs),’ ‘Time-lapsed Imagery (TLI),’ ‘Remote Sensing,’ ‘Red Relief Image Map,’ ‘Logistic Regression,’ ‘LOD representation,’ ‘Knowledge Guided Dynamic,’ ‘In situ visualization,’ ‘Head Mounted Display,’ ‘Information Value Model,’ ‘Electrical Resistivity Tomography (ERT),’ ‘Closest Point (ICP) algorithm,’ ‘Airborne Laser Scanning (ALS),’ ‘3D Ground-Penetrating Radar (3D GPR),’ and ‘Triangular Irregular Network (TIN) - Surface Modeling’.

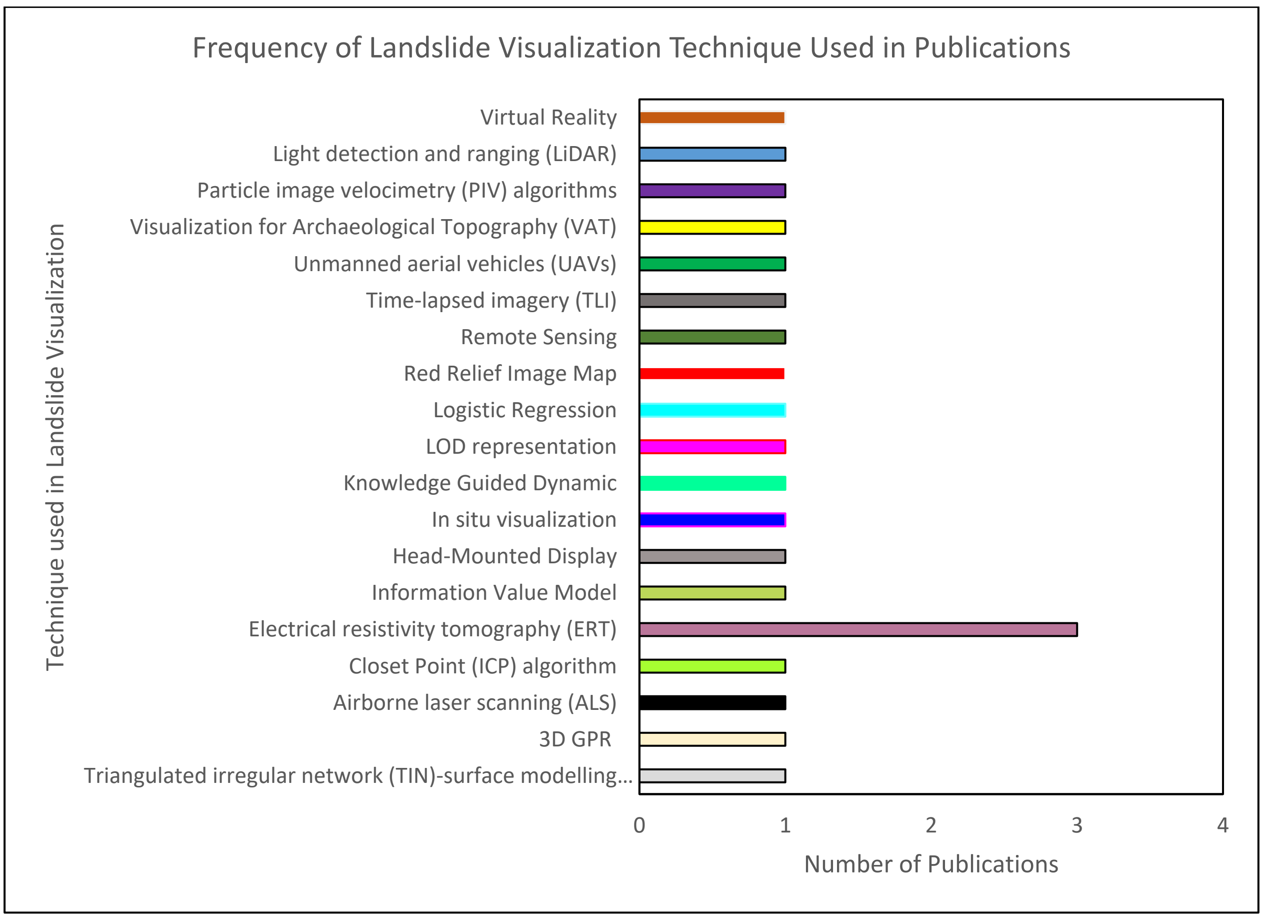

Figure 5. Landslide visualization technique used in publications from the year 2018 until early 2023

According to Figure 5, it was found that ‘Electrical Resistivity Tomography (ERT)’ was used in three articles to produce a visualization of landslides. ERT is a geophysical method widely used near landslide areas with a complex geological environment. The ERT technique can produce land images in two dimensions (2D) and also three dimensions (3D) [32]. This method is used by [14, 21, 25]. [21] used the ERT method together with 3D GPR to produce landslide visualization. He uses a combination of these techniques to create visualizations in 3D form. [14] also used the ERT technique to make visualization in 3D format. [25] have produced a visualization model in 2D form using the ERT technique.

According to [33], studies utilizing ERT techniques often present results in either 2D or 3D format. However, in recent times, 3D ERT techniques have gained popularity among researchers. The use of 3D ERT helps mitigate errors and artefacts that can arise from limitations in the 2D model. Additionally, 3D ERT provides smoother and more accurate results than its 2D counterpart [33]. In this study, two of the three publications utilizing ERT produced visualization models in 3D form, while only one employed the 2D approach. Moreover, it is worth noting that other visualization techniques, apart from ERT, were used in only one publication from 2018 until February 2023.

3.5 Data Used In Landslide Visualization

Based on Figure 6, 11 data types are commonly used in producing landslide visualization. These include ‘Digital Elevation Model (DEM),’ ‘Digital Terrain Model (DTM),’ ‘Knowledge Template,’ ‘Electromagnetic VLF-R Data,’ ‘Cloud Data of Discrete Points,’ ‘Ground-Penetrating Radar (GPR) Data,’ ‘Electric Resistivity Tomography (ERT) Data,’ ‘Airborne Lidar,’ ‘Target Ground Sampling Distance (GSD),’ ‘Area of Interest,’ and ‘In Situ Data.’ Notably, one article, the work of [18], does not specify the data used due to the applied technique, ‘time-lapsed imagery (TLI).’ TLI is a visualization technique that enables real-time analysis, allowing researchers to monitor slope movements continuously. This technique provides detailed information about the slope activity, facilitating researchers’ understanding of the process.

In addition, according to Figure 6, it is evident that ‘Digital Elevation Model (DEM)’ data is the most commonly used in landslide visualizations, appearing in 8 publications. Among the publications that utilize DEM data is the study conducted by [3, 15, 16, 19, 22, 23, 27, 28].

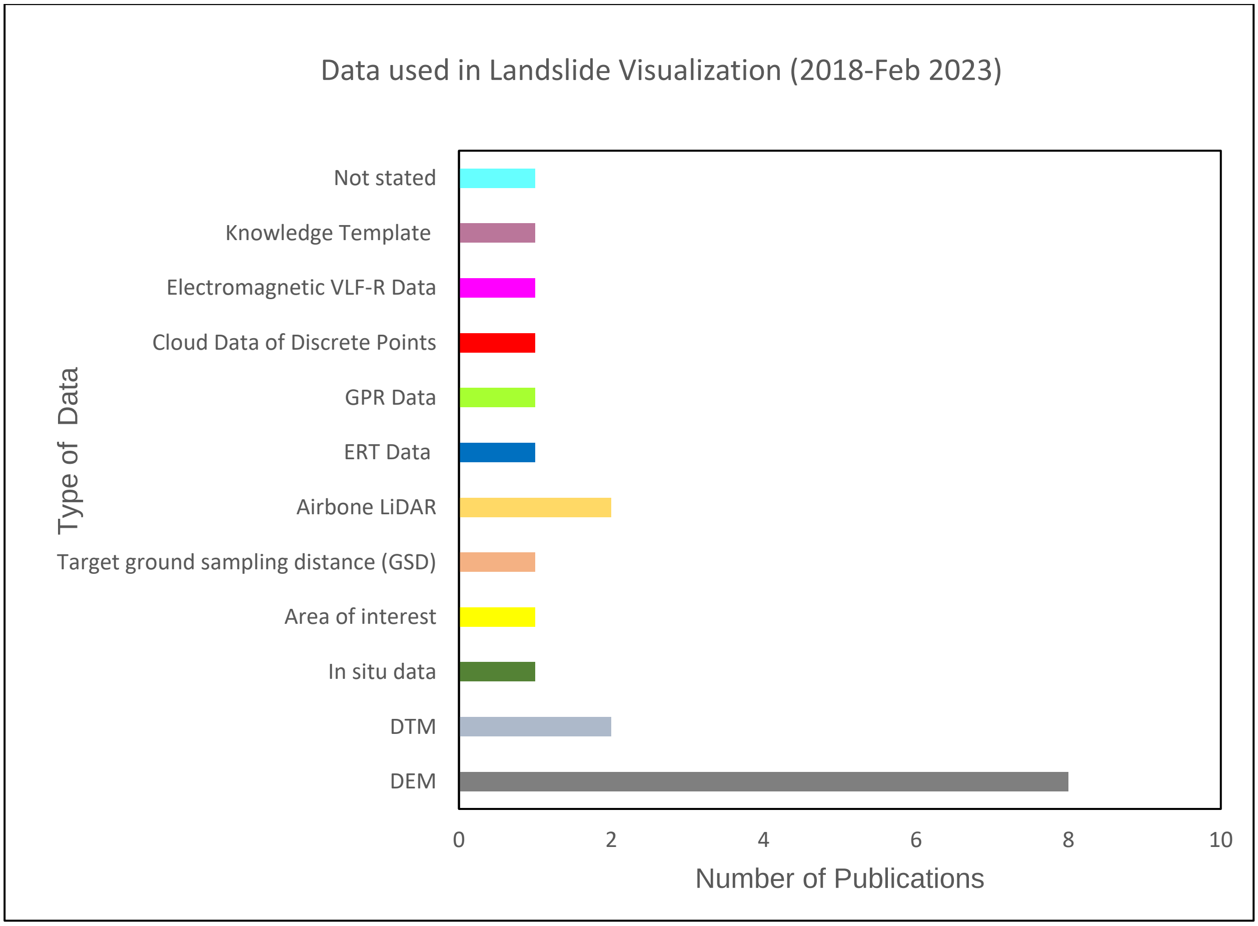

Figure 6. Type of data used in landslide visualization study from the year 2018 until early 2023

DEM can provide information on soil patterns, slope movements, landslide history, and topographic variability [34]. Furthermore, DEM serves as the basis for determining factors that cause landslides. These factors include the slope angle, the orientation of the slope, and the elevation [35]. Moreover, [36] emphasized that DEM is crucial data for creating landslide models as it provides valuable information about soil and slope attributes. He also categorized DEM based on its resolution. For instance, 'Aster GDEM' and 'SRTM DEM' have a moderate spatial resolution of 30m to 90m, allowing them to offer only a semi-global picture of the earth's surface [36]. Another notable DEM type is the 'TanDEM-X DEM,' commonly used in scientific studies, and the 'WorldDEM,' designed for commercial use. Both DEMs are the latest and offer the most up-to-date depiction of the earth's surface with a resolution of 12 m.

The 'Alos Palsar DEM' also provides elevation data with a resolution of 10 m. This DEM is obtained from image recordings using the Palsar satellite microwave channel. The article by [15] used in this study also utilizes ‘DEM Alos Palsar’ data as height data due to its consistent resolution, which aligns with the data forming the results of their ‘Information Value Model’ model. This choice is essential as DEM resolution is crucial in producing highly accurate landslide models [35]. Moreover, using DEM data allows for analyzing the terrain before and after a landslide event, aiding in the swift assessment of land deposits’ volume and identifying factors contributing to the disaster [22]. As a result, many researchers prefer using DEM data over other sources due to its versatility and effectiveness.

In addition, DTM data and ‘Airborne LiDAR’ data were each used in 2 publications. Similar to DEM, DTM is also elevation data but focuses more on the ground surface without including objects or buildings [37]. Additionally, ‘Airborne LiDAR’ allows researchers to obtain 3D data for the area affected by the landslide, capturing the surrounding area’s topography, buildings, and trees [38]. Therefore, these two data are used in two publications. The other data was only used in one publication from 2018 to February 2023.

3.6 Trend 2D and 3D Landslide Visualization

2D represents a flat dimension with only length and width, making it a two-dimensional plane represented by the x and y axes. In contrast, 3D involves three dimensions, x, y, and z representing length, width, and height. As a result, 2D visualization is limited to representing objects on a flat surface, which may not be suitable for studying real-world space. On the other hand, 3D visualization offers a more comprehensive representation of objects and their structure in a disaster or any given context. It enriches the visualization with navigation features, allowing researchers to explore and study the subject matter more fully and realistically [39].

Based on Figure 7, the production of 3D visualization is higher than 2D lately. Researchers who produced landslide visualization in 3D are [2, 14, 15, 17, 20, 21, 22, 23, 24, 26, 27, 28]. Meanwhile, researchers who produced a visualization of landslides in 2D form are [3, 14, 16, 18, 19, 25]. The percentage of 3D visualizations produced between 2018 and early 2023 is 66.7%, while 2D visualizations account for only 33.3%. This stark difference is attributed to the fact that 3D visualization offers a more precise and comprehensive picture of land or slope movement mechanisms compared to 2D visualizations [40]. Then, 3D also helps integrate geophysical and geological data for visualization in 3 dimensions [41]. Moreover, as stated in [42], 3D visualization reveals characteristics and information about landslides that cannot be obtained through 2D visualization. Figure 8 shows an increasing trend in 3D visualization, with one publication in 2020 and four at the beginning of 2023.

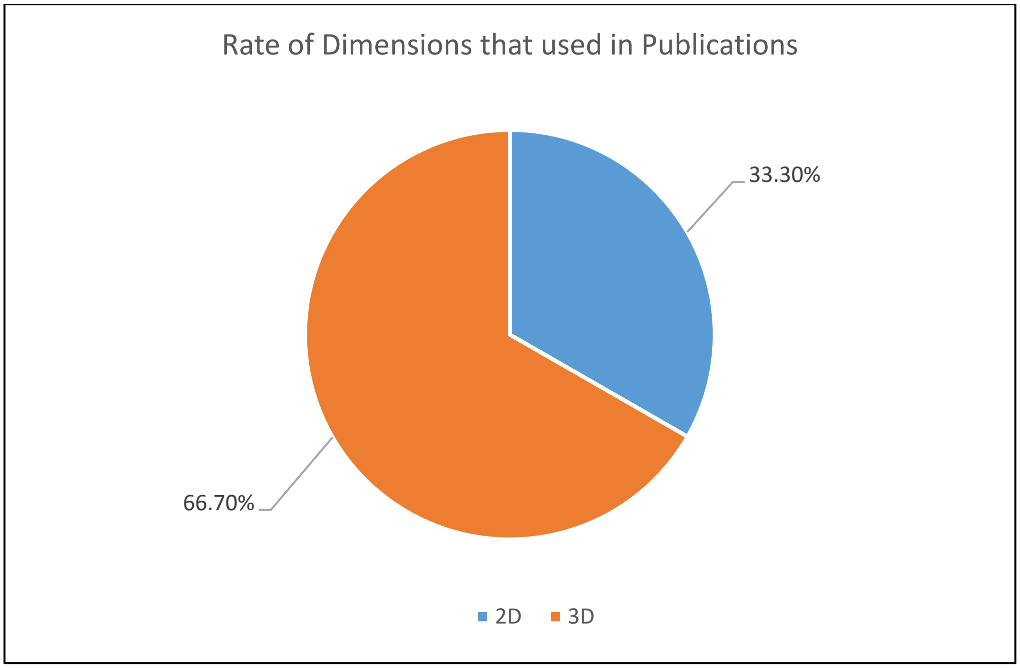

Figure 7. Rate of dimensions (2D and 3D) used in publications

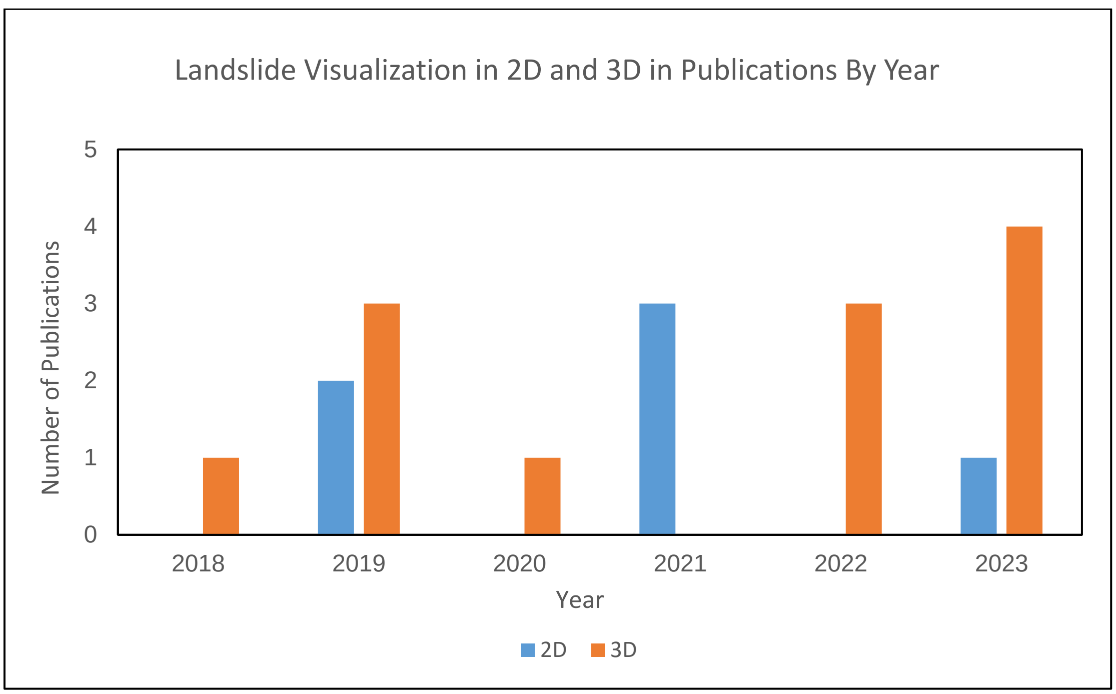

Figure 8. 2D and 3D landslide visualization produced in publications from 2018 until early 2023

Although 3D visualization has shown an unstable trend, it was produced in higher numbers than 2D in 2021, with three publications. Additionally, at the beginning of 2023, it was discussed in one publication. This indicates that researchers still produce 2D visualizations of landslides alongside 3D. The choice between 2D or 3D dimensions depends on the specific analysis and geometry of the slope [42]. According to [42], visualizations related to slope stability in 3D are more complex and require extensive data analysis compared to visualization in 2D.

Furthermore, some researchers produce visualizations in both dimensions in 2D and also in 3D [14]. The researcher used the ERT technique in this study to create visualizations in both dimensions. This is because there is a growing need to combine 3D and 2D visualization methods. Using both dimensions offers various advantages to researchers in gathering information about landslides. As mentioned earlier, 3D visualization provides a broader and more detailed picture of landslide disasters, while 2D visualization allows for representing time series data [39].

4.0 Conclusion

Landslides are natural disasters that significantly threaten human lives and infrastructure and cause extensive losses. This analysis focuses on publications published between 2018 and February 2023 to gather the latest information on landslide visualization. The study covers various aspects, including publication trends, sources, study areas, visualization techniques used, data utilized, and the trends in 2D and 3D visualization. Only articles from WOS and Scopus databases are considered in this review study, comprising 17 articles on landslide visualization.

According to the study's findings, the publication trend on landslide visualization shows a consistent increase. All 17 publications were sourced from the 14 journals listed in Figure 4, with the journal 'Remote Sensing' having the highest number of publications. The study areas were chosen from 13 different countries, with China being the most frequently selected as a study area in the publications, followed by Slovenia.

Additionally, 19 visualization techniques or methods were identified as being used in the publications to produce landslide visualizations. The ERT technique stands out, being used in 3 publications more than any other method. Furthermore, 11 data types were identified in the publications for producing landslide visualizations, with DEM data being the most popular among researchers, utilized in 8 publications. Combining these techniques and data allows for creating both 2D and 3D visualizations. The analysis shows that 3D visualization is predominant in most publications compared to 2D. This trend indicates that researchers nowadays are more inclined to produce three-dimensional landslide visualizations. However, 2D visualization is still employed by researchers due to its unique advantages.

This review lacks recent studies on landslide visualization (2018-Feb 2023), where only 17 publications can be identified. However, all 17 of these publications provide valuable information. Therefore, the proposal to publish more future articles related to landslide visualization can provide helpful and detailed information about this dangerous disaster.

Acknowledgement

The authors would like to thank Ministry of Higher Education for supporting this study via Long Term Research Grant Scheme (LRGS) No. 203.PJJAUH.6776003.

References

[1] D. M. Cruden, ‘A simple definition of a landslide’, Bull. Int. Assoc. Eng. Geol. - Bull. l’Association Int. Géologie l’Ingénieur, vol. 43, no. 1, pp. 27–29, 1991, doi: 10.1007/BF02590167.

[2] Y. Thiery et al., ‘Improvement of landslide hazard assessments for regulatory zoning in France: STATE–OF–THE-ART perspectives and considerations’, Int. J. Disaster Risk Reduct., vol. 47, no. March, 2020, doi: 10.1016/j.ijdrr.2020.101562.

[3] T. Naruephorn, W. L. Woo, P. Parathai, C. Aryupong, P. Jitsangiam, and D. Rinchumphu, ‘Automated Landslide-Risk Prediction Using Web GIS and Machine Learning Models’, Sensors (Basel, Switzerland), vol. 21, no. 13. sensors, pp. 2–32, 2021, doi: 10.3390/s21134620.

[4] A.A. Ab Rahman, N. Abd Majid, and S.N. Selamat, ‘A comprehensive deriving the factors of landslide happened in Malaysia’, Int. J. Emerg. Technol., vol. 11, no. 5, pp. 310–314, 2020.

[5] K. Ben Sim, M. L. Lee, and S. Y. Wong, ‘A review of landslide acceptable risk and tolerable risk’, Geoenvironmental Disasters, vol. 9, no. 1. 2022, doi: 10.1186/s40677-022-00205-6.

[6] Helen and Nicole Kostis, ‘SVS: Global Landslide Catalog (update 2019)’, NASA : Scientific Visualization Studio, Mar. 13, 2019. https://svs.gsfc.nasa.gov/4710 (accessed Aug. 23, 2022).

[7] USGS, ‘What is a landslide and what causes one? | U.S. Geological Survey’, USGS Science for a Changing World, 2019. https://www.usgs.gov/faqs/what-landslide-and-what-causes-one (accessed Jun. 29, 2022).

[8] Y. S. Bong, M. H. Zulkifly, I. Sati, and H. Harahap, ‘GIS Analysis & Landslide Susceptibility Mapping (LSM) in Murum Reservoir Region, Sarawak.’, vol. 7, pp. 456–459, 2018.

[9] W. S. Udin, N. N. Yahaya, and S. I. M. Shariffuddin, ‘Landslide Susceptibility Assessment Using Geographic Information System in Aring, Gua Musang, Kelantan’, in IOP Conference Series: Earth and Environmental Science, 2021, vol. 842, no. 012008, pp. 0–5.

[10] F. Guzzetti et al., ‘Geographical landslide early warning systems’, Earth-Science Rev., vol. 200, Jan. 2020, doi: 10.1016/J.EARSCIREV.2019.102973.

[11] Y. Zhang et al., ‘Prediction of landslide displacement with dynamic features using intelligent approaches’, Int. J. Min. Sci. Technol., vol. 32, no. 3, pp. 539–549, May 2022, doi: 10.1016/J.IJMST.2022.02.004.

[12] S. Yussof, N. B. Husin, Z. Ibrahim, M. M. Din, A. A. Ghapar, and F. Abdullah, ‘Review of Visualization Techniques for Landslide and Flood Disaster Data’, Res. J. Appl. Sci. Eng. Technol., vol. 9, no. 9, pp. 700–705, 2015, doi: 10.19026/rjaset.9.2614.

[13] S. Jiang, J. Ma, Z. Liu, and H. Guo, ‘Scientometric Analysis of Artificial Intelligence (A.I.) for Geohazard Research’, Sensors (Basel)., vol. 22, no. 20, pp. 1–22, 2022, doi: 10.3390/s22207814.

[14] Sismanto, M. D. Erintina, and L. T. Wahyuni, ‘Identification slip surface using resistivity and VLF-R mode in Goa Kiskendo Yogyakarta Indonesia’, Int. J. GEOMATE, vol. 16, no. 53, pp. 177–183, 2019, doi: 10.21660/2019.53.43734.

[15] S. Sudaryatno et al., ‘Visualized information value model result of landslide vulnerability in Purworejo’, no. November 2019, p. 9, 2019, doi: 10.1117/12.2546121.

[16] T. Verbovšek, T. Popit, and Ž. Kokalj, ‘VAT method for visualization of mass movement features: An alternative to hillshaded DEM’, Remote Sens., vol. 11, no. 24, pp. 1–14, 2019, doi: 10.3390/rs11242946.

[17] C. Zhang, D. Zha, S. Zhou, H. Zhou, and H. Jiang, ‘3D visualization of landslide based on close-range photogrammetry’, Instrum. Mes. Metrol., vol. 18, no. 5, pp. 479–484, 2019, doi: 10.18280/i2m.180507.

[18] M. W. Khan et al., ‘Low-cost automatic slope monitoring using vector tracking analyses on live-streamed time-lapse imagery’, Remote Sens., vol. 13, no. 5, pp. 1–17, 2021, doi: 10.3390/rs13050893.

[19] A. Novak and K. Oštir, ‘Towards better visualization of alpine quaternary landform features on high-resolution digital elevation models’, Remote Sens., vol. 13, no. 21, 2021, doi: 10.3390/rs13214211.

[20] G. Abram, A. Solis, Y. Liang, and K. Kumar, ‘In Situ Visualization of Regional-Scale Natural Hazards With Galaxy and Material Point Method’, Comput. Sci. Eng., vol. 24, no. 2, pp. 31–39, 2022, doi: 10.1109/MCSE.2022.3155074.

[21] M. Gaballah and T. Alharbi, ‘3-D GPR visualization technique integrated with electric resistivity tomography for characterizing near-surface fractures and cavities in limestone’, J. Taibah Univ. Sci., vol. 16, no. 1, pp. 224–239, 2022, doi: 10.1080/16583655.2022.2040242.

[22] L. Fu et al., ‘A Three-Dimensional Visualization and Optimization Method of Landslide Disaster Scenes Guided by Knowledge’, ISPRS Int. J. Geo-Information, vol. 11, no. 6, 2022, doi: 10.3390/ijgi11060340.

[23] R. Bi et al., ‘Multi-View Analysis of High-Resolution Geomorphic Features in Complex Mountains Based on UAV–LiDAR and SfM–MVS: A Case Study of the Northern Pit Rim Structure of the Mountains of Lufeng, China’, Appl. Sci., vol. 13, no. 2, 2023, doi: 10.3390/app13020738.

[24] G. H. Alene, H. Vicari, S. Irshad, A. Perkis, O. Bruland, and V. Thakur, ‘Realistic visualization of debris flow type landslides through virtual reality’, Landslides, vol. 20, no. 1, pp. 13–23, 2023, doi: 10.1007/s10346-022-01948-x.

[25] O. Jabrane, D. El Azzab, P. Martínez-Pagán, M. A. Martínez-Segura, H. Mahjoub, and M. Charroud, ‘Contribution of Python-based BERT software for landslide monitoring using Electrical Resistivity Tomography datasets. A case study in Tghat-Fez (Morocco)’, Data Br., vol. 46, p. 108763, 2023, doi: 10.1016/j.dib.2022.108763.

[26] Z. Yang, J. Li, J. Hyyppä, J. Gong, J. Liu, and B. Yang, ‘A comprehensive and up-to-date web-based interactive 3D emergency response and visualization system using Cesium Digital Earth: taking landslide disaster as an example’, Big Earth Data, vol. 00, no. 00, pp. 1–23, 2023, doi: 10.1080/20964471.2023.2172823.

[27] V. Yordanov, Q. X. Truong, and M. A. Brovelli, ‘Estimating Landslide Surface Displacement by Combining Low-Cost UAV Setup, Topographic Visualization and Computer Vision Techniques’, Drones, vol. 7, no. 2, 2023, doi: 10.3390/drones7020085.

[28] Y. Hu et al., ‘Construction and optimization of three-dimensional disaster scenes within mobile virtual reality’, ISPRS Int. J. Geo-Information, vol. 7, no. 6, 2018, doi: 10.3390/ijgi7060215.

[29] R. Huang and W. Li, ‘Formation, distribution and risk control of landslides in China’, J. Rock Mech. Geotech. Eng., vol. 3, no. 2, pp. 97–116, 2011, doi: 10.3724/sp.j.1235.2011.00097.

[30] Z. Lin, Q. Chen, W. Lu, Y. Ji, W. Liang, and X. Sun, ‘Landslide Susceptibility Mapping Based on Information-GRUResNet Model in the Changzhou Town, China’, Forests, vol. 14, no. 3, p. 499, 2023, doi: 10.3390/f14030499.

[31] M. Jemec Auflič, Š. Kumelj, T. Peternel, and J. Jež, ‘Understanding of landslide risk through learning by doing: Case study of Koroška Bela community, Slovenia’, Landslides, vol. 16, no. 9, pp. 1681–1690, 2019, doi: 10.1007/s10346-018-1110-1.

[32] A. Perrone, V. Lapenna, and S. Piscitelli, ‘Electrical resistivity tomography technique for landslide investigation: A review’, Earth-Science Rev., vol. 135, pp. 65–82, Aug. 2014, doi: 10.1016/J.EARSCIREV.2014.04.002.

[33] M. Kamiński, P. Zientara, and M. Krawczyk, ‘Application of airborne laser scanning and electrical resistivity tomography in the study of an active landslide and geology of the cliff, Jastrzębia Góra, Poland’, Bull. Eng. Geol. Environ., vol. 82, no. 4, 2023, doi: 10.1007/s10064-023-03153-z.

[34] B. Azmoon, A. Biniyaz, and Z. Liu, ‘Use of High-Resolution Multi-Temporal DEM Data for Landslide Detection’, Geosci., vol. 12, no. 10, 2022, doi: 10.3390/geosciences12100378.

[35] M. Kamiński, ‘The impact of quality of digital elevation models on the result of landslide susceptibility modeling using the method of weights of evidence’, Geosci., vol. 10, no. 12, pp. 1–21, 2020, doi: 10.3390/geosciences10120488.

[36] J. Brock, P. Schratz, H. Petschko, J. Muenchow, M. Micu, and A. Brenning, ‘The performance of landslide susceptibility models critically depends on the quality of digital elevations models’, Geomatics, Nat. Hazards Risk, vol. 11, no. 1, pp. 1075–1092, 2020, doi: 10.1080/19475705.2020.1776403.

[37] Michal Dlugosz, ‘Digital Terrain Model (DTM) As A Tool For Landslide Investigation In The Polish Carpathians’, VERSITA, Vol. 5, 2012, Accessed: Apr. 27, 2023. [Online]. Available: https://www.igipz.pan.pl/tl_files/igipz/ZGiHGiW/sgcb/sgbc_46/dlugosz.pdf.

[38] Gottfried Mandlburger, ‘Recent Developments in Airborne Lidar | GIM International’, GIM International, Apr. 19, 2019. https://www.gim-international.com/content/article/recent-developments-in-airborne-lidar-2 (accessed Apr. 27, 2023).

[39] M. Vuckovic, J. Schmidt, T. Ortner, and D. Cornel, ‘Combining 2D and 3D Visualization with Visual Analytics in the Environmental Domain’, Inf. 2022, Vol. 13, Page 7, vol. 13, no. 1, p. 7, Dec. 2021, doi: 10.3390/INFO13010007.

[40] A. J. Hendron and F. D. Patton, ‘The vaiont slide — A geotechnical analysis based on new geologic observations of the failure surface’, Eng. Geol., vol. 24, no. 1–4, pp. 475–491, Dec. 1987, doi: 10.1016/0013-7952(87)90080-9.

[41] T. Nordvik, G. Grøneng, G. V. Ganerød, B. Nilsen, C. Harding, and L. H. Blikra, ‘Geovisualization, geometric modelling and volume estimation of the Åknes rockslide, Western Norway’, Bull. Eng. Geol. Environ., vol. 68, no. 2, pp. 245–256, Feb. 2009, doi: 10.1007/S10064-009-0198-X/METRICS.

[42] K. T. Chang and H. C. Huang, ‘Three-dimensional analysis of a deep-seated landslide in central Taiwan’, Environ. Earth Sci., vol. 74, no. 2, pp. 1379–1390, 2015, doi: 10.1007/s12665-015-4128-x.