

Comparative Analysis of Cut & Fill Using Commercial and Open-Source GIS Software

Muhamad Firdaus Che Amat¹, Noor Suhaiza Sauti^{1*}

¹Department of Civil Engineering, Politeknik Sultan Haji Ahmad Shah, 25350 Kuantan, Malaysia

*Corresponding author E-mail: suhaiza@polisas.edu.my

Abstract

The market offers a diverse array of GIS software, both paid and free. Consequently, it is crucial to identify the most appropriate software for specific spatial analysis applications. This study aims to evaluate and compare two GIS software platforms: ArcMap (ESRI) (commercial) and Quantum GIS (QGIS) (open-source), in performing Cut & Fill analysis. The research addresses key issues such as processing efficiency, functional capabilities, user-friendliness, and cost considerations for users of both software platforms. The study's methodology involves data collection and performing Cut & Fill analysis on both platforms to assess processing efficiency, functionality, user-friendliness, and cost. The findings indicate that ArcMap performs Cut & Fill analysis more rapidly and provides specialized, user-friendly tools, despite its high cost. Conversely, QGIS, while slower and more complex, is more cost-effective and flexible. User feedback highlights the ease of use and accuracy of ArcMap, whereas QGIS is recognized for its affordability and customization capabilities. In conclusion, this study identifies the strengths and weaknesses of both GIS software, providing valuable information for users to select the appropriate software based on specific task requirements and available resources.

Keywords: cut & fill, GIS software, commercial, open source

1.0 Introduction

Geographic Information Systems (GIS) are critical in modern spatial analysis, providing tools to improve decision-making in a variety of industries, including urban planning, environmental management, and infrastructure construction. The market's varied selection of GIS software, which includes both commercial and open-source solutions, needs a thorough examination to determine the best platform for certain applications.

Cut & Fill analysis is a method used to determine the amount of material that needs to be excavated (cut) or added (fill) during construction or site modification processes. With advancements in GIS technology, various software can perform this analysis (ESRI, 2025). However, questions arise regarding the accuracy and capabilities between commercial software like ArcMap and open-source software like QGIS.

This research will carefully analyze and compare two popular GIS software platforms: ArcMap, a commercial product, and QGIS, an open-source alternative. The emphasis is on their ability to do Cut & Fill analysis, which is a critical activity in topographic and building projects. This study addresses critical topics such as processing performance, functional capabilities, user friendliness, and economic concerns, offering a thorough evaluation for potential users.

2.0 Literature review

The initial phase of this study will provide a comprehensive overview of the GIS software currently available on the market, encompassing both commercial and free options. Additionally, an examination of previous research on the application of GIS software for cut and fill analysis will offer a clearer understanding of the study's focus.

2.1 Commercial and open-access GIS software

GIS have evolved significantly, offering powerful tools for spatial analysis and mapping. GIS platforms are generally categorized into two types: commercial software and open-source software. Each type has distinct features, advantages, and limitations tailored to

different needs and budgets. The choice between open-source and commercial GIS software is often driven by the specific requirements of the project, the resources available, and the user's technical expertise. This decision is crucial as it impacts the efficiency, cost-effectiveness, and overall success of the spatial analysis tasks (Badea & Badea, 2016).

According to extant literature and applications, there are various GIS software options, as shown in Table 1. QGIS, GRASS GIS, GDAL, and other open access and commercial GIS software are available on the market. Paid GIS software include Global Mapper, MapInfo Professional, ArcMap, and many others. Numerous studies have examined the differences between commercial and open-source GIS platforms, focusing on aspects such as functionality, user-friendliness, cost, and processing efficiency

Table 1: Details of current GIS software

Software	Type	Description	References
QGIS (Quantum GIS)	Open-access	A popular open-source GIS software known for its extensive functionality and active community support.	(Badea & Badea, 2016; Chamat, 2018; Stone, 2018)
GeoServer	Open-access	Primarily a server-based application designed for sharing, processing, and editing geospatial data.	(Ballatore et al., 2011; Geoserver team, 2024)
GRASS GIS (Geographic Resources Analysis Support System)	Open-access	A powerful tool for geospatial data management and analysis.	(Badea & Badea, 2016; Hengl et al., 2009; Migliaccio et al., 2010; Nasr, 2007)
GDAL (Geospatial Data Abstraction Library)	Open-access	A library for reading, writing, and manipulating geospatial data.	(Qin et al., 2014; Warmerdam, 2008)
SAGA GIS (System for Automated Geoscientific Analyses)	Open-access	A GIS software with a focus on spatial analysis and geoprocessing.	(Hengl et al., 2009; Karmaker et al., 2023)
Whitebox GAT (Geospatial Analysis Toolbox)	Open-access	An open-source GIS software for advanced geospatial analysis and data visualization.	(Cao & Ames, 2012; Lindsay, 2014)
ArcMap (ESRI)	Commercial	A comprehensive and widely used commercial GIS software from ESRI - suite with advanced mapping and spatial analysis capabilities.	(ESRI, 2024c; Nasr, 2007; Stone, 2018; WHO/HQ/WHE/HIM/MAP (GIS team), 2018)
MapInfo Professional	Commercial	A desktop GIS software (Pitney Bowes) known for its ease of use and powerful mapping tools.	(Moller, 2024; Nasr, 2007)
Geomedia (Hexagon Geospatial)	Commercial	A GIS software offering advanced data management, visualization, and analysis tools.	(Intergraph, 2016)
Global Mapper (Blue Marble Geographics)	Commercial	A versatile GIS software known for its user-friendly interface and extensive data format support.	(GIS Geography, 2023; Mills, 2023)

Regarding functionality and workflow, commercial GIS platforms like ArcMap are renowned for their extensive toolsets and specialized functions that facilitate complex analyses. Conversely, open-source platforms like QGIS often require users to integrate multiple functions to achieve similar outcomes, which can be less intuitive for beginners (WHO/HQ/WHE/HIM/MAP (GIS team), 2018).

User experience is a crucial factor in the adoption of GIS software. Research indicates that commercial platforms typically offer more refined interfaces and superior user support,

making them more accessible for non-experts. In contrast, while open-source platforms are highly customizable, they often present a steeper learning curve (Stone, 2018).

Cost is always a significant consideration in GIS application development. One of the primary advantages of open-source GIS platforms is their cost-effectiveness. For instance, QGIS is free to use, making it an appealing option for organizations with limited budgets. On the other hand, commercial platforms like ArcMap can be costly, with licensing fees that may be prohibitive for some users (Badea & Badea, 2016).

Apart from the factors discussed above, some other factors to consider when choosing between commercial and open source GIS software are scalability, varying community support and resources, customization and flexibility, training and learning curve, and data security and privacy (ESRI, 2024b; Kibui, 2024). Integration with other tools and systems, scalability is important to ensure that the software can handle increasing data and user demands as the project grows. Integration with other tools and systems is also important to maintain an efficient workflow (WHO/HQ/WHE/HIM/MAP (GIS team), 2018). Community support and resources vary, with commercial software offering professional support and open source software relying on community assistance.

Customization and flexibility are key advantages of open source software, allowing for customized solutions, while commercial options may offer limited customization. Training and learning curves should be evaluated, as commercial platforms often provide structured training, while open source solutions may require more self-directed learning (WHO/HQ/WHE/HIM/MAP (GIS team), 2018).

Finally, data security and privacy are important, especially when handling sensitive information, with commercial software typically offering robust security measures and open source solutions requiring additional configuration. Taking these factors into account helps in making informed decisions that align with project needs, budgets, and technical capabilities.

2.2 Previous studies on GIS software for cut and fill analysis

Cut and fill analysis is a critical component of many engineering projects, such as highway building, land development, and mining. GIS software has substantially improved the quality and efficiency of these investigations by utilizing DEMs and other spatial data. This literature review examines prior research on the use of GIS software in cut and fill analysis.

Early research focused on building algorithms for automating cut and fill computations with DEMs. Pan et al. (2005) suggested an automatic analysis approach based on ARC/INFO GRID that used pre-cut-fill DEMs and road coverage data to model post-cut-fill situations. This strategy attempted to lessen the labor-intensive character of previous approaches while increasing precision.

Chamat, (2018) research emphasizes the need of correct cut and fill calculations in earthworks, which are required for projects such as road building and drainage. The study focuses on the use of Quantum-GIS software to improve the route selection process for river connection projects. The software helps to calculate cut and fill volumes, eliminating manual work and saving time. The same approach can be used for road and drainage projects, increasing efficiency and accuracy.

Additionally, Kim et al. (2014) studied the use of GIS software (ArcGIS) and object-oriented 3D visualization modeling to optimize highway alignment construction. Highway design is difficult and time-consuming, including cut and fill calculations, cost estimation, and timetable planning. To automate this process and increase efficiency, the study

developed an object-oriented data model that meets ISO 10303 requirements. Multiple highway alignment possibilities were generated and compared using Building Information Modeling (BIM) technology, which considered cut and fill amounts, prices, and schedule. The prototype 3D model was tested on a highway project in Seoul, Korea, demonstrating its capacity to investigate several design alternatives and compare prices and timelines early in the design process. Overall, the research aims to improve highway design and construction practices by leveraging advanced modeling techniques to streamline the planning process.

The evolution of GIS software for cut and fill analysis has significantly improved the efficiency and accuracy of this important engineering task. From early algorithms using DEMs to modern applications involving the use of competitive free software (QGIS) and the combination of GIS and BIM for more efficient modeling of building structures, offering more accurate and user-friendly solutions for cut and fill analysis.

3.0 Materials and Methods

To accomplish the research's objectives, the methodology encompasses several important phases, as illustrated in Figure 1.

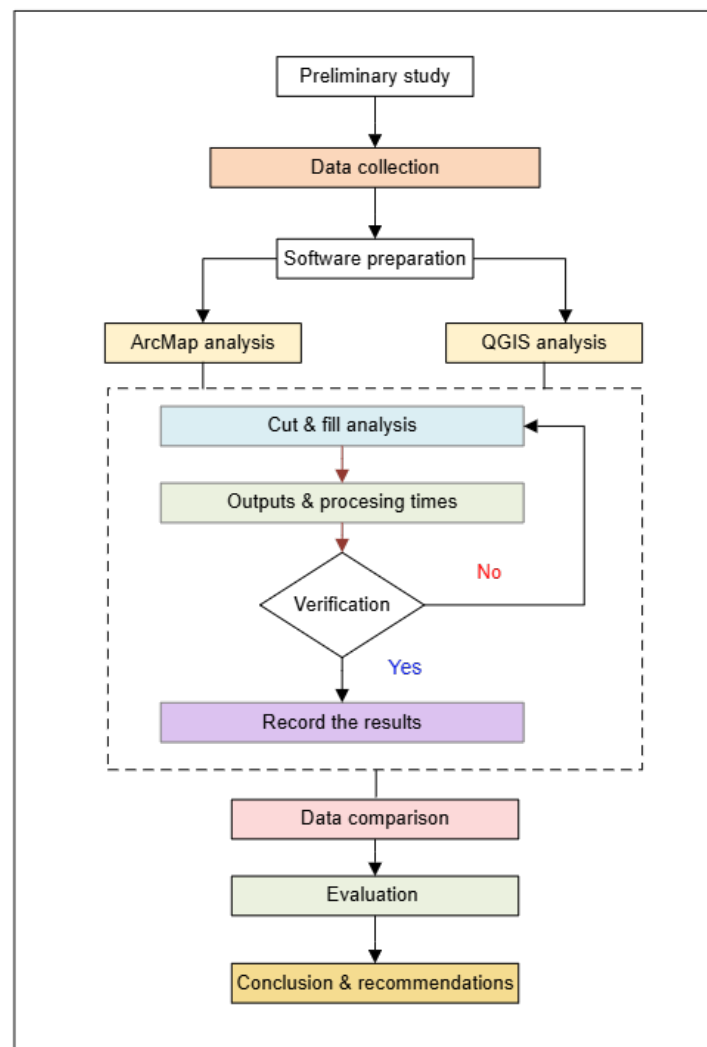


Figure 1: Research methodology

3.1 Data collection

A Digital Elevation Model (DEM) is a 3D digital representation of the Earth's surface, which depicts the elevation or height of each point on the terrain. It captures various topographic features, including slope, aspect and other terrain attributes. In this study, a DEM with a resolution of 10 x 10 pixels for the study area, namely Kg Bukit Batu, Kandang, Melaka for the year 2014 was prepared. The dataset utilized comprises high-resolution DEM for the construction site simulation area. The surface data encompasses both the pre-modification, represented by the original DEM, and the post-modification, which refers to the DEM following modifications.

3.2 Software preparation

The software preparation phase involves installing and setting up the latest versions of ArcGIS and QGIS, ensuring both are configured with identical settings, including coordinate systems and projection parameters. It also includes aligning analysis parameters such as resolution and cell size, importing the same source data into both platforms, and configuring the specific tools for cut & fill analysis. A preliminary validation check is performed to ensure consistency and accuracy, allowing for a fair comparison of results between the two software.

3.3 Cut and fill analysis

The cut & fill analysis was conducted using two chosen GIS software packages. This process involved loading the DEM source data, setting up the analysis tools, and executing the analysis to determine the volume of material to be excavated and filled. The results, which included volume, affected area, and processing time, were meticulously recorded. Quality assurance steps, such as thorough validation and detailed reporting, ensured the analysis's accuracy and reliability. This methodical approach provided a thorough and precise evaluation of terrain modifications.

3.3.1 ArcMap

The initial step involves preparing DEM data that accurately represents the surface of the study before modification and one after modification. These two sets of DEM data are then input into ArcMap software (Figure 2).

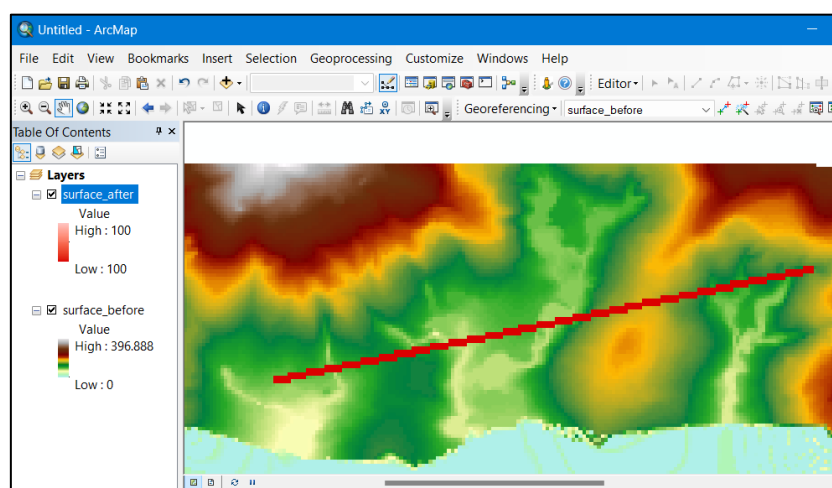


Figure 2: DEM in ArcMap

Cut and Fill analysis is conducted using ArcToolbox to process the data and produce a new raster that delineates the cut and fill area (Figure 3).

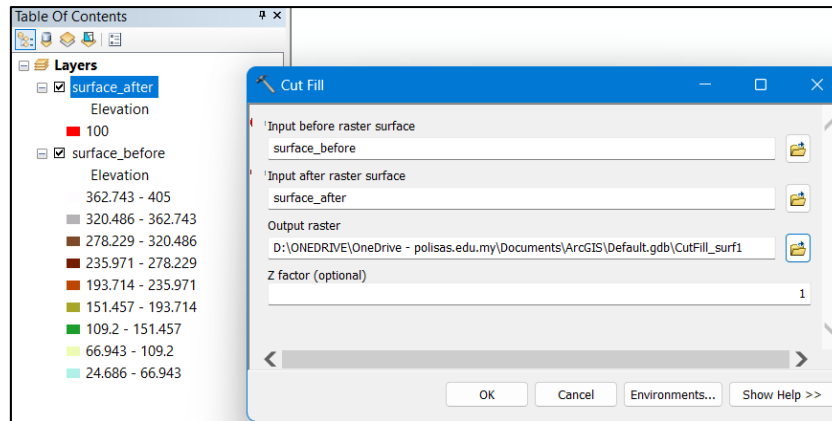


Figure 3: Cut & Fill function in ArcMap

The output raster will display areas where material has been removed (cut) and added (filled)(Figure 4). Typically, the cropped area is shown in blue and fills the other inner area in red. To see detailed statistics, including the volume of material cut and filled, Open the output raster attribute table.

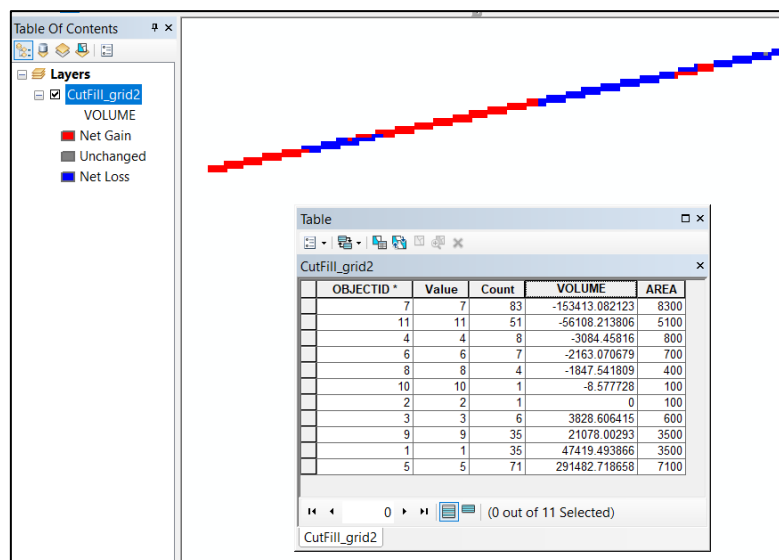


Figure 4: Results of the Cut and Fill analysis in ArcMap

3.3.2 QGIS

Conducting Cut and Fill analysis with QGIS software also necessitates the same DEM dataset. The original topography is modeled into a pre-modification surface (*tin_before_kontur*) based on an existing contour plan. Conversely, the roadway design is modeled into a post-modification surface (*tin_after_jalan*) according to its specified width and height characteristics (Figure 5).

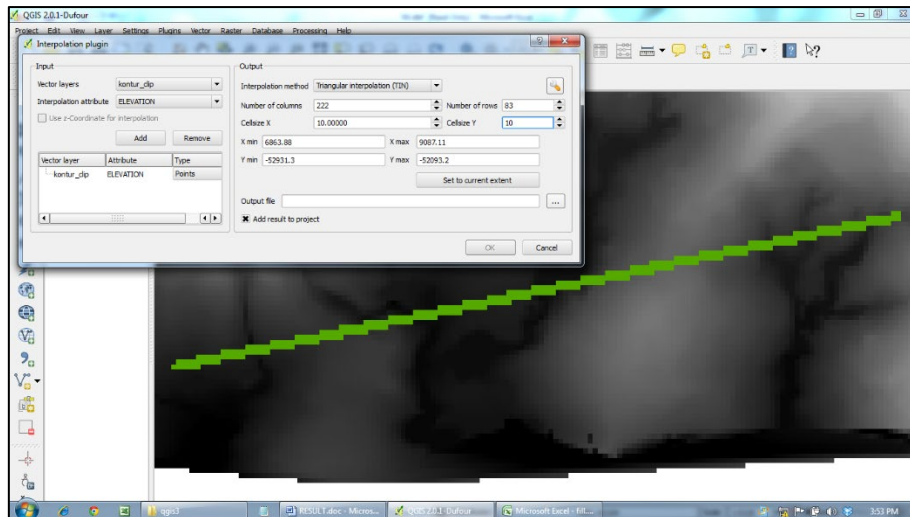


Figure 5: Cut & Fill function in QGIS

To calculate the difference between DEM, Cut & Fill is calculated using the formula $\text{tin_after_kontur} - \text{tin_before_jalan}$. Therefore, if the Digital Number (DN) is (+) it means that it needs to be filled (Fill) and if the value is (-) it needs to be cut. To implement it, the Raster Calculator function has been used (Figure 6).

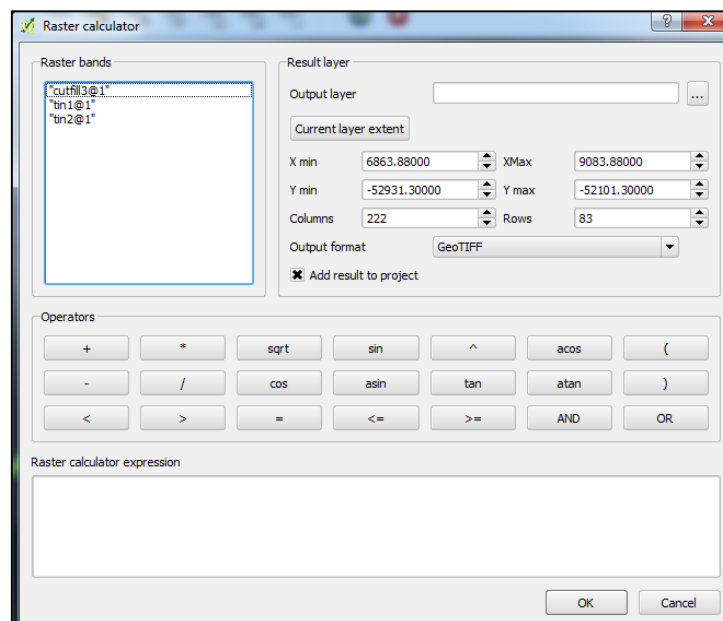


Figure 6: Raster Calculator dialog box

The calculation results will then be converted to vector form (shapefile format) using the Polygonize (Raster to Vector) tool (Figure 7). The results of the analysis will be displayed as in Figure 8.

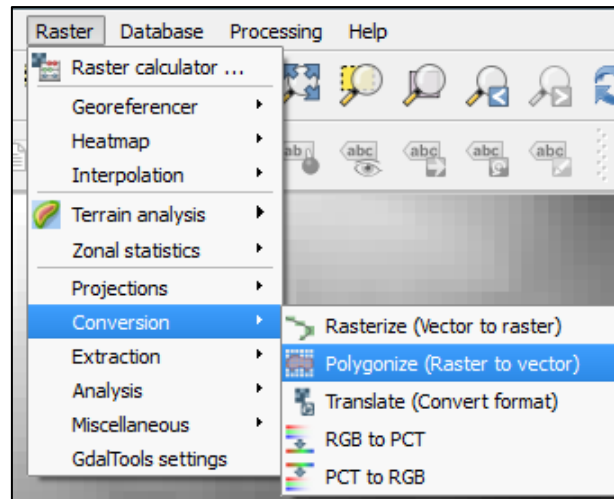


Figure 7: Polygonize function in QGIS

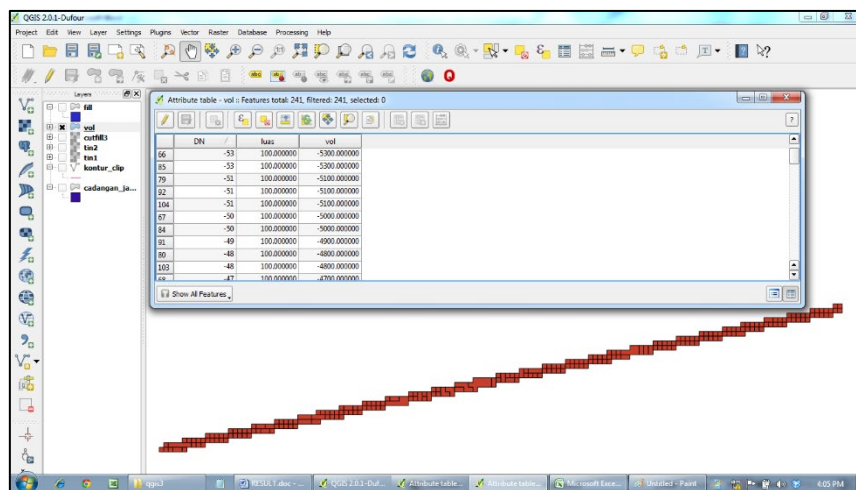


Figure 8: Spatial data and attribute data for Cut and Fill analysis

First, calculate the area before determining the volume, as the volume is derived using the following formula:

$$\text{VOLUME (vol)} = \text{AREA} \times \text{HEIGHT (DN)} \text{----- formula(1)}$$

Area calculations are performed using the field calculator function (Figure 9).

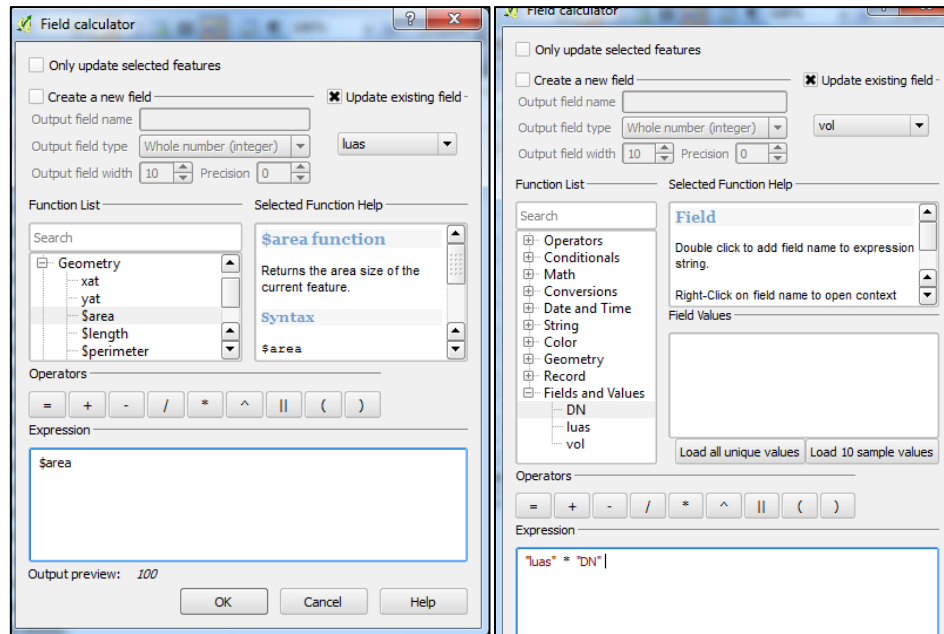


Figure 9: Field Calculator dialog box

The result of the calculation will be displayed in the form of an attribute table (Figure 10).

	DN	luas	vol
138	10	1000.000000	10000.000000
161	30	700.000000	21000.000000
87	-60	600.000000	-36000.000000
137	11	500.000000	5500.000000
232	15	500.000000	7500.000000
192	-10	300.000000	-3000.000000
181	-9	300.000000	-2700.000000
182	-8	300.000000	-2400.000000

Figure 10: The calculation results are presented in tabular form

Subsequently, the data is divided into two new layers: layer_cut (red) and layer_fill (blue). This operation facilitates the calculation of the total cut and fill volumes (Figure 11).

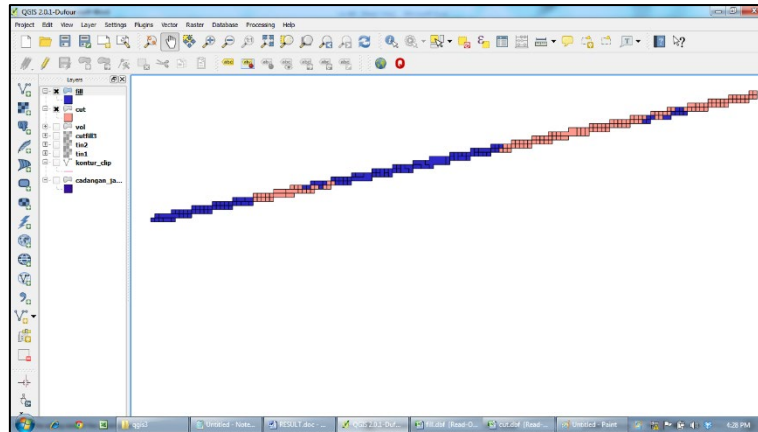


Figure 11: Display of Cut and Fill analysis results in QGIS software

Finally, the total volume of both data layers was calculated using Microsoft Excel software (Figure 12).

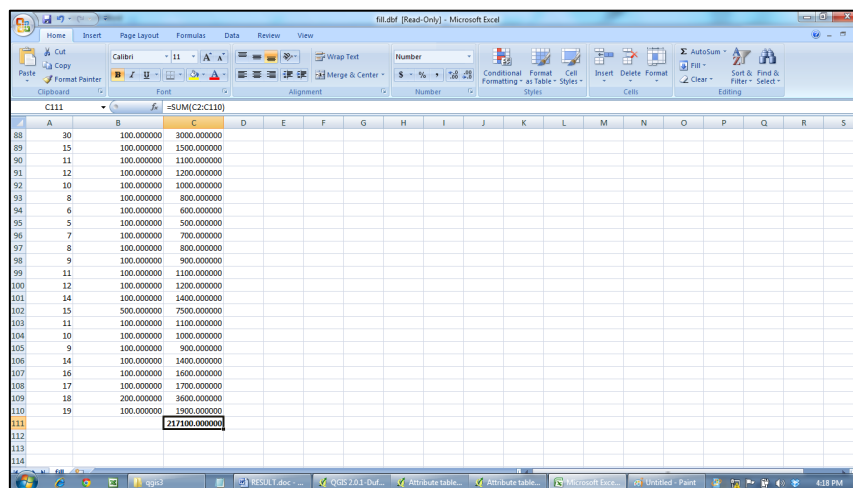


Figure 12: Total volume calculation in MS Excel

3.4 Data comparison and evaluation

The analytical results of the two applications will be compared based on four primary criteria: processing efficiency, functional capabilities, user friendliness, and cost. Processing efficiency is determined by comparing the time it takes to perform the analysis on each platform. Functional capabilities are evaluated based on the instruments provided and their usefulness in executing the necessary analysis. User-friendliness is measured by workflow complexity and interface intuitiveness. Finally, economic factors are examined by contrasting the license fees for ArcMap with the free, open-source nature of QGIS. These findings are then synthesized to show the benefits and shortcomings of each platform, allowing consumers to make informed judgments.

The conclusion will provide a detailed summary of the study's findings in terms of the benefits and limitations of each software examined for a specific function, namely cut and fill analysis. Following that, recommendations for choosing the most suitable software will be made, as well as future research for improvement.

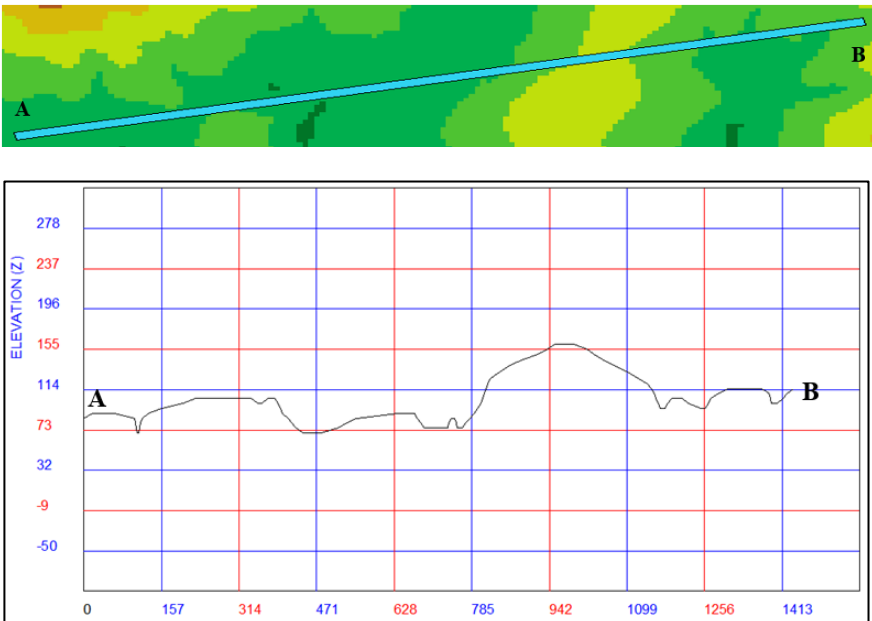
4.0 Discussion of analysis and findings

The results of Cut & Fill analysis using ArcMap and QGIS can be evaluated based on several key factors: processing volume and time, ease of use of the analysis tool, and cost of use (licensed versus free options) along with resource demands - Central Processing Unit (CPU) and Random-Access Memory (RAM).

4.1 Volume & processing time results (m³)

ArcMap, particularly with the Spatial Analyst extension, provides highly accurate volume calculations. The Cut & Fill tool in ArcMap allows for precise determination of volume changes between two surfaces, ensuring reliable results for both cut and fill operations. Compared to QGIS that also offers accurate volume calculations through its Raster Calculator and Zonal Statistics tools. The accuracy is comparable to ArcMap, especially when using high-resolution DEMs. Tables 2, 3 and 4 present the results of the conducted analysis. Based on these comparative tables, slight differences were observed in terms of surface profile, location, volume of soil, and the area requiring filling and cutting.

Table 2.0: Comparison of the Proposed Road Route Profile Using Commercial GIS Software (ArcMap) and open source GIS Software (QGIS)

Software	Output
Commercial GIS	

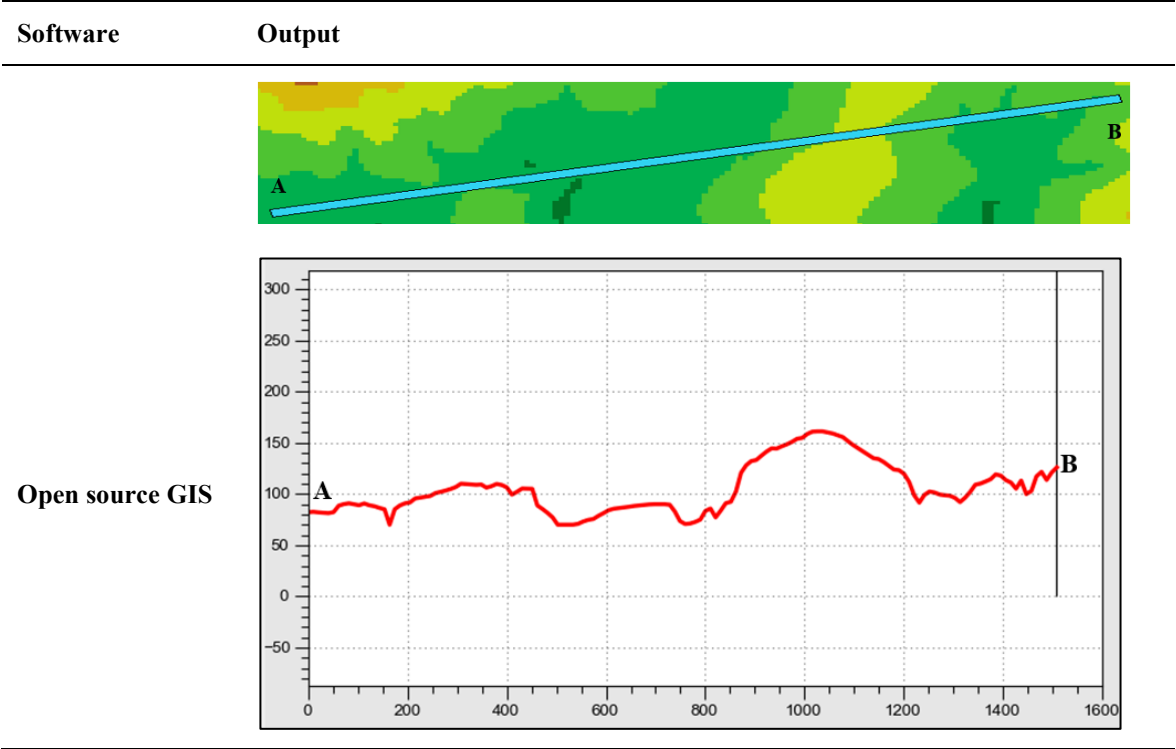
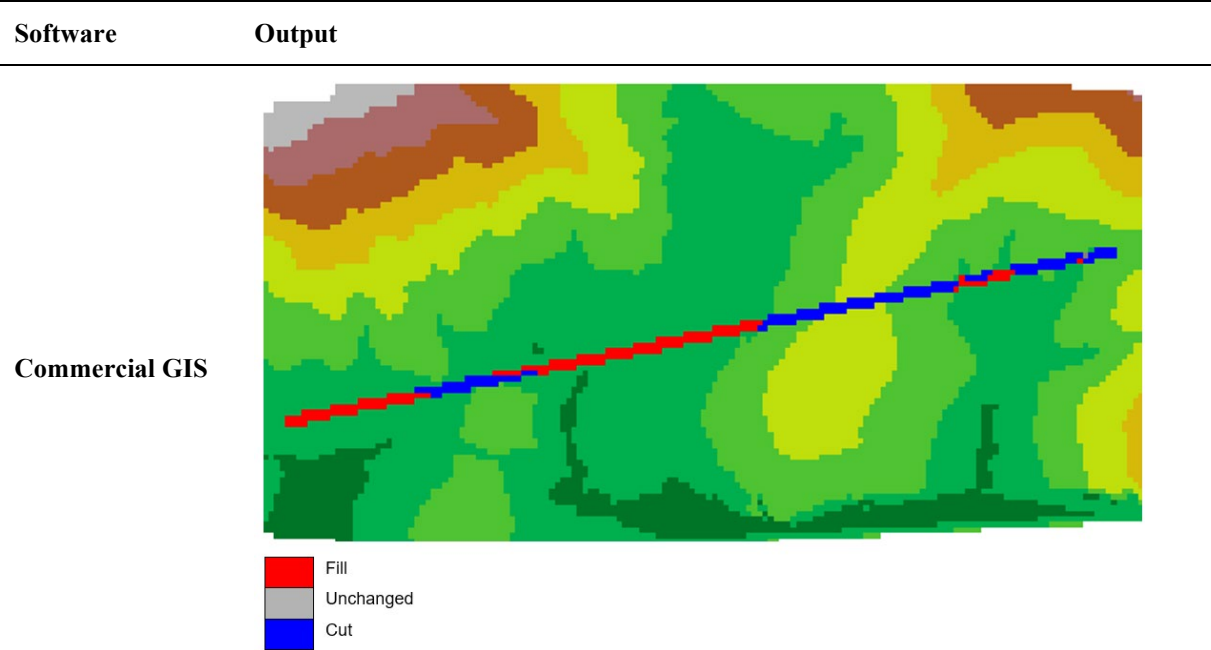
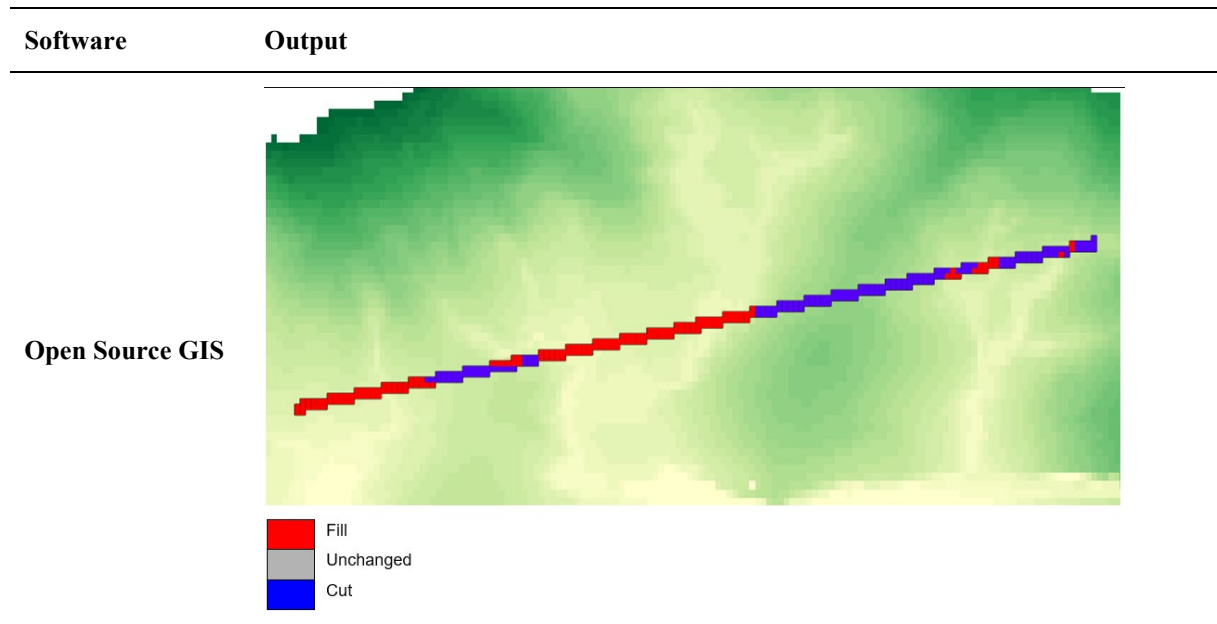


Table 3: Comparison of Locations Requiring Filling and Cutting



**Table 4:** Comparison of Volume and Area Requiring Filling and Cutting

Category	Item	Commercial GIS software	Open source GIS software	Difference
Volume	Fill	216,625 m ³	217,100 m ³	475 m ³
	Cut	363,809 m ³	362,300 m ³	1,509 m ³
Area	Fill	15,400 m ²	15,200 m ²	200 m ²
	Cut	14,700 m ²	14,300 m ²	400 m ²
	Unchanged	100 m ²	600 m ²	500 m ²

Table 4 presents a detailed comparison of commercial and open source GIS software in terms of volume and area calculations for filling and cutting. The commercial software estimated 216,625 m³ of fill volume, while the open access software calculated 217,100 m³. The difference was only 475 m³, demonstrating equal accuracy with a slight overestimation by the open access software.

In terms of cut volume, the commercial software calculated 363,809 m³ compared to 362,300 m³ by the open source software, with a difference of 1,509 m³, again suggesting consistent results with a slight overestimation by the commercial software. When analyzing the fill area, the commercial software estimated 15,400 m² and the open access software 15,200 m², a minimal difference of 200 m², showing close alignment in their estimations.

Similarly, for the cut area, the commercial program estimated a cut area of 14,700 m², while the open access software predicted 14,300 m², with a discrepancy of 400 m², showing comparable accuracy. However, there was a significant discrepancy in the unchanged area, with the commercial software estimating 100 m² and the open source software 600 m², a difference of 500 m². This suggests that the open access software may be more conservative in identifying unchanged areas or using different thresholds. Overall, both software types indicate good accuracy and consistency in volume and area calculations, with slight variances presumably due to different algorithms or data processing methods. The significant disparity in unaltered area requires further investigation.

A comparison of the processing times for cut & fill analyses recorded (multiple sets) for this study area shows that ArcMap averaged 5 minutes while QGIS averaged 7 minutes per

analysis session. ArcMap typically excels in processing speed for cut & fill analyses, especially for large datasets. Proprietary algorithms and tightly integrated tools are designed to handle complex geospatial calculations efficiently, provided the system meets the hardware requirements of the software (ESRI community, 2024). However, reliance on licensed extensions such as Spatial Analyst or 3D Analyst can increase initial setup time and cost.

QGIS offers competitive performance in processing time but may experience slower calculation speeds for very large datasets or when using complex workflows. As an open source platform, QGIS relies on user-configured settings and community-developed plugins, which can affect performance consistency. However, advances in the QGIS processing framework have significantly improved its speed and efficiency, especially when leveraging high-performance hardware (Chamat, 2018).

4.2 Ease of use of analysis tools

Comparing ArcMap and QGIS for cut-and-fill analysis highlights distinct strengths and workflows in each software. ArcMap employs tools like Cut Fill and Interactive Cut and Fill, which require two overlapping raster surfaces to compute volume changes (ESRI community, 2024). These tools are seamlessly integrated into ArcGIS Pro and ArcMap, offering a specialized viewer that differentiates cut areas (blue) from fill areas (red). While ArcMap's workflow is efficient, it necessitates a dedicated license such as Spatial Analyst or 3D Analyst and uses bilinear resampling for precision.

On the other hand, QGIS provides a more adaptable approach with its Raster Surface Volume Tool, which utilizes a Digital Elevation Model (DEM) for volume calculations. The process in QGIS typically involves clipping the DEM, reprojecting data, generating contours, and employing volume tools. As an open-source platform, QGIS is highly customizable, enabling users to tailor the interface to their needs. Additionally, it supports numerous plugins that enhance functionality, such as polygon tools and zonal statistics for validating volume calculations (Duarte et al., 2021). This flexibility allows QGIS to handle diverse data sources, including LiDAR and point clouds.

ArcMap offers a user-friendly interface with clearly documented tools and workflows, making it easy to navigate and perform tasks (WHO/HQ/WHE/HIM/MAP (GIS team), 2018). Its interactive cut-and-fill analysis feature in ArcGIS Pro is particularly intuitive, enabling users to dynamically visualize and refine their analysis. Meanwhile, QGIS stands out for its flexibility and simplicity, especially appealing to those experienced with open-source GIS platforms. Tasks like loading a DEM, conducting raster calculations, and producing zonal statistics are simple and efficient in QGIS, ensuring accessibility for users of varying skill levels (Badea & Badea, 2016).

In summary, ArcMap delivers precise, visualization-focused tools for cut-and-fill analysis but requires specific licenses and matching raster surfaces. Conversely, QGIS offers a versatile, user-friendly alternative with broad data compatibility and customizable plugins. The choice between the two depends on the project's requirements and available resources.

4.3 Cost of use and resource requirements

ArcMap and ArcGIS Pro operate under a paid licensing model, which can be expensive. However, this license provides access to advanced capabilities, professional technical support, and regular software updates (Migliaccio et al., 2010). In contrast, QGIS is free and completely open source, appealing to users on a budget. Despite being free, QGIS delivers powerful functionality and benefits from an active and supportive community (Stone, 2018).

Both tools are effective for cut-and-fill analysis, each offering unique advantages. Choosing between them depends on factors such as budget, system specifications, and required features.

ArcMap cost varies based on the chosen licensing model. To perform Cut & Fill analysis, users need tools like the Cut & Fill tool and the Spatial Analyst or 3D Analyst extensions, which incur additional costs. A standard ArcMap license typically ranges from \$1,500 to \$3,000, depending on whether it is a single-use or concurrent-use license. This license provides access to basic mapping and analysis functionalities. For advanced analysis such as Cut & Fill, users must purchase the Spatial Analyst or 3D Analyst extensions, each costing an additional \$1,500 to \$3,000. These extensions offer tools specific to raster analysis, including Cut & Fill functionality (ESRI, 2024a).

Additionally, ESRI offers an annual maintenance and support plan, usually costing around 20% of the initial license price per year. This plan includes software updates, bug fixes, and access to technical support. Overall, the total cost to perform Cut & Fill analysis in ArcMap can range from \$3,000 to \$6,000 or more, depending on the specific licenses and extensions required (ESRI, 2024a).

In terms of resource requirements, ArcMap and ArcGIS Pro are resource-intensive, requiring significant CPU and RAM power, especially when dealing with large data sets or running complex analyses. High-performance hardware is often required to achieve peak performance. QGIS, on the other hand, is often lighter, which reduces the demand on system resources. It handles large data sets efficiently, making it an ideal solution for users with limited hardware resources.

5.0 Conclusion and future research

This study evaluates and compares two GIS software platforms, ArcMap (commercial) and QGIS (open-source), for their performance in conducting Cut & Fill analysis. The research focuses on processing efficiency, functional capabilities, user-friendliness, and cost considerations. Through data collection and analysis, the study finds that ArcMap offers faster processing, specialized tools, and a user-friendly interface, though at a high financial cost. QGIS, while slower and more complex, is highly cost-effective, customizable, and flexible.

The results suggest that differences in outcomes may stem from variations in the algorithmic processes used by each software, particularly in contour-to-grid interpolation. User feedback highlights ArcMap's ease of use and accuracy, whereas QGIS is praised for its affordability and adaptability.

The study concludes by emphasizing the strengths and limitations of both platforms, offering insights for users to choose the appropriate software based on their needs and resources. It also suggests future research to validate the accuracy of Cut & Fill analysis through field comparisons, providing a more comprehensive understanding of the software's effectiveness.

References

- Agazu, B. G., & Kero, C. A. (2024). Innovation strategy and firm competitiveness: a systematic literature review. *Journal of Innovation and Entrepreneurship*, 13(1). <https://doi.org/10.1186/s13731-024-00381-9>
- Badea, A. C., & Badea, G. (2016). Considerations on Open Source GIS Software Vs Proprietary GIS Software. *RevCAD Journal of Geodesy and Cadastre, Osi*, 15–27.
- Ballatore, A., Tahir, A., McArdle, G., & Bertolotto, M. (2011). A comparison of open source geospatial technologies for web mapping. *International Journal of Web Engineering and*

- Technology*, 6(4), 354–374. <https://doi.org/10.1504/IJWET.2011.043440>
- Cao, Y., & Ames, D. P. (2012). A strategy for integrating open source GIS toolboxes for geoprocessing and data analysis. *IEMSs 2012 - Managing Resources of a Limited Planet: Proceedings of the 6th Biennial Meeting of the International Environmental Modelling and Software Society, July 2012*, 1505–1511.
- Chamat, L. R. (2018). Calculation of Cut and Fill of Earthworks with Quantum-GIS. *IJSRD-International Journal for Scientific Research & Development*, 6(03), 2321–0613. www.ijrsrd.com
- Duarte, L., Queirós, C., & Teodoro, A. C. (2021). Comparative analysis of four QGIS plugins for web maps creation. *Granja*, 34(2), 8–25. <https://doi.org/10.17163/LGR.N34.2021.01>
- ESRI. (2024a). *Buy GIS Software|ArcGIS Product Pricing - ESRI Store*. <https://int-store.esri.com/en-us/store/overview>
- ESRI. (2024b). *Performance and scalability pillar*. ESRI. <https://architecture.arcgis.com/en/framework/architecture-practices/performance-and-scalability/overview.html>
- ESRI. (2024c). *What is ArcGIS?* <https://www.esri.com/en-us/arcgis/geospatial-platform/overview>
- ESRI. (2025). *Cut Fill (Spatial Analyst)*. https://pro.arcgis.com/en/pro-app/latest/tool-reference/spatial-analyst/cut-fill.htm?utm_source=chatgpt.com
- ESRI community. (2024). *3D Workflows - Perform a cut and fill analysis*. <https://doc.arcgis.com/en/3d/workflows/analysis/calculating-volumes.htm>
- Geoserver team. (2024). *Geoserver*. Open Source Geospatial Foundation. <https://geoserver.org/>
- GIS Geography. (2023). *Global Mapper Software by Blue Marble (Review)*. <https://gisgeography.com/global-mapper-software-blue-marble/>
- Hengl, T., Grohmann, C. H., Bivand, R., Conrad, O., & Lobo, A. (2009). SAGA vs GRASS: A Comparative Analysis of the Two Open Source Desktop GIS for the Automated Analysis of Elevation Data. *Proceedings of Geomorphometry, January*, 22–27.
- Intergraph. (2016). *Introduction to GeoMedia*.
- Karmaker, S., Banerjee, S., Coors, V., & Bauer, S. (2023). Comparison of Simulation Tools for Solar Energy Potential Analysis : a case in Weinstadt , Stuttgart , Germany. *AGSE 2022, March*.
- Kibui, W. (2024). *Choosing the Right GIS Development Platform for Your Needs*. Life in GIS. <https://www.lifeingis.com/choosing-the-right-gis-development-platform-for-your-needs/>
- Kim, H., Orr, K., Shen, Z., Moon, H., Ju, K., & Choi, W. (2014). Highway Alignment Construction Comparison Using Object-Oriented 3D Visualization Modeling. *Journal of Construction Engineering and Management*, 140(10), 1–12. [https://doi.org/10.1061/\(asce\)co.1943-7862.0000898](https://doi.org/10.1061/(asce)co.1943-7862.0000898)
- Lindsay, J. B. (2014). The Whitebox Geospatial Analysis Tools project and open-access GIS. *Proceedings of the GIS Research UK 22nd Annual Conference, April 2014*. <http://www.uoguelph.ca/geography/people/faculty/lindsay.shtml>
- Migliaccio, F., Di Milano, P., Carrion, D., & Zambrano, C. (2010). *A comparison between free/open-source and commercial geospatial software tools, based on a case study. March 2019*. <https://www.researchgate.net/publication/258433891>
- Mills, M. (2023). *The Global Mapper Academic Program*. Blue Marble Geographics. <https://www.blumaplegeo.com/blog/the-global-mapper-academic-programs/>
- Moller, P. (2024). *MapInfo Monday: Looking back at 200 articles*. Precisely. <https://community.precisely.com/discussion/mapinfo-monday-looking-back-at-200-articles>
- Nasr, M. R. (2007). *Open Source Software: The use of open source GIS software and its impact*

- on organizations* (Issue June). Middlesex University.
- Pan, X., Nakamura, H., Liu, Y., & Lang, Y. (2005). Automatic Analysis Algorithm for Side-Slope Cut-Fill Based on Digital Elevation Model. *Geoinformatics*, 16(1), 35–40. <https://doi.org/10.6010/geoinformatics.16.35>
- Qin, C. Z., Zhan, L. J., & Zhu, A. X. (2014). How to Apply the Geospatial Data Abstraction Library (GDAL) Properly to Parallel Geospatial Raster I/O? *Transactions in GIS*, 18(6), 950–957. <https://doi.org/10.1111/tgis.12068>
- Stone, J. (2018). *Open Source or Commercial GIS, or both?* Geospatial World. <https://geospatialworld.net/blogs/open-source-or-commercial-gis-or-both/>
- Warmerdam, F. (2008). The Geospatial Data Abstraction Library. In *Open Source Approaches in Spatial Data Handling* (pp. 87–104). https://doi.org/10.1007/978-3-540-74831-1_5
- WHO/HQ/WHE/HIM/MAP (GIS team). (2018). *Comparison of Geographic Information Systems (GIS) software* (Issue 12 March). <https://www.who.int/health-cluster/resources/publications/OpenSourceGISComparison.pdf>