

Title: A Systematic Review of Open-Source GIS Platforms: Capabilities, Limitations, and Adoption

Partab Rathore¹

¹State key laboratory of information Engineering in surveying mapping and Remote Sensing,
Wuhan University, Wuhan 430079, China

Muhammad Junaid Ahmad^{2*}

²State key laboratory of information Engineering in surveying mapping and Remote Sensing,
Wuhan University, Wuhan 430079, China

Muhammad Zain³

³Institute of Geology, University of The Punjab, Lahore, Pakistan

Ayesha Shafiq⁴

⁴Institute of Geology, University of The Punjab, Lahore, Pakistan

Muhammad Junaid Bin Zulfiqar⁵

⁵Institute of Geology, University of The Punjab, Lahore, Pakistan

Corresponding Author: junaidinayat325@gmail.com

Abstract

The integration of Geographic Information Systems (GIS) with remote sensing and artificial intelligence (AI) is transforming the landscape of spatial analysis. This review explores the evolution, capabilities, and adoption of prominent open source GIS platforms including QGIS, GRASS GIS, gvSIG, SAGA GIS, ILWIS, and Whitebox GAT. These tools have emerged as robust alternatives to proprietary software, offering flexibility, extensibility, and community-driven innovation. The paper examines their origins, key features, licensing models, and comparative strengths in handling raster-vector analysis, plugin support, and web-based mapping. It further highlights adoption trends in academia, government, and non-profit sectors, along with educational integration and migration patterns from commercial platforms. Current limitations such as steep learning curves and performance with large datasets are addressed. The review concludes by outlining future directions, including AI integration, real time analytics, cloud deployment, and enhanced interoperability. By synthesizing literature and case examples, this

338



paper underscores how open-source GIS, in combination with remote sensing and AI, is shaping a new era in spatial intelligence.

Keywords: Geographical Information System (GIS), Remote Sensing, Artificial Intelligence, Open-Source GIS, Spatial Analysis.

INTRODUCTION

What is GIS?

Geography has played a central role in human survival, development, and decision-making since prehistoric times. From ancient hunters predicting animal movement to modern urban planners designing smart cities, spatial understanding has always been a crucial tool. Today, the vast amount of geographic knowledge we rely on is collected, organized, and analyzed using Geographic Information Systems (GIS) [1]. A GIS is a computer-based system designed to collect, manage, store, analyze, and display **spatial data** data that is linked to specific locations on Earth. These systems allow users to not only identify where things are but also understand what they are, by analyzing the attributes and relationships of spatial features. For example, GIS can quantify the exact location of Mount Everest, the depth of the Titanic, or the migration patterns of endangered species, while simultaneously analyzing surrounding factors such as land use, pollution, or accessibility. GIS supports informed decision-making in countless areas, including disaster response, infrastructure planning, environmental protection, agriculture, and public health [2].

The development and application of GIS have been significantly enhanced by technological advances in satellite positioning systems (GNSS), high resolution remote sensing, and computing power. These innovations have made spatial analysis faster, more accurate, and more widely accessible [3].

What is Open-Source Software?

Open-source software refers to computer programs whose **source code is freely available**, allowing anyone to inspect, modify, and enhance the software. It promotes transparency, collaboration, and community driven innovation. Unlike proprietary software, which is restricted by licensing fees and closed development, open-source tools empower users to adapt the software to their specific needs without financial or legal constraints [4].



Why is Open-Source GIS Important?

The rise of open-source GIS platforms represents a major step forward in democratizing access to spatial technologies. Tools such as QGIS, GRASS GIS, gvSIG, SAGA GIS, and Whitebox GAT offer powerful capabilities comparable to commercial software like ArcGIS, but at no cost. This accessibility has been especially critical for researchers, educators, small governments, NGOs, and developing countries, where funding for commercial licenses is limited [5]. Moreover, open source GIS fosters transparency and reproducibility in scientific research. Users can review and verify the methods used in spatial analysis, develop custom plugins, and contribute to global knowledge through active development communities. This collaborative environment encourages rapid innovation and widespread adoption across various fields [6]. Open-source GIS also plays a pivotal role in responding to environmental challenges, managing public services, and improving governance. From mapping flood prone areas to monitoring wildlife recovery, these tools have enabled timely and cost-effective decision making with real-world impact [7].

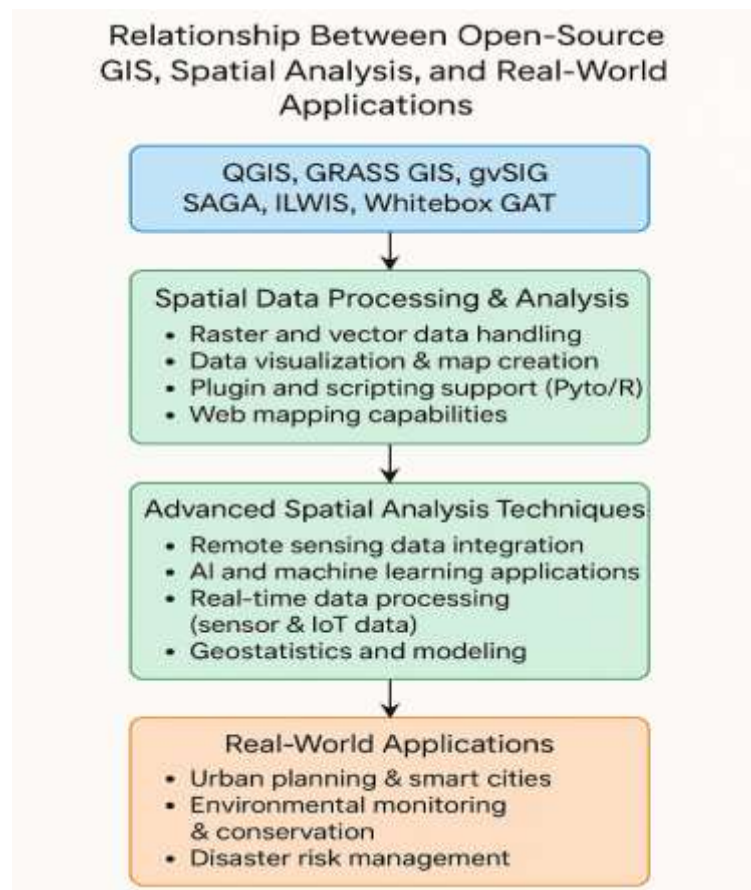
Purpose and Scope of This Review

This review paper aims to provide a **systematic overview** of major open source GIS platforms, examining their core **capabilities**, identifying key **limitations**, and analyzing their **adoption trends** across academic, governmental, and private sectors. The paper seeks to:

- Compare the main features of leading open source GIS software
- Evaluate usability, performance, and community support
- Identify challenges in training, scalability, and technical limitations
- Highlight real-world applications through literature examples
- Assess global adoption patterns and emerging trends

Through this review, we aim to present a balanced and insightful assessment of open source GIS, offering valuable guidance for students, professionals, researchers, and organizations seeking to explore or enhance their use of these tools.





Overview of Popular Open Source GIS Platforms

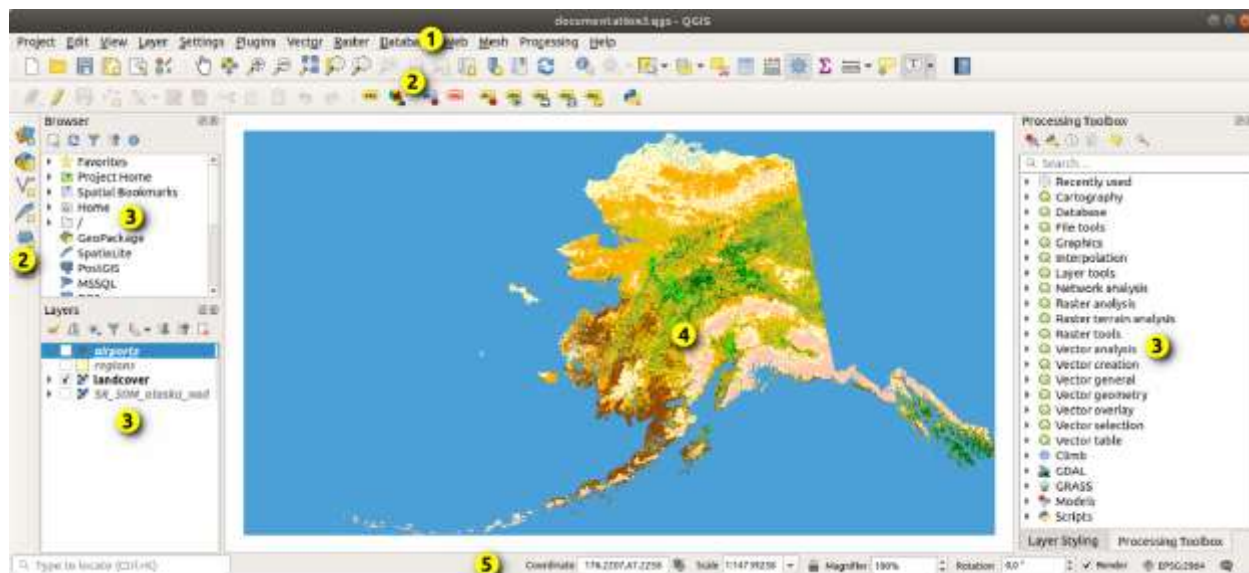
Open-source GIS platforms have emerged as powerful alternatives to commercial software, offering a range of spatial data handling, analysis, and visualization capabilities [7]. The following section provides a detailed overview of six widely used open-source GIS tools: **QGIS**, **GRASS GIS**, **gvSIG**, **SAGA GIS**, **ILWIS**, and **Whitebox GAT**. For each, we discuss the origin, developer, core features, and licensing model.

QGIS

QGIS, originally known as Quantum GIS, was initiated in 2002 by Gary Sherman as a personal project. It quickly gained traction within the open source community due to its modular architecture and user friendly interface. QGIS is developed and maintained by an international community of volunteers and organizations under the coordination of the QGIS Project Steering Committee [5]. It operates under the umbrella of the Open Source Geospatial Foundation

341

(OSGeo). QGIS supports a broad range of vector, raster, mesh, and point cloud formats. It integrates with external tools like GRASS GIS, SAGA GIS, and PostGIS, and is extensible through Python and C++ plugins. The software offers advanced cartographic output, spatial analysis, georeferencing tools, map layouts, and compatibility with various web services (WMS, WFS, WCS). Its active plugin ecosystem enables tailored functionalities for specific research or operational needs. QGIS is licensed under the GNU General Public License (GPL), which permits free use, modification, and redistribution [5, 8].



GRASS GIS

The Geographic Resources Analysis Support System (GRASS GIS) was developed in 1982 by the U.S. Army Corps of Engineers as a land management tool. Over time, it evolved into one of the most comprehensive open source GIS platforms and was officially released under GPL in 1999 [9]. GRASS is maintained by the GRASS Development Team, a global group of contributors, and supported by OSGeo. Its development is academically driven, with strong collaboration from research institutions. GRASS GIS provides over 350 modules for raster and vector analysis, image processing, geostatistics, and 3D modeling. It is known for its command line efficiency, but also includes a graphical user interface. GRASS is particularly suited for complex spatial modeling, environmental simulation, and large-scale geospatial analysis. It can be used as a standalone

application or integrated into QGIS as a processing backend. The software is distributed under the GNU General Public License (GPL), promoting open access and collaborative development [10].

gvSIG

gvSIG originated in 2004 as a project funded by the Generalitat Valenciana (the government of the Valencia region in Spain). Its objective was to provide a free, professional grade GIS system for managing spatial data in public administration. The software is developed and maintained by the gvSIG Association, a non-profit organization that promotes free software use in spatial sciences [11]. Development involves public institutions, universities, and private entities. gvSIG offers extensive vector and raster data handling, spatial analysis, topology tools, and geoprocessing capabilities. It supports Open Geospatial Consortium (OGC) standards and includes advanced layout tools, scripting interfaces, and a modular plugin system. gvSIG is also notable for its multilingual support and its adaptation for mobile and 3D environments. gvSIG is released under the GNU General Public License (GPL), enabling free use and distribution [5].

SAGA GIS

System for Automated Geoscientific Analyses (SAGA GIS) was developed in 2004 at the Department of Physical Geography at the University of Göttingen in Germany. It was initially designed to support terrain analysis and environmental modeling in geosciences. SAGA GIS is developed by the SAGA User Group Association and contributors from multiple academic and research institutions [12]. SAGA is well-known for its wide range of geoscientific and terrain analysis tools. It excels in digital elevation model (DEM) processing, hydrological modeling, and grid based spatial analysis. The modular framework allows developers to contribute independently developed tools. SAGA is frequently used alongside QGIS, R, and Python, enhancing its flexibility for advanced geospatial workflows. SAGA GIS is released under the GNU General Public License (GPL), though some components may be under the Lesser GPL (LGPL) for broader compatibility [13].

ILWIS

The Integrated Land and Water Information System (ILWIS) was originally developed in 1984 by the International Institute for Geo-Information Science and Earth Observation (ITC) in the Netherlands. It was first released for public use in 1988 and became open-source in 2007. ILWIS is now maintained by a community of developers under 52°North, in collaboration with ITC and



other academic partners [14]. ILWIS combines both raster and vector capabilities within a single platform and offers tools for remote sensing, spatial modeling, image classification, and land use analysis. It is commonly used in hydrology, agriculture, and land management projects. ILWIS has been evolving under the ILWIS 4 (Next Generation) initiative to support modern standards and cloud based deployment. ILWIS is distributed under the GNU General Public License (GPL), allowing free academic and commercial use [15].

Whitebox GAT

Whitebox Geospatial Analysis Tools (Whitebox GAT) was launched in 2009 by Dr. John Lindsay at the University of Guelph, Canada. It succeeded the earlier Terrain Analysis System and was designed to support experimental and research oriented geospatial workflows. Whitebox GAT is maintained by the open source community, with initial and continuing contributions from academic researchers in Canada and elsewhere [16]. Whitebox GAT offers over 500 tools for raster analysis, hydrological modeling, terrain classification, and LiDAR data processing. It emphasizes transparency in geospatial analysis and rapid tool development. The platform supports scripting in Python and Java, and a newer version, WhiteboxTools, has been integrated with Python, R, and QGIS to extend its usability. The software is licensed under the GNU General Public License (GPL), fostering open collaboration and free distribution [17].

Platform	Year of Origin	Developer/Institution	Key Features	License
QGIS	2002	QGIS Development Team (OSGeo-supported)	- Wide support for raster, vector, mesh, and point cloud data - Plugin architecture (Python/C++) - Integration with GRASS, SAGA, PostGIS - Advanced cartography & symbology - Web services (WMS, WFS, WCS)	GPL
GRASS GIS	1982	GRASS Development Team, OSGeo	- Over 350 modules for raster/vector/3D analysis - Spatial modeling and image processing - Time-series analysis - Command-line and GUI support - Integrates with QGIS and R	GPL



gvSIG	2004	gvSIG Association (Valencian Govt. Initiative)	- Desktop GIS with multilingual support - Strong vector/raster processing - OGC standards compliance - Plugin-based architecture - 3D, mobile, and web mapping capabilities	GPL
SAGA GIS	2004	SAGA User Group (University of Göttingen)	- Specialized in geoscientific terrain analysis - DEM and hydrology tools - Grid-based modeling - Modular tool framework - Python and R scripting support	GPL / LGPL
ILWIS	1988	ITC (University of Twente), 52°North	- Combines raster and vector analysis - Remote sensing and classification tools - Hydrological and land use modeling - Simple GUI and scripting options - ILWIS 4 supports cloud and modern web standards	GPL
Whitebox GAT	2009	University of Guelph (John Lindsay), open-source contributors	- 500+ tools for hydrology, LiDAR, and terrain analysis - Transparent processing environment - Python/Java scripting - Integration with WhiteboxTools in Python, R, and QGIS - Designed for experimental workflows	GPL

Capabilities and Strengths

Open-source GIS platforms offer a range of functionalities that support various types of geospatial analysis, from basic mapping to advanced terrain modeling and remote sensing [18]. This section outlines the core strengths of leading open-source GIS tools across six main capabilities: raster and vector analysis, plugin extensibility, data visualization and cartography, web mapping, scripting integration, and user support infrastructure.

Raster and Vector Analysis

Raster and vector processing form the foundation of any GIS system. Raster data, often derived from remote sensing, is essential for terrain modeling, land cover classification, and environmental monitoring, while vector data enables mapping of roads, boundaries, and infrastructure [19].



- **QGIS** supports both raster and vector formats through integration with the GDAL/OGR libraries. It allows for spatial joins, overlays, buffer operations, and advanced raster calculator functions. Its compatibility with GRASS and SAGA expands its analytical capabilities significantly [10].
- **GRASS GIS** is renowned for its raster-based analysis modules. It offers strong support for image classification, hydrological modeling, surface interpolation, and map algebra. GRASS also includes comprehensive vector tools for topology, network analysis, and spatial querying [20].
- **gvSIG** provides reliable support for raster and vector operations, including basic editing, topological correction, and layer symbology. It is well-suited for municipal and regional planning tasks [17].
- **SAGA GIS** is particularly strong in raster terrain and geoscientific analysis. Its modules for hydrology, geomorphometry, and surface analysis are highly optimized for large datasets.
- **ILWIS** supports raster and vector data natively and offers interactive image classification, cross-section analysis, and basic modeling tools in an integrated environment [21, 22].

Plugin Support and Extensibility

Extensibility through plugins is a defining characteristic of modern GIS software. It enables users to tailor tools to their needs without modifying the core software [23].

- **QGIS** features a rich plugin repository with thousands of community-developed and official plugins. These cover domains like geostatistics, remote sensing, time-series analysis, web mapping, and hydrology. The PyQGIS API allows users to create custom tools in Python [5, 24].
- **GRASS GIS** does not rely on a plugin marketplace but allows integration of new modules via scripting. Modules are tightly bound to its command-line interface.
- **gvSIG** offers plugin extensibility, though it is less comprehensive compared to QGIS. Its Java-based architecture allows development of domain-specific extensions [5].
- **SAGA GIS** supports tool module development but lacks a centralized plugin repository. Its architecture enables researchers to contribute specialized tools.
- **ILWIS** includes scripting functionality but plugin development is more limited. However, the newer ILWIS 4 architecture is being refactored for improved modularity and extensibility [25].



Data Visualization and Cartography

Map creation and data visualization are essential for communicating geospatial information effectively.

- **QGIS** provides extensive cartographic tools including advanced labeling, symbology styles, layer blending, and customizable print composer layouts. Users can generate publication-ready maps and thematic charts.
- **GRASS GIS** includes tools for rendering raster and vector maps and supports 3D visualizations through NVIZ. Its outputs can be exported for use in other mapping environments [26].
- **gvSIG** offers map layout tools and supports multiple view management, which is particularly useful in multi-scale projects. Thematic mapping and symbology features are available, although less refined than QGIS.
- **SAGA GIS** includes basic map visualization features primarily oriented toward analysis rather than presentation. Its strength lies more in scientific outputs than in aesthetic design.
- **ILWIS** provides user-friendly layout design, legend creation, and thematic layer display. While suitable for internal reporting, its output options are limited for professional cartography [27].

Web Mapping Capabilities

Web GIS is crucial for sharing spatial data interactively with broader audiences and stakeholders.

- **QGIS** supports web mapping through tools like QGIS Server, QGIS2Web, and integration with external services like GeoServer and MapServer. These features allow publishing of interactive maps via web platforms or cloud environments.
- **GRASS GIS, SAGA, gvSIG, and ILWIS** do not natively support robust web mapping. While GRASS and SAGA can export data for use in web services, they are typically backend tools rather than front-end mapping solutions.
- Some efforts exist to extend web capabilities in gvSIG and ILWIS, but these are generally under active development and not yet mature for enterprise-scale deployment [5].



Python and R Integration

Scripting languages like Python and R are widely used in geospatial data analysis for automation, data processing, and machine learning.

- **QGIS** has full support for Python via the PyQGIS API, allowing automation of map production, custom GUI development, and spatial data handling. R can be used within QGIS through dedicated plugins such as Processing R Provider.
- **GRASS GIS** provides a Python scripting shell and full access to GRASS modules via PyGRASS and GRASS-R interfaces. This enables efficient automation and integration with scientific workflows.
- **SAGA GIS** supports scripting through bindings in R (via RSAGA package) and Python, though the integration is less seamless than in QGIS [28, 29].
- **gvSIG** offers a scripting console but has limited third-party integration. Development is ongoing to improve compatibility with Python.
- **ILWIS** supports scripting in Python and Groovy in its newer versions, but broader integration with analytical libraries is still emerging [5].

Community Support and Documentation

A strong user and developer community ensures software evolution, bug fixing, and availability of learning resources.

- **QGIS** has one of the most active open source GIS communities. It hosts regular user conferences, publishes detailed user manuals, and provides an extensive library of tutorials.
- **GRASS GIS** also enjoys strong academic backing. Its documentation is structured and detailed, catering to both beginners and expert users.
- **gvSIG** is actively supported by the gvSIG Association, with documentation in multiple languages and regional training programs.
- **SAGA GIS** has a dedicated research user base and a modest but responsive forum presence. Documentation is functional, though not as rich as QGIS or GRASS.
- **ILWIS** benefits from support by ITC and 52°North. While documentation for older versions is comprehensive, newer resources are still catching up with recent software updates [5, 30].



Feature	QGIS	GRASS GIS	gvSIG	SAGA GIS	ILWIS
Raster Data Support	✓	✓	✓	✓	✓
Vector Data Editing	✓	✓	✓	✗	✓
Plugin Marketplace	✓	✗	Limited	✗	✗
3D Visualization Tools	✓	✓	✗	✗	✗
Web Mapping Capabilities	✓	✗	✗	✗	✗
Python Integration	✓	✓	Limited	✓	Limited
R Integration	✓	✓	✗	✓	✗
Cartographic Output Tools	Advanced	Moderate	Moderate	Basic	Moderate
Community Support Level	Strong	Strong	Moderate	Moderate	Moderate
Documentation Quality	Extensive	Comprehensive	Sufficient	Moderate	Improving

Limitations and Challenges

While open-source GIS platforms have gained substantial popularity due to their flexibility, cost effectiveness, and extensibility, they are not without limitations. Understanding these challenges is essential for selecting the right tools, especially in large scale, high stakes projects. This section outlines some of the main drawbacks commonly associated with open-source GIS tools in comparison to commercial alternatives.

Steep Learning Curve for New Users

One of the primary obstacles for adopting open-source GIS tools is the steep learning curve, particularly for users with little prior GIS experience. While platforms like QGIS have made strides in improving user interfaces and tutorials, tools like GRASS GIS and SAGA GIS still require significant time to understand module based workflows and command-line operations. For



professionals used to commercial platforms with point and click environments, this presents a barrier to efficient use [31].

Graphical User Interface (GUI) Limitations

Although QGIS and gvSIG offer relatively polished user interfaces, several open-source GIS tools such as GRASS GIS and ILWIS still lack the intuitive GUI design found in commercial systems like ArcGIS Pro. Interface elements may be outdated or fragmented, and accessing certain functionalities often requires switching between multiple windows or executing command line instructions. These factors can hinder productivity and reduce appeal for non technical users [32].

Performance with Large Datasets

Open-source GIS platforms sometimes struggle to handle extremely large or complex spatial datasets, particularly when compared to enterprise grade systems. Operations involving high resolution raster data, multi-layer vector datasets, or extensive 3D scenes may cause delays or crashes. The performance bottleneck is often due to limited memory management optimization and dependency on third-party libraries, which may not be tailored for big data processing [33].

Limited Professional Support and Maintenance

Unlike commercial platforms that offer dedicated customer support, technical hotlines, and formal service level agreements (SLAs), open source GIS solutions rely largely on community forums, mailing lists, and volunteer documentation. While many communities are active and helpful, the absence of guaranteed support can be a concern in mission critical applications or government projects where response time and accountability are crucial [34].

Plugin Stability and Compatibility Issues

While plugin systems in open-source platforms (especially QGIS) offer impressive flexibility, they can also lead to stability issues. Plugins are often developed independently, and may not be regularly updated to match new software versions. This can result in broken functionality, conflicts, or unexpected behavior during analysis. In contrast, commercial software undergoes strict QA testing before releasing new tools or updates [24].



Table 3: Summary of Limitations in Open-Source GIS Platforms

Challenge	Description
Steep Learning Curve	Requires significant time investment to understand tools and workflows, particularly in GRASS, SAGA, and command-line environments.
Limited GUI Friendliness	Interfaces may lack modern design and intuitive layout, reducing ease of use compared to commercial platforms like ArcGIS or MapInfo.
Performance with Large Data	Raster heavy or high volume vector tasks can cause lag or crashes due to less optimized data handling and processing pipelines.
Lack of Formal Support	No official customer support; relies on community forums and documentation, which may vary in quality and availability.
Plugin Instability	Plugins may be outdated, conflict with core updates, or be poorly documented resulting in inconsistent performance or broken features.

Adoption and Usage Trends

Over the past decade, open-source GIS platforms have witnessed a significant rise in adoption across academic, governmental, and non profit sectors. Their cost effectiveness, community-driven development, and flexibility have made them viable alternatives to proprietary software like ArcGIS [35]. This section explores how these tools are being increasingly integrated into research, education, and operational workflows around the world.

Adoption in Universities, NGOs, and Research Institutions

Universities and research centers worldwide have embraced open source GIS tools, particularly QGIS and GRASS GIS, due to their accessibility and extensive analytical capabilities. These platforms enable students and researchers to conduct complex spatial analyses without the financial burden of licensing fees. Numerous postgraduate GIS and environmental science programs now include open source software as a core part of their curriculum. Additionally, NGOs and development agencies use QGIS for land use planning, water resource management, and disaster risk analysis, particularly in low resource settings where budget constraints limit access to commercial tools [2].

Published Research Using Open-Source GIS

The number of peer reviewed publications utilizing QGIS, GRASS GIS, and SAGA GIS has grown steadily. Researchers use these tools for a wide range of applications, including land cover



classification, urban expansion monitoring, hydrological modeling, and biodiversity mapping. For instance:

- QGIS has been widely used in habitat suitability modeling, groundwater potential analysis, and socio-environmental vulnerability mapping.
- GRASS GIS has been employed in time series analysis of satellite data, erosion modeling, and vegetation change detection.
- SAGA GIS features prominently in studies related to terrain analysis, catchment hydrology, and geomorphometric mapping. This trend indicates growing academic trust in the analytical reliability and reproducibility of open-source GIS tools [36].

Integration into GIS Education

Many higher education institutions are shifting from proprietary software to open-source GIS as part of a broader move toward open educational resources (OER). QGIS, in particular, is now taught in introductory and advanced GIS courses due to its user friendly interface, robust documentation, and active global community. Students are trained not only in spatial analysis but also in plugin development and automation using Python. The ability to use real world tools without restrictive licenses enhances learning outcomes and promotes skill portability [37].

Migration from ArcGIS to QGIS

There is a notable shift in both public and private sectors from licensed systems like ArcGIS to open-source alternatives such as QGIS. This migration is driven by several factors:

- **Cost savings** associated with license free software.
- **Increasing compatibility** of QGIS with widely used data formats and services (e.g., GeoTIFF, Shapefile, WMS).
- **Active development community** that frequently releases updates and security patches.
- **Improved usability**, with QGIS offering similar workflows to ArcGIS in data editing, spatial queries, and map creation. Several European municipalities and international organizations have officially transitioned to QGIS as their primary GIS platform, showcasing its maturity and institutional trustworthiness [38].



Table 4: Summary of Adoption and Usage Patterns

Sector	Open-Source GIS Usage
Universities	Used extensively in teaching and research. QGIS and GRASS are common in coursework and postgraduate studies.
Research Journals	Increasing citations of studies using QGIS, GRASS, and SAGA. Used in climate studies, ecology, geology, and remote sensing.
NGOs	Applied in community mapping, disaster response, environmental monitoring, and participatory planning in low-resource contexts.
Government	Adopted by municipalities and departments for land records, urban planning, and public service mapping especially in Europe and Latin America.
Education	Integrated into GIS curricula worldwide; enables hands on training without licensing restrictions. Supports open science and reproducible research practices.
Migration Trend	Growing replacement of ArcGIS with QGIS in government and academia due to cost, customization, and transparency advantages.

Future Directions and Trends

As spatial data becomes more complex and central to decision-making across sectors, the role of open-source GIS platforms is expected to evolve significantly. Emerging technologies such as artificial intelligence (AI), cloud computing, and real time data streams are reshaping how geospatial information is processed and utilized [39]. This section outlines the anticipated trends and opportunities that will influence the future landscape of open source GIS development and usage.

Integration with Artificial Intelligence and Machine Learning

The combination of open-source GIS with AI and machine learning (ML) is an emerging frontier in spatial analysis. Platforms like QGIS and GRASS GIS are increasingly being integrated with Python libraries such as TensorFlow, Scikit-learn, and PyTorch to perform predictive modeling, pattern recognition, and image classification tasks. For example, machine learning algorithms can be used within QGIS for land cover classification, crop disease detection from satellite imagery, and urban expansion prediction. The continued integration of AI capabilities will expand the analytical power of GIS, making it more adaptive to big data and real time applications, particularly in environmental monitoring and smart city planning [40, 41].



Cloud-Based and Web GIS Deployment

Cloud computing is redefining how GIS platforms are accessed and deployed. Open-source solutions are beginning to offer cloud-based versions or integrations, allowing users to manage geospatial workflows without relying on local infrastructure. Initiatives like QGIS Cloud and the use of Docker containers for GRASS GIS highlight the move toward web enabled spatial analysis. This trend enables collaboration across teams and geographies, increases scalability, and facilitates integration with other web based systems such as decision support dashboards and mobile data collection tools [42].

Real Time and Sensor Based GIS Applications

The growing use of Internet of Things (IoT) devices and remote sensors is generating massive streams of spatial temporal data. Open source GIS platforms are beginning to adapt by supporting the ingestion and processing of real-time data. For instance, QGIS plugins and PostgreSQL/PostGIS backends allow dynamic updating of maps based on sensor feeds for applications like traffic monitoring, flood forecasting, and air quality tracking. This real-time capability will be a significant area of development, particularly for disaster response systems and environmental surveillance networks [43].

Enhanced Interoperability and Open Standards

Adherence to open standards such as those set by the Open Geospatial Consortium (OGC) will continue to be a priority in future GIS development. Open source platforms are already at the forefront of supporting standards like WMS, WFS, and GeoPackage, which ensure seamless data exchange across systems. As spatial analysis becomes more interdisciplinary, enhancing interoperability between GIS platforms and external tools (e.g., statistical packages, simulation software, and CAD systems) will be vital for integrated analysis and reporting [44].

User Centric Design and Usability Improvements

To attract a wider range of users, open-source GIS tools are gradually shifting toward more intuitive, user friendly interfaces. The development of drag and drop tools, guided workflows, and context-aware help systems will likely reduce the learning curve and make these platforms more accessible to non-specialists, including policy makers and local administrators. This shift in design philosophy reflects a broader movement toward democratizing spatial technologies and empowering more users to engage with geospatial data [45].



Strengthening Community and International Collaboration

The success of open-source GIS relies heavily on strong community engagement. The future will see increased international collaboration through coding sprints, developer conferences, open data projects, and training programs. These efforts will not only ensure continuous improvement of the software but also expand the reach of GIS education and practice in developing regions. Collaboration between academia, government, and industry will be essential to sustain innovation and ensure that tools remain aligned with real world needs [46, 47].

Table 5: Emerging Trends in Open-Source GIS Development

Trend	Description and Future Potential
AI & Machine Learning Integration	Enables advanced classification, modeling, and automation in GIS workflows using Python libraries and deep learning techniques.
Cloud-Based GIS	Facilitates remote access, scalability, and team collaboration through tools like QGIS Cloud and Dockerized GRASS GIS.
Real-Time GIS	Supports sensor based mapping and analysis of live spatial data (e.g., weather, traffic, pollution) through streaming and dynamic updating.
Open Standards Compliance	Promotes data interoperability and system integration using formats like WMS, WFS, and GeoJSON, enabling seamless cross-platform workflows.
Improved User Interfaces	Simplifies operation through GUI enhancements, tooltips, and visual customization, making GIS accessible to broader, non-technical audiences.
Global Community Expansion	Strengthens sustainability and innovation through volunteer contributions, multilingual documentation, and increased adoption in developing countries.

CONCLUSION

The integration of Geographic Information Systems (GIS) with remote sensing and artificial intelligence has revolutionized the landscape of spatial analysis. Open source GIS platforms such as QGIS, GRASS GIS, gvSIG, SAGA GIS, ILWIS, and Whitebox GAT have emerged as robust alternatives to proprietary software, offering extensive capabilities for data management, analysis, and visualization. Their adaptability, active communities, and support for modern



computational tools have made them increasingly relevant in research, education, and policy making. This review highlights the functional strengths of these platforms including their ability to handle raster and vector data, plugin extensibility, support for scripting, and cartographic capabilities while also acknowledging their current limitations such as steep learning curves, GUI constraints, and plugin stability. Despite these challenges, the global adoption of open source GIS continues to grow across universities, NGOs, and government institutions, with many shifting from commercial systems to open alternatives. Looking ahead, the future of open source GIS lies in deeper integration with artificial intelligence, real time data processing, cloud deployment, and enhanced interoperability with other scientific tools. The evolution of user friendly interfaces and collaborative development will further democratize access to spatial technologies, empowering users across disciplines and regions to engage meaningfully with geospatial data. In sum, open source GIS is not only a technological tool but also a driver of inclusive innovation. As spatial data continues to shape how societies plan, manage, and respond to change, these platforms will play an increasingly critical role in delivering accessible, intelligent, and scalable spatial solutions for the challenges of the modern world.

REFERENCES

1. Sucharyna Thomas, L., C.R. Wickham-Jones, and A.J. Heppenstall, *Combining agent-based modelling and geographical information systems to create a new approach for modelling movement dynamics: A case study of Mesolithic Orkney*. Open Archaeology, 2022. **8**(1): p. 987-1009.
2. Patel, J., N. Sharma, and S. Mohan, *Introduction to Remote Sensing and GIS*, in *Smart Buildings and Cities with Remote Sensing and GIS*. 2025, Chapman and Hall/CRC. p. 3-34.
3. Zhang, B., et al., *Progress and challenges in intelligent remote sensing satellite systems*. IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing, 2022. **15**: p. 1814-1822.
4. Prokakis, E., *Free and Open-Source Software: Freedom, Transparency and Efficiency in the Digitalization Era*. Journal of Politics and Ethics in New Technologies and AI, 2022. **1**(1): p. e31230-e31230.
5. Löwe, P., et al., *Open Source–GIS*, in *Springer Handbook of Geographic Information*. 2022, Springer. p. 807-843.



6. Hu, T., et al., *FAIR principles in workflows: A GIScience workflow management system for reproducible and replicable studies*. International Journal of Applied Earth Observation and Geoinformation, 2025. **138**: p. 104477.
7. Daud, M., F.M. Ugliotti, and A. Osello, *Comprehensive analysis of the use of Web-GIS for natural hazard management: A systematic review*. Sustainability, 2024. **16**(10): p. 4238.
8. de Lange, N., *Geoinformation systems*, in *Geoinformatics in Theory and Practice: An Integrated Approach to Geoinformation Systems, Remote Sensing and Digital Image Processing*. 2023, Springer. p. 375-433.
9. Lemenkova, P., *Reclassification Scheme for Image Analysis in GRASS GIS Using Gradient Boosting Algorithm: A Case of Djibouti, East Africa*. Journal of Imaging, 2025. **11**(8): p. 249.
10. Lemenkova, P. and O. Debeir, *GDAL and PROJ libraries integrated with grass GIS for terrain modelling of the georeferenced raster image*. Technologies, 2023. **11**(2): p. 46.
11. Antunes, C., et al., *Environmental Noise-Integrating and sharing geographic data sets*. REVISTA INTERNACIONAL MAPPING, 2023. **32**(210): p. 28-34.
12. La Licata, M., et al., *FTIR-derived soil degradation indices and stochastic modelling of organic matter–sediment dynamics in a Mediterranean watershed: A Northern Apennines case study*. PLoS One, 2025. **20**(8): p. e0330252.
13. Pearson, R.A., et al., *GeoFabrics 1.0. 0: An open-source Python package for automatic hydrological conditioning of digital elevation models for flood modelling*. Environmental Modelling & Software, 2023. **170**: p. 105842.
14. Mitra, S., et al., *An Overview of Morphometry Software Packages, Tools, and Add-ons*. Advances in Remote Sensing Technology and the Three Poles, 2022: p. 49-57.
15. Singh, A. and V. Vyas, *A Review on remote sensing application in river ecosystem evaluation*. Spatial Information Research, 2022. **30**(6): p. 759-772.
16. Ho, Y.-F., et al., *GEDTM30: global ensemble digital terrain model at 30 m and derived multiscale terrain variables*. PeerJ, 2025. **13**: p. e19673.
17. Xia, J., et al., *Open Vector Analysis*, in *Open GIS*. 2024, Springer. p. 175-198.
18. Sharma, S., et al., *Remote Sensing and GIS in Natural Resource Management: Comparing tools and emphasizing the importance of in-situ data*. Remote Sensing, 2024. **16**(22): p. 4161.
19. Malakar, K.D., S. Roy, and M. Kumar, *Practical approaches to GIS data analysis*, in *Geospatial Technologies in Coastal Ecologies Monitoring and Management*. 2025, Springer. p. 159-190.



20. Kaushik, P. and S. Jabin, *Advancements and Challenges in Business Applications of SAR Images*, in *Big Data Analytics*. 2021, Auerbach Publications. p. 87-111.
21. Lemenkova, P., *Big Earth data processing using machine learning for integrated mapping of the dead sea fault, Jordan*. Glasnik Šumarskog fakulteta Univerziteta u Banjoj Luci, 2021(31): p. 79-103.
22. AbdelRahman, M.A. and A.A. Afifi, *Digital mapping of soil properties using geomatics: integration of GIS, GPS, and remote sensing applications*. Arabian Journal of Geosciences, 2024. **17**(12): p. 330.
23. Lamas, V., et al., *GIS-Publisher: Simplifying web-based GIS application development for enhanced data dissemination*. SoftwareX, 2024. **28**: p. 101942.
24. Duarte, L. and A.C. Teodoro, *GIS open-source plugins development: A 10-year bibliometric analysis on scientific literature*. Geomatics, 2021. **1**(2): p. 206-245.
25. Thakuri, S., et al., *Open-source data alternatives and models for flood risk management in Nepal*. Remote Sensing, 2022. **14**(22): p. 5660.
26. Wang, C., et al., *CartoAgent: a multimodal large language model-powered multi-agent cartographic framework for map style transfer and evaluation*. International Journal of Geographical Information Science, 2025: p. 1-34.
27. Gnanappazham, L., K.A. Prasad, and V. Dadhwal, *Geospatial tools for mapping and monitoring coastal mangroves*, in *Mangroves: Ecology, Biodiversity and Management*. 2021, Springer. p. 475-551.
28. Chen, C., J. Judge, and D. Hulse, *PyLUSAT: An open-source Python toolkit for GIS-based land use suitability analysis*. Environmental Modelling & Software, 2022. **151**: p. 105362.
29. Chen, G., et al., *GeoJSEval: an automated evaluation framework for large language models on JavaScript-based geospatial computation and visualization code generation*. ISPRS International Journal of Geo-Information, 2025. **14**(10): p. 382.
30. Kumar, N., et al., *Open-source satellite data and GIS for land resource mapping*, in *Geospatial Technologies in Land Resources Mapping, Monitoring and Management*. 2018, Springer. p. 185-200.
31. Girgin, S., J. Gohil, and I. Mydur, *A streamlined GIS interface for Citizen Science activities: QGIS Light*. The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, 2025. **48**: p. 127-134.



32. Szemán, I., *Comparison of the most popular open-source GIS software in the field of landscape ecology*. Acta Geographica Debrecina Landscape & Environment series, 2012. **6**(2): p. 76-92.
33. Sui, D., *Opportunities and impediments for open GIS*. Transactions in GIS, 2014. **18**(1): p. 1-24.
34. Mason, B.C. and S. Dragicevic, *Web GIS and knowledge management systems: An integrated design for collaborative community planning*, in *Collaborative geographic information systems*. 2006, IGI Global Scientific Publishing. p. 263-284.
35. Ahmad, M., *Mapping for Good: Harnessing OpenStreetMap for Corporate Philanthropy*, in *Navigating Business Through Essential Sustainable Strategies*. 2025, IGI Global. p. 279-302.
36. Lemenkova, P., *SAGA GIS for computing multispectral vegetation indices by Landsat TM for mapping vegetation greenness*. Contemporary Agriculture, 2021. **70**(1-2): p. 67-75.
37. Abernathy, D.R., *The next layer: Towards open pedagogy in geospatial education*. Transactions in GIS, 2023. **27**(5): p. 1467-1478.
38. Hazra, S., K.S. Bora, and P.A. Singh, *Mapping World: A Comparative Analysis of Functionality and Usability between QGIS and ArcGIS*. Recent Advances in Computer Science and Communications, 2025. **18**(4): p. E26662558332529.
39. Alamri, S., *The geospatial crowd: emerging trends and challenges in crowdsourced spatial analytics*. ISPRS International Journal of Geo-Information, 2024. **13**(6): p. 168.
40. Alam, M.M., L. Torgo, and A. Bifet, *A survey on spatio-temporal data analytics systems*. ACM Computing Surveys, 2022. **54**(10s): p. 1-38.
41. Lemenkova, P., *Machine Learning Algorithms of Remote Sensing Data Processing for Mapping Changes in Land Cover Types over Central Apennines, Italy*. Journal of Imaging, 2025. **11**(5): p. 153.
42. Pettit, C., et al., *Open access, open source and cloud computing: a glimpse into the future of GIS*. Handbook of Planning Support Science, 2020: p. 56-71.
43. Li, W., M. Batty, and M.F. Goodchild, *Real-time GIS for smart cities*. 2020, Taylor & Francis. p. 311-324.
44. Bermudez, L., *New frontiers on open standards for geo-spatial science*. Geo-spatial information science, 2017. **20**(2): p. 126-133.
45. Jelokhani-Niaraki, M., *Collaborative spatial multicriteria evaluation: A review and directions for future research*. International Journal of Geographical Information Science, 2021. **35**(1): p. 9-42.



46. Malakar, K.D. and S. Roy, *GIS for All: Challenges and Future Directions*, in *Mapping Geospatial Citizenship: The Power of Participatory GIS*. 2024, Springer. p. 73-85.
47. Coetzee, S., et al., *Open geospatial software and data: A review of the current state and a perspective into the future*. ISPRS International Journal of Geo-Information, 2020. **9**(2): p. 90.

