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Teaching geography with GIS: a systematic review, 2010-2024

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Abstract. This systematic review synthesizes research on teaching geography with Geographic Information Systems (GIS) published between 2010 and 2024. Based on an analysis of 257 papers spanning all educational levels and diverse national contexts, six key themes emerged: (1) integration of GIS in geography curricula; (2) teacher training and professional development; (3) impact on student learning; (4) pedagogical approaches and strategies; (5) challenges and barriers to implementation; and (6) advances in GIS technologies. The literature provides robust evidence that learning with GIS when implemented with appropriate pedagogical framing, supports the development of students' geographic knowledge, spatial thinking abilities, inquiry skills, and problem-solving capabilities. However, the extent and depth of GIS integration in classrooms remain uneven due in large part to pervasive issues related to teacher preparation, technical support, and curricular positioning. The proliferation of web-based platforms, open-source software, and mobile applications in recent years has dramatically expanded access to GIS and opened up new possibilities for student-centred, data-driven, inquiry-oriented learning. Newer research also critically examines issues of representation, power, and ethics inherent in GIS-based knowledge production and considers how GIS can be leveraged to support education for sustainable development. Realizing the full potential of GIS in geography education will require sustained efforts to build teacher capacity, develop exemplary curricular materials and assessments, and critically engage with the affordances and constraints of emerging geospatial tools and datasets.

Keywords: geographic information systems (GIS), geography education, spatial thinking, teacher training, educational technology, systematic review

1. Introduction

Geographic Information Systems (GIS) have transformed the landscape of geography education over the past several decades. By enabling the interactive visualization, analysis, and interpretation of a wide array of geospatial data, GIS offers powerful means for students to investigate real-world problems, develop critical spatial thinking skills, and engage in authentic scientific inquiry and knowledge creation [29, 45, 66]. The integration of geospatial technologies into geography classrooms has been driven by concurrent advancements in computing and internet infrastructure, dramatic growth in the availability and accessibility of geodata from governmental and non-governmental providers, the development of more user-friendly web-based and mobile GIS platforms, and increasing recognition of the importance of spatial thinking across the curriculum [38, 68].

This systematic review synthesizes research on teaching and learning with GIS in formal geography education at the primary, secondary, and tertiary levels published between 2010 and 2024. This 15-year period saw significant developments in web-GIS

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platforms, open-source desktop software, mobile applications, and data availability that collectively reshaped the landscape of GIS education [3, 7, 8, 24]. Advances in the interface of GIS with other technologies like virtual and augmented reality, 3D representations, and location-based gaming have fostered novel and immersive learning experiences [15, 53, 63]. At the same time, many of the fundamental challenges of meaningfully integrating GIS in geography teaching and learning – from limited teacher preparation to technical and pedagogical barriers – have endured [34, 37].

By critically analyzing the state of research across diverse educational contexts, this review aims to identify effective strategies and approaches, persistent issues and challenges, and promising trajectories for leveraging GIS to support powerful geography teaching and learning. In contrast to prior reviews focused more narrowly on particular GIS technologies, pedagogies, or implementations in specific courses or student populations, the present synthesis takes a relatively broad view in order to surface key themes, patterns, and trends characterizing the broader landscape of GIS integration in geography education as represented in the contemporary research literature. The overarching goal is to provide an up-to-date, evidence-based foundation for geography educators, curriculum developers, and researchers to build upon in their individual and collective efforts to harness the pedagogical affordances of GIS for geography education.

2. Methods

The methodology for this systematic review followed the PRISMA framework [58]. The Dimensions academic search platform, which indexes over 128 million research publications across multiple databases, was searched on December 2, 2024 using the query string: ("Geographic Information System*" OR "GIS" OR geospatial OR geoinformation) AND (educat* OR teach* OR learn*) AND geograph*. The search was limited to the publication years 2010 to 2024 (inclusive) and publications classified as articles or book chapters written in the English language.

The initial database search yielded 1,486 results. The author screened publication titles and abstracts to identify empirical or conceptual papers that substantively addressed the use of GIS for teaching and learning in formal geography education from primary grades through undergraduate tertiary levels. Exclusion criteria included papers that only mentioned GIS tangentially, focused primarily on technical or methodological aspects of GIS unrelated to education or described applications of GIS exclusively in informal or non-geography educational contexts. The full texts of the 459 papers that passed the initial screening were then retrieved through Research4Life for further evaluation.

Based on a thorough review of full-text publications, 257 articles and chapters met the criteria for inclusion in the final qualitative synthesis. For each included publication, key information was systematically extracted and recorded in a spreadsheet database. Extracted details included full citation, publication venue, study location and educational context (e.g. country, grade level), stated research questions or objectives, methodological approach (e.g. research design, data collection and analysis methods), specific geospatial technologies used (e.g. desktop, web-based, mobile GIS), pedagogical strategies, and major findings or conceptual arguments. Iterative thematic analysis grounded in an inductive approach [12] was used to identify recurrent patterns and salient categories that captured core aspects of teaching and learning geography with GIS reflected across the corpus of reviewed literature.

Figure 1 summarizes the literature search, screening, and inclusion process using a PRISMA flow diagram [58].

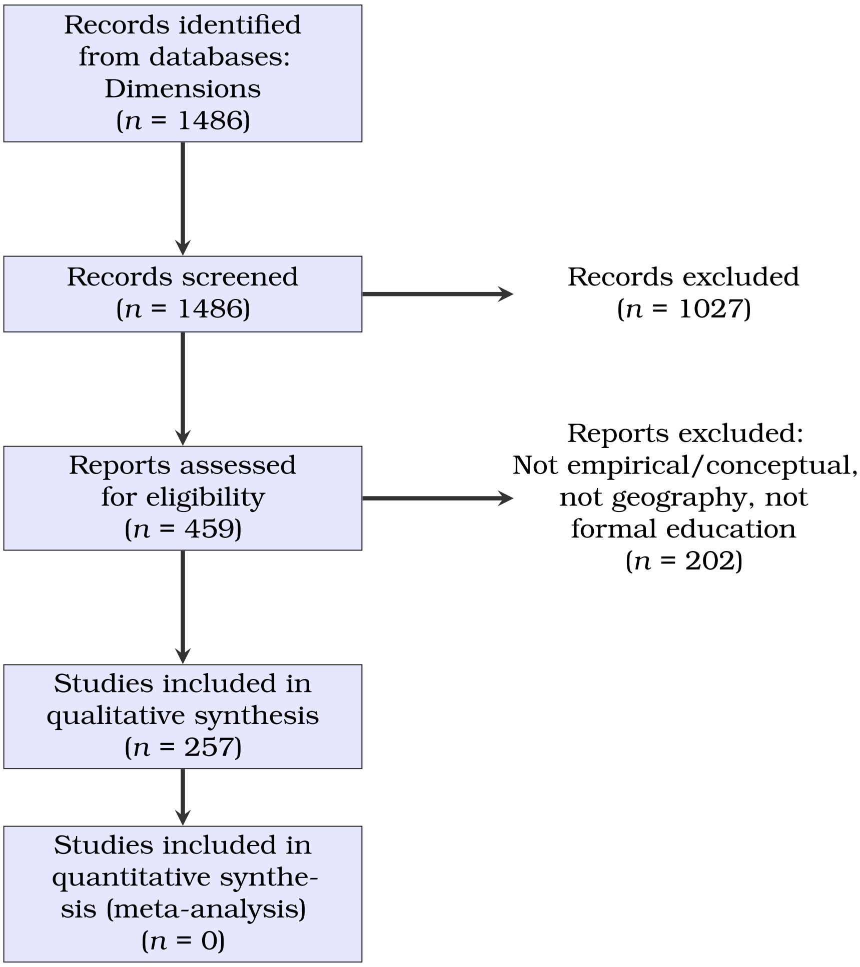

Figure 1: PRISMA flowchart of the literature search, screening, and inclusion process.

3. Results and discussion

Six overarching and inter-related themes were constructed through the qualitative synthesis process to capture core aspects of teaching geography with GIS reflected in the contemporary research literature (figure 2): (1) integration of GIS in geography curricula; (2) teacher education and professional development; (3) impacts on student learning outcomes; (4) dominant pedagogical approaches and strategies; (5) challenges and barriers to implementation; and (6) influences of advances in GIS technologies. The sections below summarize and discuss key findings in each of these thematic areas, providing linkages to supporting evidence from the set of publications reviewed.

3.1. Integration of GIS in geography curricula

The body of literature published between 2010 and 2024 documents expanded efforts to incorporate geospatial technologies into formal geography curricula across all grade levels and in a diverse array of national and subnational contexts spanning six continents. In primary and secondary education, countries as varied as Australia [48], Finland [75], India [35], Indonesia [4], Rwanda [1], South Africa [13, 26, 32], Turkey [20], and the United States [37, 44] have integrated GIS technologies and geospatial thinking approaches, to at least some extent, in their national or provincial curriculum standards and frameworks. However, the review also reveals considerable variation in how GIS is positioned within curricula from place to place, ranging from being a mandatory, assessed component to an encouraged but optional enhancement largely dependent on school priorities and individual teacher interest [6, 75]. For

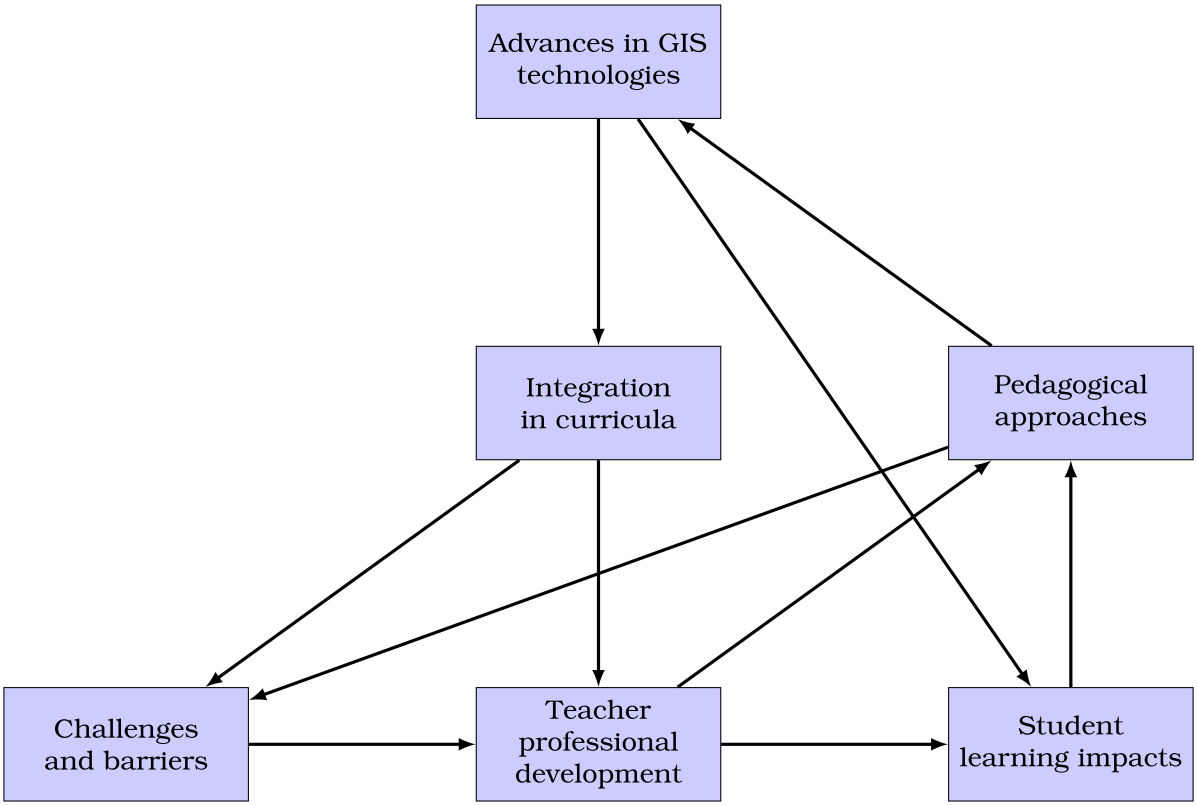

Figure 2: Conceptual diagram of the six major themes in teaching geography with GIS.

example, GIS was incorporated into the secondary geography curriculum in Singapore in 1998 and is now compulsory and examined as part of the subject [81]. In contrast, the integration of GIS in the national curriculum of England has been more episodic and tenuous; it featured most prominently in the late 2000s but appears to have waned in emphasis in subsequent curriculum revisions [28]. The devolved nature of educational governance in countries such as Australia, Canada, and the United States has resulted in an uneven landscape of GIS presence in curricula across states and provinces [59].

At the level of higher education, GIS is now thoroughly embedded in undergraduate and graduate geography degree programs, both in the form of standalone courses and as a methodological approach that cuts across much of the curriculum [72, 79]. The growth of GIS in academic geography has been driven in part by a desire to equip students with cutting-edge technological skills seen as enhancing employability in an expanding geospatial sector [5, 65, 73]. Moreover, the evolution of more user-friendly web-based GIS platforms has enabled the incorporation of geospatial analysis into a broader range of human geography and human-environment courses and research, going beyond a previous tendency to limit GIS training to more technically oriented subfields [25, 36]. The modalities of GIS course offerings vary across institutions, with a mix of geography departments hosting their own GIS courses, cross-listing courses with other academic units such as environmental science or engineering, and outsourcing instruction to dedicated geospatial science or technology programs [10].

Within the geography teacher preparation, equipping pre-service educators to make effective use of geospatial technologies in their future secondary and even primary classrooms has emerged as an important priority and focus of research [37, 39, 67]. The challenges of preparing new teachers to teach with GIS are compounded by the inconsistent presence of geospatial technologies in the curriculums of many teacher education programs [21, 37]. Even programs that include a dedicated course on GIS in geography education find it difficult to provide adequate depth given the limited instructional time and credit hours available [39]. Consequently, research suggests new geography teachers often enter the profession feeling underprepared to design and deliver meaningful GIS-enhanced lessons and learning activities, which in turn constrains the adoption and effective use of these tools in primary and secondary classrooms [41].

3.2. Teacher professional development

Closely related to the issues around pre-service teacher education with respect to GIS is the overriding importance of providing in-service teachers with ongoing, high-quality professional development opportunities. The review indicates that even in jurisdictional contexts where the use of GIS is explicitly encouraged or expected in geography curriculum standards, the actual extent and nature of classroom implementation is heavily mediated by teachers' readiness in terms of their relevant technological, pedagogical, and content knowledge (TPACK) [23, 76]. Consequently, building the capacity of current teachers to make effective use of geospatial technologies through professional development is crucial to realizing the potential benefits for student learning [20, 74].

The literature from 2010-2024 highlights two primary models or approaches to GIS-focused teacher professional learning: short-term university-led workshops and more sustained, institutionally-supported training programs. At the most basic level, many geography departments and geospatial centres have hosted short workshops for local teachers, often in partnership with GIS software vendors [43, 71]. These workshops typically focus on developing some level of familiarity with GIS software. They may cover basic geographic and cartographic concepts. However, given their limited duration (usually no more than a few days), there is rarely sufficient time to deeply explore subject-specific pedagogical strategies and lesson development [83]. Examples of such one-off trainings have been reported in diverse contexts, including Belgium [83], Italy [64], Rwanda [1], Turkey [20], and several states in the US [8], often with funding from government or donor-supported educational initiatives. Follow-up studies suggest that while these brief introductory experiences may stimulate teachers' interest in GIS and equip them with some new skills, the transition to regularly incorporating geospatial tools and pedagogy in the classroom is far from automatic [1, 20, 40].

The second model – sustained, multi-pronged teacher professional development initiatives typically created through strategic institutional partnerships – is less commonly reported in the literature but appears to hold greater promise for meaningfully and lastingly shifting the landscape of GIS integration [17]. One notable example is the GeoCapabilities project, a multi-year collaboration between universities, schools, and curriculum authorities in the United Kingdom, United States, and several European countries focused on building teachers' capacity to enhance students' powerful geographical knowledge via GIS [27, 28]. A core premise of the project is that realizing the educational potential of GIS in geography requires competent and creative teachers who can harness these tools in the service of clearly articulated curriculum goals. Participating teachers engaged in intensive face-to-face and online training, collaboratively designed and implemented classroom modules leveraging GIS to develop key geographic concepts and spatial thinking skills, and shared their experiences through conferences and workshops. Another exemplar is the multi-year HEAT (Harnessing Emergent Geospatial Technologies) program, which provided training and support for Japanese high school teachers to design and conduct GIS-based lessons [62]. Such collaborative initiatives, while demanding significant resources and coordination, show promise for promoting pedagogically robust uses of GIS by teachers.

3.3. Impacts on student learning

Many studies addressed the key question of the extent to which GIS supports or enhances student learning in geography. The available evidence, drawn primarily from classroom-based research at the secondary and undergraduate levels, indicates that the use of GIS can positively impact several dimensions of geographic understanding and skills.

First, multiple studies demonstrated gains in students' spatial thinking abilities as a result of working with GIS [42, 52, 54]. Through manipulating, analyzing, and visualizing geospatial data, students develop more sophisticated mental models of space and place [13, 14, 52]. Learning to think spatially with GIS also supports reasoning about geographic relationships, such as the connections between physical and human systems. However, realizing these benefits requires well-designed instructional activities that make the spatial concepts and practices explicit [18].

Second, research provides evidence that GIS contributes to students' understanding of geographic content knowledge. Across a range of topics – from geology to population geography to natural hazards – the use of GIS has been shown to deepen students' grasp of core concepts and processes. The dynamic nature of GIS enables students to explore patterns, visualize relationships, and test hypotheses in ways that promote conceptual change. Case studies also highlight how integrating GIS analysis into physical and human geography courses can reveal the explanatory power of a geographic perspective [80].

A third strand of research examined the effects of learning with GIS on the development of geographic inquiry and problem-solving skills. Consistent with a growing emphasis in geography education on the student-driven investigation of real-world issues, GIS offers tools to support questioning, data gathering and analysis, and communication of evidence-based arguments [18, 29]. Scaffolded project-based learning with GIS has been found to enhance students' abilities to ask geographic questions, critically evaluate information, and construct knowledge through open-ended exploration [47, 82]. In the context of undergraduate geography research experiences, GIS allows students to conduct authentic spatial analysis and contribute to knowledge-building in the discipline.

Cutting across these lines of evidence are indications that effective learning with GIS hinges on appropriate pedagogical approaches. Simply providing access to the technology does not ensure meaningful engagement or conceptual understanding; indeed, if poorly implemented, GIS can become a distraction or impediment to learning [3]. The benefits for spatial thinking, content knowledge, and inquiry skills are most clearly demonstrated when GIS is integrated into student-centred, problem-based instructional designs aligned with learning goals in geography [29, 38].

3.4. Pedagogical approaches and strategies

The reviewed literature highlighted a range of pedagogical strategies for teaching with GIS, which can be categorized into five main approaches: (1) GIS as content in standalone courses; (2) GIS as a tool integrated across the curriculum; (3) GIS for problem- and project-based learning; (4) GIS for student research experiences; and (5) GIS for inter-disciplinary inquiry.

The most prevalent model at the undergraduate level remains the standalone GIS course, where students learn the concepts and techniques of spatial analysis as the primary focus [68, 72]. While valuable for building geospatial competencies, such courses can disconnect GIS from its applications in answering geographic questions if not closely coordinated with other parts of the curriculum [10]. An alternative approach is to incorporate GIS across multiple courses as a tool for geographic analysis [68]. This requires instructors of diverse regional and systematic geography courses to possess TPACK – technological, pedagogical, and content knowledge – for designing effective GIS-based lessons [34].

In both secondary and tertiary contexts, uses of GIS that engage students in problem-solving and creating new knowledge, rather than just skill acquisition, appear to hold the greatest educational potential [29, 38, 57]. Problem- and project-based learning with GIS can encompass case studies of geographic issues [22], inquiry into questions generated by students [18], and service-learning addressing community needs. Integrating fieldwork, where students collect data with mobile technologies for subsequent GIS analysis, can make projects more place-based and personally relevant [19, 38]. Research experiences that leverage GIS range from course-embedded projects to summer research assistantships to thesis and dissertation work [43].

The interdisciplinary capabilities of GIS, in conjunction with trends toward problem-focused and integrative learning in higher education, opens opportunities for linking geography with allied fields. Blending spatial analysis with methods and perspectives from other disciplines can enhance students' understanding of complex issues and better prepare them for real-world applications. Examples of interdisciplinary teaching with GIS include having geography students collaborate with peers in engineering on geodesign problems [70], examining spatial dimensions of environmental injustice with sociology students [31], and integrating geographic and historical thinking using historical GIS [49, 55]. Notable in the more recent literature was attention to how GIS can support education for sustainable development by engaging students in the examination of social-ecological challenges and potential solutions [2, 77].

3.5. Challenges and barriers to implementation

Despite significant growth in the availability and use of GIS in geography education over recent decades, the literature also reveals persistent challenges and barriers to implementation. The most frequently cited obstacles can be grouped into four categories: technological, pedagogical, curricular, and institutional.

Technological barriers refer to the hardware, software, and data required to use GIS in classrooms. While the widespread availability of web-based platforms like ArcGIS Online and open-source desktop programs like QGIS have dramatically lowered the entry barrier, schools in many parts of the world still lack adequate computing infrastructure and internet connectivity to support GIS instruction [20, 32, 50]. Data access, particularly to high-quality localized datasets, remains a constraint even in well-resourced contexts [3, 38]. Moreover, the rapid pace of software development and changing license terms create challenges for keeping school computer labs and curricula up to date [20].

Pedagogical barriers centre on limitations in teachers' knowledge, skills, and confidence in teaching with GIS. Across educational levels and countries, lack of teacher preparation emerges as a major impediment to effective GIS integration [32, 37]. Many teachers struggle not only with the technological aspects of GIS but more fundamentally with how to teach geographic concepts and practices using these tools [23, 34]. Developing teachers' capacity to harness the affordances of GIS for student-centred, inquiry-oriented learning requires sustained professional development and support [33].

At the curricular level, the place of GIS within geography standards and frameworks is often unclear or inconsistent [38]. Without a strong positioning of spatial analysis and other geospatial practices in curriculum documents, the use of GIS can seem disconnected from core learning goals [28]. This is exacerbated by high-stakes testing regimes which limit time for open-ended technology-supported inquiries. The constantly evolving nature of geospatial data and tools also poses difficulties for developing stable curricular materials [40].

Institutional barriers encompass a range of organizational, cultural, and policy-related factors that shape the uptake of GIS. Departmental sharing norms, resources for acquiring hardware and software, technical and pedagogical support staff, and administrative buy-in all influence the extent to which GIS becomes embedded in geography programs [16]. Relatedly, disciplinary divisions between human and physical geography at the university level can hinder the spread of GIS training and limit opportunities for applied, integrative projects at the undergraduate level [25].

While the specific manifestations of these challenges differ across contexts, they point to the need for coordinated strategies at multiple levels – technological, pedagogical, curricular, and institutional – to support the meaningful integration of GIS in geography education. Overcoming barriers requires more than just making the tools available; it demands fundamental shifts in curriculum design, instructional practices, and the culture of the discipline itself.

3.6. Advances in GIS technologies

As a technology-dependent teaching and learning medium, geography education with GIS is profoundly shaped by the rapid pace of change in the development of hardware, software, and data sources. The literature over the 2010 to 2024 period documented significant shifts in the modes and affordances of GIS that altered the landscape of classroom implementation.

Early in the period, the dominant paradigm was desktop GIS software running locally on personal computers. The relatively high cost and complexity of commercial platforms like ArcGIS Desktop, as well as hardware requirements, created barriers to adoption in schools and restricted use to specialized lab settings [20, 78]. The emergence of more user-friendly and web-based options opened new possibilities. ArcGIS Online, launched in 2012, marked a significant transition to cloud-based mapping and analysis that could be accessed from any computer or mobile device with an internet connection [3, 46]. Open-source alternatives to proprietary software, most notably QGIS, also matured considerably in their functionality and ease of use while eliminating software license costs [9, 69]. These developments have dramatically expanded access to GIS in educational settings around the world.

Mobile GIS represented another key advancement with implications for geography teaching and learning. Widespread student ownership of smartphones and tablets, coupled with the development of GIS apps and mobile data collection tools, enables fieldwork to be integrated with subsequent geospatial analysis more readily [38]. Students can now collect geotagged notes, photos, and sensor measurements in the field and synthesize their observations with other spatial datasets using GIS (figure 3). Mobile augmented reality platforms like Esri's AuGeo offer opportunities for immersive, place-based learning as well [63].

Web GIS platforms have evolved to include not only basic mapping and query functions but also capabilities for spatial analysis, 3D scene creation, and app development that previously required desktop software expertise [7, 30]. Story maps (figure 4), interactive web apps that combine maps, narrative text, and multimedia, have become a popular medium for students to communicate the results of GIS projects to public audiences [24, 66]. The ability to readily publish and share GIS work on the web fosters greater interaction between the classroom and community. At the same time, the growing ease of generating polished digital map products raises issues of credibility, quality, and reflexivity that educators must grapple with [61].

Beyond shifts in software and hardware, important changes have occurred in spatial data creation, access, and integration over the past decade. Increasing volumes of high-resolution remote sensing imagery, real-time sensor feeds, crowdsourced citizen science observations, and open government datasets have given educators and students a wealth of material to incorporate into GIS-based projects [28, 38]. The linked open data movement and semantic web standards have also enabled greater interoperability between GIS and other data sources [51]. Learning to find, assess, and synthesize spatial data from diverse sources is becoming an essential geographic competency.

Advances at the interface of GIS with other technologies are forging tools and approaches with considerable educational potential. Unmanned aerial vehicles (drones) equipped with GPS and cameras are being used to engage students in the production of high-resolution imagery and surface models of their local environments. The melding of GIS with game engines and virtual reality systems (figure 5) supports immersive role-play simulations for situated geographic learning [15, 63]. Machine learning and data mining of geocoded social media, although posing privacy concerns, can be harnessed to explore the geographies of everyday life [11, 56]. Innovations in tangible interfaces, such as 3D physical landscapes scanned into GIS, show promise for grounding abstract spatial concepts in embodied interactions [60]. While the

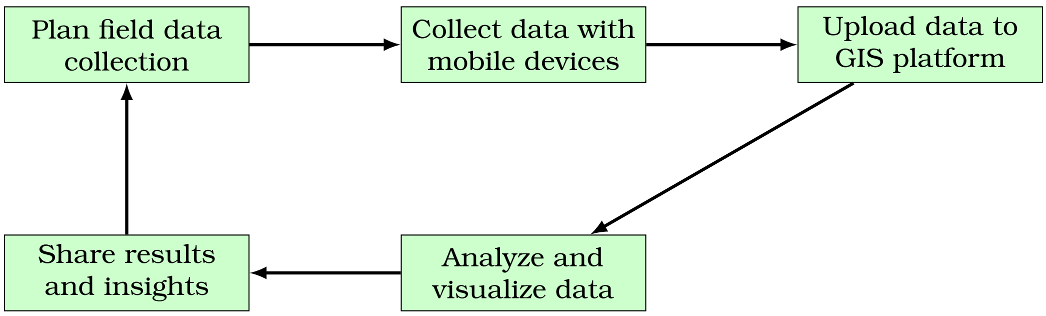

Figure 3: Workflow for mobile data collection in geography fieldwork.

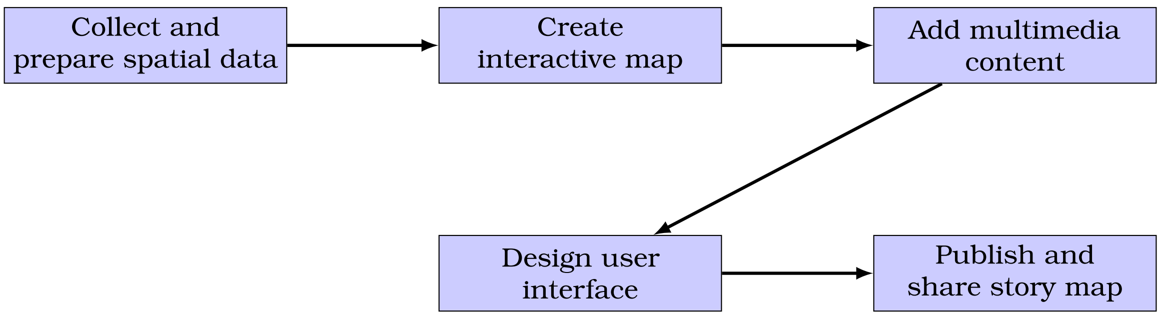

Figure 4: Workflow for creating story maps in geography education.

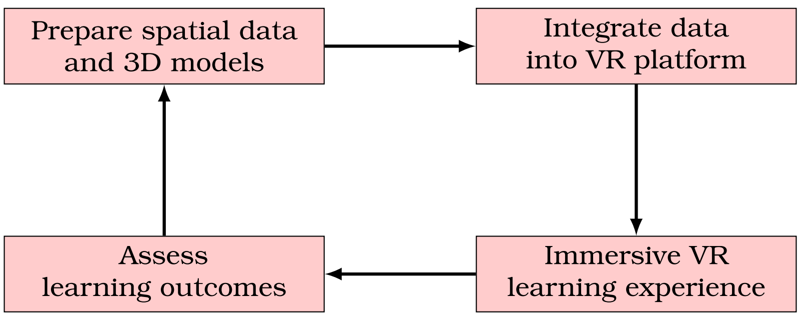

Figure 5: Workflow for integrating GIS with virtual reality in geography education.

educational efficacy of these emerging geo-enabled technologies is still being studied, they point to a broadening array of modalities through which students can engage in geographic inquiry using GIS.

4. Conclusion

This systematic review has demonstrated the significant growth and evolution of GIS in geography education between 2010 and 2024. The synthesis of research across diverse educational contexts reveals that learning with GIS when implemented with appropriate pedagogical support, can enhance students' spatial thinking skills, geographic content knowledge, problem-solving abilities, and engagement with the discipline. However, the review also highlights persistent challenges related to teacher preparation, technological infrastructure, and curricular integration that need to be addressed to realize the full potential of GIS in geography classrooms.

Table 1 summarizes key gaps in the current research landscape and promising directions for future studies to advance understanding of effective GIS integration. Priority areas include longitudinal investigations of teacher professional development outcomes, comparative studies of student learning with GIS versus traditional meth-

Table 1
Gaps and opportunities for future research in teaching geography with GIS.

Research gap	Opportunities for future research
Teacher professional development	- Longitudinal studies on the impact of professional development on teacher practices and student outcomes - Comparative studies of different professional development models (workshops, online, hybrid) - Investigations of how teachers develop TPACK for GIS integration
Student learning outcomes	- Experimental designs comparing GIS-based and traditional instruction - Studies across diverse student populations and geographic contexts - Assessment of spatial thinking skills and problem-solving abilities
Pedagogical strategies	- Design-based research on the effectiveness of different GIS-based instructional approaches - Qualitative studies of student experiences and perceptions - Exploration of project-based, interdisciplinary, and community-engaged learning with GIS
Technological innovations	- Usability and learning impact studies of web GIS, mobile apps, and virtual/augmented reality - Integration of GIS with data science, citizen science, and digital humanities - Critical analyses of the social and ethical implications of emerging GIS tools and data
Long-term impacts	- Longitudinal tracking of student outcomes beyond a single course or grade level - Studies of how GIS learning influences career trajectories and civic engagement - Investigations of the role of GIS education in promoting workforce diversity in STEM

ods, design-based research on optimal pedagogical strategies, critical analyses of emerging technological innovations, and long-term impact studies that follow students into higher education and careers.

Addressing these research needs will require close collaboration among geography educators, GIS scholars, learning scientists, and educational policymakers. As GIS technologies and data continue to evolve rapidly, research must keep pace to inform evidence-based practices for preparing all students to think spatially and use geospatial tools for geographic inquiry and problem-solving. At the same time, scholars must also critically examine the social and political dimensions of GIS education, including issues of representation, ethics, equity, and power.

Geography education in the 21st century has the potential to cultivate the next generation of geospatial thinkers and changemakers. Realizing this potential will require sustained research and development efforts that creatively rethink the curriculum, pedagogy, and purposes of GIS-enabled geography learning for an increasingly complex and interconnected world. This systematic review provides a roadmap for future scholarship and practice at the dynamic intersection of geography education and geospatial technologies.

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