Digital Twins for Geospatial Decision-making

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Abstract:

Integrating digital twin (DT) technologies with Geographic Information Systems (GIS) marks a transformative shift in geospatial analysis, enabling continuous synchronization for an accurate representation of the physical landscape, offering decision-makers dynamic and context-specific insights for informed decision-making. Geospatial data, crucial across various domains, has historically faced challenges in integration, visualization, and interpretation due to its vast and fragmented nature. The emergence of the DT concept has the potential to address these constraints by creating virtual replicas of real-world objects in a digital environment. The seamless integration of DT technologies with existing GIS (integrated DT-GIS) enables multiple stakeholders to make collaborative decisions through interactive processes. This review aims to investigate the state of the art of the use of integrated DT-GIS across domains such as urban planning, disaster management, and water resource and environmental management, challenges that hinder the full potential of integrated DT-GIS, and some improvements that can be made to enhance the capabilities of integrated DT-GIS for geospatial analysis to enhance the decision-making process.

1. Introduction

Geospatial data plays a critical role in data-driven decision-making across many fields. It offers valuable insights into spatial relationships, patterns, and dynamics. From urban planning to environmental management, disaster response, and infrastructure development, the importance of geospatial information cannot be overstated. Interactive access, real-time representation, and interdisciplinary collaboration to geospatial data are essential for strategic planning and sustainable development. However, the vast and diverse nature of spatial data fragmented across sources, presents persistent challenges for decision-makers, researchers, and stakeholders alike, making it difficult for them to access, integrate, and interpret geospatial data and ultimately making it difficult to harness the full potential of geospatial data in various decision-making scenarios (J.-G. Lee & Kang, 2015; Li et al., 2021).

Traditional Geographic Information Systems (GIS) have been foundational in capturing, analyzing, and interpreting spatial data. However, these systems face inherent limitations, such as static representations and challenges adapting to dynamic, real-time scenarios, interactivity and simulation capabilities, and data integration complexities, making it difficult to access and utilize geospatial information seamlessly (“Web-Based Agricultural Infrastructure Digital Twin System Integrated with GIS and BIM Concepts,” 2023). Innovative solutions are being sought to overcome these constraints, leading to the emergence of the DT concept and related technologies as a transformative paradigm in geospatial analysis in the informed decision-making processes through integrating with existing GIS technologies.

A DT is a virtual counterpart of a physical, real-world object, system, or process. It replicates the physical entity in a digital environment, capturing its characteristics, behavior, and interactions in real-time (Semeraro et al., 2021; VanDerHorn & Mahadevan, 2021). Figure 1 represents a simple conceptual representation of a DT. Integrating DT technologies into GIS introduces a new segment in geospatial analysis, providing a dynamic, immersive, and contextualized approach beyond static mapping. Therefore, these attributes of this combined system offer comprehensive replicas of physical entities, enabling the provision of the incorporation of real-time sensor data from Internet of Things (IoT) devices and context-specific representations of the physical environment. This is particularly valuable in scenarios where live data is critical for decision-making (Bakhtiari et al., 2024; Deng et al., 2021; Gong et al., 2015). This ensures that geospatial data remains continuously synchronized, allowing for a more accurate and up-to-date representation of the physical space.

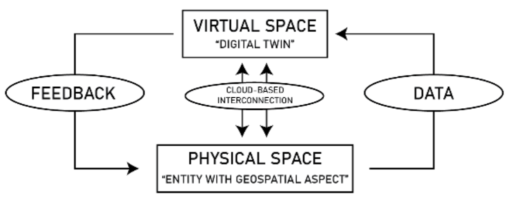

Figure 1. Simple conceptual representation of DT

Furthermore, integrated DT-GIS enables sophisticated spatial modeling and 3D visualization and simulation capabilities, providing a refined understanding of complex spatial dynamics (Chen et al., 2023a; D. Park & You, 2023). Predictive analytics, another strength of DTs, can be integrated with GIS to model future scenarios based on historical and real-time data, aiding in anticipating spatial trends.

Presently, there is a growing momentum in adopting integrated DT-GIS across diverse domains primarily based on geospatial data, including but not limited to urban planning, disaster response, infrastructure development, water resources, and environmental management, among others. Deploying DT technologies to enhance geospatial analysis can streamline processes, improve understanding, and support informed decision-making processes.

Despite these promising technological advancements, there is still a long way to go to take advantage of the immense potential of the DT concept due to some challenges in integrated DT-GIS. Addressing these challenges will eventually make wider use of these integrated systems for different scenario analyses in many domains. Application of this integration can help improve decision-making, enhance operational efficiency, and reduce costs. Overall, the future of geospatial analysis looks promising with the integrated DT-GIS.

This study aimed to investigate the multifaceted applicative potential of integrated DT-GIS in various geospatial domains by providing a concise overview of the state-of-the-art of integrated DT-GIS applications and investigating how they contribute to the informed decision-making process. Collective significant challenges faced by these systems are emphasized, with future directions for more robust integration. This study ultimately serves as a valuable resource for students, academics, researchers, and legislators seeking the latest developments in the geospatial DT landscape. The rest of the article is structured as follows: Section 2 introduces the methodology; Sections 3 and 4 present results and discussion, respectively. A conclusion follows this in Section 5.

2. Methodology

To accomplish the objective of the study, the first step was to select the major domains that integrate DTs for geospatial analysis and informed decision-making. Therefore, urban planning and smart cities, disaster management, and water resource and environmental management were selected as the emerging domains in the field of geospatial analysis, which are integrated with DTs for effective decision-making processes.

The paper followed a systematic approach to realize a well-organized list of publications to identify current challenges and future directions for integrated DT-GIS in selected geospatial domains. The search for publications was carried out in the Scopus database. A manageable number of papers was retrieved by applying different search string combinations as described in the following text.

For this search, a three-field keyword process was used. The first keyword string (Q1), *'digital twin'* was used for the first field. For the second search field, the following keyword string (Q2) was added *(framework OR platform OR "web-based")* to filter out web-based platforms or frameworks, as collaborative decision-making is one of the focus areas. The more easily accessible the system is, the better for more collaborative decision making. These two search terms were fixed for all searches carried out for separate geospatial domains. For the third search field, domain-specific keywords were used.

Q3.1 - *("water resources" OR environmental OR "groundwater" OR watershed OR catchment OR "water quality" OR "climate change")*
Q3.2 - *(disaster OR flooding OR earthquake OR storm OR "extreme weather" OR droughts)*
Q3.3 - *("urban planning" OR "smart city")*

Finally, three sets of search strings were performed (Table 1) to identify relevant literature. The initial search resulted in 311 articles. It is important to note that there may be missed articles within this search result which serve same purpose but without specifically including the keyword "digital twin".

After examining the paper title, abstract, and keywords (for only original research articles – inclusion criteria), 50 articles were collected, and four duplicates were eliminated. At the end of the first stage, 46 articles were carried out for further analysis.

#	Search query	No of articles
1	Q1 AND Q2 AND Q3.1	n = 167
2	Q1 AND Q2 AND Q3.2	n = 42
3	Q1 AND Q2 AND Q3.3	n = 102
	Total	n = 311

Table 1. List of search queries performed in the Scopus database for three pre-identified geospatial domains.

The inclusion and exclusion criteria were applied to select articles for full-text review in the next step. This study employed specific inclusion criteria, such as focusing on studies that covered a large geographic area (e.g., urban scale, watershed/catchment, or a city) and incorporating a good number of geospatial data sources. Additionally, papers that provide detailed information about the DT framework, model, or platform were prioritized. The exclusion criteria were access to the full paper, the language of the content, and the type of the article. Articles without access to download the full paper and published in languages other than English were excluded. Material other than original research articles was also excluded. After applying these criteria, 19 articles were taken forward for full-text analysis.

3. Results

3.1 Overview of the section

The results and discussion of this academic paper highlight the versatile application of integrated DT-GIS across a spectrum of disciplines crucially reliant on geospatial data. Specifically, this section presents an investigation into the current state of integration of DTs to enhance the decision-making processes in various disciplines for managing diverse geospatial datasets. The advancements in integrated DT-GIS have demonstrated significant potential, but persistent challenges must be overcome to create effective DT models for effective geospatial analysis. The discussion covers the current state of integrated DT-GIS, the challenges associated with the current implementations, and the future directions for implementing better models/ frameworks for geospatial analysis for decision-making processes.

3.2 State of the art of DTs for geospatial data management

In this section, the investigation into the state-of-the-art usage of integrated DT-GIS and how they are being employed to improve decision-making processes across pre-selected domains (urban planning and smart cities, water resources and environmental management, and disaster management) for analyzing diverse geospatial datasets were presented. Overall, the results highlight the potential of integrated DT-GIS to transform the selected domains by offering a consolidated approach to analyze and visualize geospatial data, which enhances decision-making processes.

3.2.1 Sustainable urban planning and smart cities: Integrated DT-GIS have transformed urban planning, offering decision-makers the capability for simulative and predictive analyses based on real-time monitoring (via IoT devices) and visualizations of urban data, leading to provide better feedback to decision-making processes (Nica et al., 2023; Weil et al., 2023). This technology facilitates dynamic adjustments to city systems, optimization of local mobility (Rathore et al., 2018), and strategic enhancements to urban green and blue areas, all guided by insights derived from analytical and simulation data.

Furthermore, integrated DT-GIS play a pivotal role in cost-efficient and effective decision-making, effectively managing the complexities associated with urbanization by assessing the impacts of proposed changes, planning new developments, and anticipating consequences (Liu et al., 2023). These benefits contribute to more sustainable and resilient urban environments and smart city development in various scenarios (Omrany et al., 2022; Pignatelli et al., 2023).

One study has shown these integrated platforms can be used in different data dissemination layers, such as the basic layer to provide basic information about the city, the 3d layer to visualize the urban and city 3D assets, the digital twin layer to integrate real-time data, and augmented layer to enhance the digital twin data for decision-making process (Dani et al., 2023). Some examples included a street network, a wind flow simulation to their platform, and implemented DT platform with VR support and presented to the general public through a diverse public participation process to enhance the public participation and collaboration process (Dembski et al., 2020).

Furthermore, another research group managed to develop an integrated DT-GIS platform to manage large-scale individual (vehicles and pedestrians) mobility data and route planning with the support of public closed-circuit television systems and the universal game engine Unity 3D (A. Lee et al., 2022). Another use of integrated DT-GIS for urban scale was presented as a platform for real-time identification and simulation of fire development, which aids smart firefighting practices in fire-resilient smart cities (Zhang et al., 2022).

With a growing population, the stress on urban infrastructures is increasing continuously, and well-functioning infrastructures are the key to social, economic, and environmental development. Therefore, another research group managed to implement a platform to retrieve, store, and 3D visualization of urban infrastructure issues through citizens using their mobile devices (Supangkat et al., 2023), which ultimately helps for fast and effective decision-making. Climate change also has a significant effect on urban development due to various environmental concerns. (Truu et al., 2021) managed to develop a support system for reducing pluvial flood risks by linking land development (considering land use and soil type), urban drainage system, and other factors that contribute to the flood risk to evaluate the response of drainage and catchment for different rainfall events. Also, further integration of power, water, and telecommunication infrastructure to evaluate flood-caused failures was another approach to highlight the capabilities of integrated DT-GIS in the effective decision-making (Hofmeister et al., 2024).

Traffic optimization is another key benefit of using integrated DT-GIS for urban and smart city environments (Fujishima et al., 2023). (Xu et al., 2023) implemented a web-based platform to manage urban mobility. This platform aimed to reduce traffic congestion, incidents, and fuel consumption through real-time situation awareness, optimizing traffic signals, and traffic prediction and evaluation of transportation performance.

3.2.2 Effective disaster management: Integrated DT-GIS are transformative tools in disaster management, enhancing decision-making processes during crises by creating virtual duplicates of affected areas and integrating real-time data from sources like satellites and sensors. This technology provides emergency responders and decision-makers with a dynamic and detailed representation of disaster scenarios, allowing them to simulate response strategies, evaluate potential outcomes, and optimize resource allocation (Ford & Wolf, 2020). The interactive nature of integrated DT-GIS platforms enables the visualization via cutting-edge technologies of evolving situations, supporting quick and well-informed decision-making throughout crucial phases of disaster management (Bakhtiari et al., 2023; Josipovic & Viergutz, 2023). Furthermore, integrated DT-GIS platforms facilitate collaboration among diverse stakeholders, fostering a synchronized and effective response to mitigate the impact of disasters and enhance overall resilience.

Different use case scenarios of using integrated DT-GIS in disaster management were highlighted in various studies. One research group (Braik & Koliou, 2023a) explored how the integrated DT-GIS framework can be used in modeling and estimating the failures and performance states of the various elements of the electrical power network during and after hurricanes via real-time data from IoTs. This system was validated by real-world data and used in decision-making for resilience planning. Another study has shown how the DT concept can be used to enhance critical infrastructure resilience for a wide range of threats that can lead to major incidents (Brucherseifer et al., 2021; D. Yu & He, 2022).

Furthermore (Chioni et al., 2023) have worked on an integrated platform called "Territorial Digital Twins (TDTs), which demonstrates the uses of networking distributed information resources to enhance the resilience of communities in territorially imbalanced areas. Additionally (Ham & Kim, 2020) proposed an integrated framework to enhance risk-informed decision-making for infrastructure management by bringing crowd-sourced visual data into 3D virtual reality. This framework helped city decision-makers by analyzing associated potential risks in urban areas during extreme weather events.

Another group (Henriksen et al., 2023) studied the capabilities of Denmark's hydrological information and prediction model (HIP portal) in extreme weather events such as flooding and droughts. Another study explained the framework of landscape digital twin to establish a multi-disciplinary hazard overview platform considering natural hazards, infrastructure, and socio-economic factors with the aim of enhancing decision-making processes (Ugliotti et al., 2023). Additionally (S. Yu et al., 2023) developed a model to represent the data of different stages of earthquake disasters in a virtual space with simulation capabilities. This system can be used to enhance the safety of emergency rescue personnel and decision-making processes. This included real-time data monitoring of the earthquake development, analysis, and simulation through integrated DT-GIS.

3.2.3 Water Resource and Environmental Management: The integrated DT-GIS in water resource and environmental management empowers decision-makers with versatile and interactive tools that enable the visualization, simulation, and real-time analysis of geospatial data, facilitating informed decision-making to address the complexities of these highly dynamic water and environmental management applications.

Integrated DT-GIS platforms play a pivotal role in water resource management with different added advantages. (Chen et al., 2023a) developed a DT visualization framework to visualize real-time environmental sensing data for a lake via a multi-dimensional and multi-view platform, which allows the integration, management, and analysis of the lake data. Additionally, (Morlot et al., 2024) developed hydrological digital twin model to support with basin-wise adaptation policies and better water management practices due to rising human activities (changes in land use, construction of dams or reservoir, diversion of river).

Another group (Y. Qiu et al., 2023) proposed a novel DT framework for the lake to integrate, represent, and analyze multi-source monitoring data on harmful algal blooms due to climate change and the effect of eutrophication, so these results can be used to support decision-making on the prevention and control of harmful algae. (D. Park & You, 2023) developed a dam and watershed management platform based on the integrated DT-GIS framework to support multi-domain stakeholders with decision-making processes in smart water management practices and flood responses. This system is based on real-time data of rainfall, dam, and river water levels, flow rate, closed-circuit television (CCTV), and different simulation models for efficient dam operation for various rainfall events and extreme weather events. Furthermore (Y. Qiu et al., 2022) designed a web-based platform to represent real-time situations and excessive information on the watershed environment to support decision-making on watershed management.

In environmental management, integrated DT-GIS offer a comprehensive overview of ecosystems by collecting and integrating data from diverse sources like air quality, biodiversity, and land use (de Koning et al., 2023; J. Park et al., 2023). This integrated approach aids decision-makers in identifying environmental trends, evaluating the impact of human activities, and formulating strategies for conservation and restoration. The significant advantages of using integrated DT-GIS in these scenarios encompass holistic environmental monitoring (Y. Qiu et al., 2023), scenario analysis for sustainable practices (Morlot et al., 2024), optimized resource allocation (D. Park & You, 2023), ecosystem resilience planning (de Koning et al., 2023), community engagement, and education (Bakhtiari et al., 2024), and accurate environmental impact assessments (Tsakiridis et al., 2023).

Table 2 presents extracted integrated DT-GIS examples from selected articles in preselected geospatial domains. According to these studies, proper implementation of integrated DT-GIS for geospatial analysis offers significant benefits in a wide range of domains for better decision-making.

Citation	**Physical Space**	**Virtual Space**	**Application**
(Dani et al., 2023)	City	Smart City DT platform	Efficiently monitor urban conditions with real-time data
(Dembski et al., 2020)	Town	Prototype of urban DT	Smart city/ urban development
(A. Lee et al., 2022)	City (vehicles /pedestrians)	Geospatial/DT platform	Large-scale individual mobility data
(Zhang et al., 2022)	City (Buildings)	DT framework	Real-time fire detection and prediction
(Supangkat et al., 2023)	City	Digital geo twin-based platform	Smart city/ urban condition reporting
(Truu et al., 2021)	Urban areas	GIS platform	Urban pluvial flood risk management
(Xu et al., 2023)	City	Web-based DT platform	Optimizing urban transportation system
(Braik & Koliou, 2023b)	Electrical power network	DT framework	Infrastructure management in hurricanes
(Bruchersei fer et al., 2021)	City (Infrastructu res)	Conceptual DT framework	Enhance the resilience of infrastructure
(Chioni et al., 2023)	Mountain areas	DT framework	Disaster risk reduction in mountain areas
(Ham & Kim, 2020)	Urban areas	DT framework	Urban Infrastructure Risk Management
(Henriksen et al., 2023)	Country	DT for hydrology	Real-time risk information for extreme events
(Ugliotti et al., 2023)	Regions	DT framework	Multi-disciplinary and multi-scalar hazard overview
(S. Yu et al., 2023)	Urban areas	DT model	Earthquake disaster management
(Chen et al., 2023)	Lake	DT framework	Visualize real-time environmental data for a lake
(Morlot et al., 2024)	River basin	Hydrological DT model	Anthropized catchment water management
(Y. Qiu et al., 2023)	Lake	DT framework	Real-time monitoring of harmful algal blooms in lakes
(D. Park & You, 2023)	Watershed	DT framework	Real-time data monitoring for dam and watershed
(Y. Qiu et al., 2022)	Watershed	Web-based DT platform	Real-time watershed data monitoring

Table 2. Studies of DT framework developments/case studies related to urban planning, disaster management, and water resources and environmental management.

3.3 Common challenges to overcome in integrated DT-GIS

This study has comprehensively analyzed the current state of the art of integrated DT-GIS and how they are been used for better decision-making. The results revealed a growing trend in utilizing integrated DT-GIS for decision-making processes in recent years. As identified, the adoption of these integrated platforms for the decision-making process can offer unique advantages that contribute to the improvement of processes and outcomes. However, improving geospatial analysis capabilities in GIS through the integration of DT technologies faces several key challenges that need careful consideration in future developments (Weil et al., 2023).

The key challenges in the development of integrated DT-GIS for informed decision-making stem from critical data-related issues, including quality, volume, variety, security, privacy, and interoperability. The quality of data can be divided into further sub-issues such as consistency, accuracy, completeness, validity,

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and availability (Morlot et al., 2024; Xu et al., 2023). These sub-issues of data quality are pivotal for ensuring the reliability of insights derived from platforms and crucial for accurate decision support. Data for integrated DT-GIS platforms can be obtained through various means, including remote sensing, sensor data, crowdsourcing, expert knowledge, and GIS-related techniques. As a result, ensuring the high standard of data quality requires significant effort, given the diversity of data sources (Brucherseifer et al., 2021) and retrieval methodologies (Chioni et al., 2023). Data scarcity poses challenges in acquiring sufficient and diverse datasets essential for creating accurate and comprehensive digital representations. Limited data can hinder the fidelity and reliability of the integrated DT-GIS, potentially leading to incomplete or inaccurate insights. On the other hand, dealing with a large volume of data and diverse variety of data types introduces complexities related to storage, processing, and analysis (Botín-Sanabria et al., 2022; D. Park & You, 2023; Ugliotti et al., 2023). Efficient strategies are required to manage and make sense of extensive datasets, ensuring that the integrated DT-GIS can operate seamlessly and provide valuable real-time information. Balancing the trade-off between data scarcity and volume is crucial in optimizing integrated DT-GIS for effective decision support across various applications. Depending on the system, additional computing power may be required to run certain analyses and simulations and perform various tasks, which is another challenge for these integrated platforms (Sánchez-Vaquerizo, 2022; Shahat et al., 2021).

Additionally, ensuring the security and privacy of sensitive information (Ramu et al., 2022), along with addressing interoperability concerns, is imperative in the development and deployment of integrated DT-GIS. As most systems are served for multiple stakeholders, it is quite challenging to identify the role of data accessibility for each stakeholder, which makes a red alert for data misuse (Lei et al., 2023).

Besides the technical challenges of integrated DT-GIS, there are some non-technical challenges as well. These challenges include organizational resistance to change, digital literacy, and hesitation (Ramu et al., 2022; Shahat et al., 2021). There could be multiple reasons for these non-technical challenges, including lack of deep understanding among stakeholders (Morlot et al., 2024) about the potential of integrated DT-GIS, lack of trust in the results obtained, failure to include the necessity of using integrated DT-GIS in procedures, insufficient investment, lack of training and skills (de Ocaña et al., 2023). Effective communication, synergy, and collaboration among stakeholders including decision-makers, data scientists, team members, and end-users, are vital to ensure that everyone understands the benefits and functionalities of the DT (Ariyachandra & Wedawatta, 2023; Lei et al., 2023; Waqar et al., 2023).

Further down in the road, there is a fundamental conceptual concern to consider, which is, the attributes of a true DT. A true DT enables automatic bidirectional data flow, achieving full integration between the digital and physical counterparts. Most of the reviewed integrated DT-GIS on this paper, lack this complete integration, and therefore, they are more accurately termed as digital shadows (Attaran et al., 2023), as they fall short of the essential attribute of a comprehensive true nature of the DT.

Addressing these multifaceted challenges is essential to unlock the full potential of DTs in facilitating well-defined, informed decision-making processes in various applications.

4. Discussion

The future directions for improving integrated DT-GIS for geospatial analysis involve addressing both technical and non-technical challenges mentioned in the previous section. Some potential areas for improvement are discussed in below text.

A deeper integration of emerging technologies such as Artificial Intelligence (AI), Machine Learning (ML) to enable predictive analytics and pattern recognition, Augmented Reality (AR) and Virtual Reality (VR) to provide more immersive and interactive user experiences for better visualization and understanding of complex geospatial data. Internet of Things (IoT) can be used to capture real-time dynamics and improve simulations (Angheluță et al., 2023; Bakhtiari et al., 2023, 2024; Choi et al., 2023; H. Qiu et al., 2023). Combinations of these emerging technologies create a more powerful scenario analysis for integrated DT-GIS.

Furthermore, it is also important to establish standardized data formats, protocols, guidelines, and frameworks that standardize the process of data collection, processing, and communication in the context of implementing integrated DT-GIS. This will improve data quality, integrity, and sharing among stakeholders for better decision-making.

Also, there will be a growing emphasis on user-centric design, making integrated DT-GIS interfaces more intuitive and accessible to a broader range of stakeholders. One solution is to implement web-based GIS platforms instead of standalone applications, which may include proprietary commercial licenses, software and steep learning curve. This ensures that both decision-makers with varying levels of expertise and the public can effectively leverage geospatial insights.

As integrated DT-GIS systems continue to evolve and handle heterogeneous geospatial data sources, that leads to increasing emphasis on sensitivity, security, and ethical concerns of data. This will likely involve the implementation of strong security protocols, privacy-preserving mechanisms, and ethical guidelines to ensure responsible use of data for different stakeholders. One possible solution is to create mutual agreements for stakeholders involved in the integrated DT-GIS to agree upon the ownership of the copyright of the outcomes.

Efforts to improve interoperability standards and seamless integration with various data sources should continue, as interoperability is one of the most challenging tasks for handling heterogenous geospatial data sources for developing effective integrated DT-GIS. Improving interoperability will enable a more comprehensive and holistic representation of geospatial data, fostering better collaboration and decision-making across diverse domains.

Utilizing open standards and widely accepted frameworks, employing middleware solutions to translate and harmonize data from various formats, use of application programming interfaces (APIs) that facilitate data exchange between different components and data sources, emphasizing metadata standards, and developing ontologies to create common understanding of data semantics become imperative to ensure consistent integration, representation, and interpretation of geospatial information across the integrated DT-GIS.

Stakeholder awareness is a key non-technical factor that can be improved for adaptation of integrated DT-GIS for decision-making process. Without users, there is no point in developing advanced integrated DT-GIS. It is the key important part of the whole integrated DT-GIS ecosystem. Therefore, it is important to increase awareness of the integrated DT-GIS for decision-making, develop deep understanding, the work they perform, the associated benefits of their adoption in real-world scenarios, and challenges and opportunities that come with integrated DT-GIS systems. This involves strategic communication and educational initiatives. Some actions that can be implemented include developing clear and concise informational materials for diverse communication channels (websites, newsletters, social media, etc.), organizing introduction campaigns and workshops, webinars, training sessions, and creating engaging multimedia content (videos, infographics, and case studies). Also, the implementation of a feedback mechanism and the development of a community of practice for stakeholders to share experiences, ask questions, and stay updated on the latest developments are important factors for future developments.

Also, it is crucial to prioritize sustainability and resilience as the number of global issues increases. As such, it is expected that future decision-making processes through integrated DT-GIS will prioritize these values. This will involve integrating environmental factors, climate change considerations, and risk assessments into the geospatial analysis framework.

Collaborative geospatial analysis through integrated DT-GIS is a complex challenge that requires the collaboration of various stakeholders, including technologists, policymakers, domain experts, and the public. By working collaboratively, stakeholders can leverage these technologies to tackle the challenges of geospatial analysis, optimize decision-making, and enhance public safety and services.

These improvements collectively indicate a trajectory toward more sophisticated, adaptable, and user-friendly integrated DT-GIS that play a pivotal role in geospatial analysis in informed decision-making processes across diverse domains.

5. Conclusion

In summary, the use of integrated DT-GIS to make informed decisions in geospatial domains is a significant advancement in how we understand and utilize spatial information. The crucial aspect of integrated DT-GIS is the spatiotemporal relationship between data and virtual visualization and simulation, as well as semantics and geometry. These distinctive features allow integrated DT-GIS to collect time series of geospatial data from various sources, allowing decision-makers to create 'real-time' and 'data-driven' scenarios. This provides an accurate understanding of reality in various domains, including urban planning, disaster management, water and environmental monitoring, and more.

According to the discussion, integrated DT-GIS provides a comprehensive understanding of spatial contexts, allowing for dynamic simulations, predictive analyses, and real-time monitoring. Also, this combination improves the accuracy and speed of decision-support processes. Despite the promising advancements, there are several challenges that need to be addressed before the widespread implementation. These include critical data-related issues, security, and ethical considerations, as well as technical limitations in handling large-scale datasets. Additionally, some non-technical challenges for implementing integrated DT-GIS need to be addressed in a holistic way as they are mostly tied to human factors. Identified solutions to overcome these challenges are presented which help to implement better integrated models.

Most of the time, in the geospatial domain, publicly available diverse geospatial data sources such as real-time environmental sensing data, water levels, weather observations, floods, and other disaster warnings are isolated and not connected well enough to use in multi-stakeholder decision-making processes. Therefore, it is suggested to investigate ways to enhance the interoperability of isolated geospatial data sources. This leads to instantiating a semantically rich ecosystem of knowledge, data, and computational capabilities to provide cross-domain insights in informed decision-making processes.

The potential of integrated DT-GIS for geospatial analysis presents a new and exciting frontier for research and geospatial application for various domains. As we navigate through the complexities of a rapidly evolving technological landscape, there are synergies between DTs and geospatial analysis that hold the promise of unlocking new dimensions in decision-making processes. This can help in shaping a more sustainable, resilient, and informed future.

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