



Review

# Building Information Modelling in Hydropower Infrastructures: Design, Engineering and Management Perspectives

Jigme Wangchuk <sup>1</sup>, Saeed Banihashemi <sup>2,\*</sup>, Hamidreza Abbasianjahromi <sup>3</sup> and Maxwell Fordjour Antwi-Afari <sup>4</sup>

<sup>1</sup> School of Design and Built Environment, University of Canberra, Bruce 2601, Australia; u3192150@uni.canberra.edu.au

<sup>2</sup> School of Built Environment, University of Technology Sydney, Ultimo 2007, Australia

<sup>3</sup> School of Civil Engineering, K.N. Toosi University of Technology, Tehran 19697-64499, Iran; habasian@kntu.ac.ir

<sup>4</sup> School of Infrastructure and Sustainable Engineering, Aston University, Birmingham B4 7ET, UK; m.antwiafari@aston.ac.uk

\* Correspondence: saeed.banihashemi@uts.edu.au

**Abstract:** Building Information Modelling (BIM) has emerged as a transformative force in the construction industry, gaining traction within the hydropower sector. This study critically examines the adoption and application of BIM throughout the entire lifecycle of hydropower projects, addressing a notable gap in existing research, to encompass a holistic approach to the management and resilience of these critical infrastructures. The objective is to delineate the comprehensive range of BIM applications, use cases, and adoption, integrating technologies including Digital Twin, UAV, GIS, and simulation tools, across components of hydropower projects. Employing a systematic search paired with a critical review of the selected literature, this study meticulously evaluates significant contributions in this domain. Through thematic analysis, the multifaceted utility of BIM in hydropower structures, including an in-depth evaluation of its current adoption within the industry, is presented. This encompasses an analysis of both benefits and challenges inherent in BIM implementation for hydropower infrastructures. This study is a significant contribution to understanding how BIM can be leveraged to enhance the resilience of hydropower infrastructures. It provides a comprehensive view of BIM's applications, challenges, and future potential, guiding stakeholders in adopting strategies that ensure these structures withstand, adapt, and recover from disruptions while maintaining sustainable and efficient operations.

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**Keywords:** BIM; hydropower projects; dam; powerhouse; power plant; infrastructure; digital transformation

## 1. Introduction

Building Information Modelling (BIM) is emerging as a revolutionary method, a cutting-edge tool for information technology, and a unified digital platform aimed at the digital design, management, and harmonization of the responsibilities of all stakeholders in a project [1]. BIM represents a significant innovation in infrastructure projects, aiming to improve upon conventional methodologies of design, construction, and operation [2]. The purpose behind adopting BIM is to facilitate the digital examination and collection of data regarding infrastructure projects from a centralized model, as suggested by Bhattarai and Kisi [3]. A study by Dahal [4] in Nepal demonstrated that the implementation of BIM could lead to a 33% reduction in both the initial and lifecycle costs of construction projects, a 50% decrease in the time required for completing new and refurbished buildings, a 50%

reduction in greenhouse gas emissions in the construction sector, and a 50% narrowing of the trade deficit related to construction materials and products.

With respect to these benefits and impacts, BIM systems are beginning to see an increased usage in the hydropower design and construction sector in recent years. Hydropower infrastructure refers to the range of physical structures and facilities used to generate electricity from the kinetic and potential energy of water. This type of infrastructure typically includes dams and reservoirs, water intake structures, powerhouses and power plants [5]. The growing complexity, variability, and unpredictability in the field of hydropower engineering has prompted stakeholders and project participants to engage more in collaborative networks. These networks are designed to facilitate the sharing of risks, information, and resources, as well as to foster the exploration of new experiences for collective involvement in managing large-scale projects [6]. The existing literature on the application of BIM in hydropower projects has indeed laid a foundation, but it often encompasses a very general BIM semantic model, and its focus has been predominantly directed towards a limited portion of the project scope. Many of the early studies of BIM in the context of hydropower projects, which were valuable for illustrating the basic principles of BIM, often lack the specificity and granularity required for complex hydropower projects. The emphasis on collaborative work platforms integrated with BIM has garnered considerable interest among researchers. Commercial platforms like Asite and ProjectWise have started to incorporate BIM support. Nonetheless, the adoption of BIM in the realm of hydropower infrastructure remains rudimentary, primarily focusing on documentation, data management, and the visualization of BIM models [7].

#### *Unique Characteristics of Hydropower Projects*

Hydropower projects are distinct from other types of construction projects due to several unique characteristics that impact their planning, design, construction, and operation. Understanding these characteristics is crucial for effectively implementing Building Information Modelling (BIM) in this sector.

1. **Size and Scale:** Hydropower projects are typically large-scale infrastructure endeavors that span extensive geographic areas. These projects often involve the construction of dams, powerhouses, sub-stations, and extensive water conveyance systems, which require detailed and coordinated planning. The sheer size of these projects necessitates advanced tools like BIM to manage the complexity and ensure accurate and comprehensive design and construction processes [4,8].
2. **Budget and Cost:** The budget for hydropower projects is substantial, often running into billions of dollars. These projects involve significant capital investment and have long payback periods. Accurate cost estimation and budget management are critical to avoid cost overruns and ensure financial viability. BIM's 5D capabilities, which integrate cost estimation with project planning, provide a powerful tool for managing the financial aspects of hydropower projects. Studies have shown that BIM can significantly reduce human errors in cost calculations and provide more precise budget forecasts [9,10].
3. **Long Project Duration:** Hydropower projects typically have long construction timelines, often spanning several years from initial planning to final commissioning. The extended duration requires meticulous planning and scheduling to manage the various phases of the project effectively. BIM's 4D capabilities, which incorporate time-related information, are invaluable for creating detailed project schedules and ensuring that all tasks are completed on time. This helps in identifying potential delays early and implementing corrective actions promptly [11,12].
4. **Environmental and Regulatory Considerations:** Hydropower projects have significant environmental impacts, including changes to water flow, habitat disruption, and potential effects on local communities. These projects must comply with stringent environmental regulations and obtain numerous permits before construction can

begin. BIM can integrate environmental data and support compliance with regulatory requirements by providing detailed models that include environmental impact assessments and mitigation plans [13,14].

5. **Contractual Complexity:** The contractual arrangements for hydropower projects are often complex, involving multiple stakeholders, including government agencies, contractors, subcontractors, financiers, and local communities. These projects typically operate under various contract types, such as Engineering, Procurement, and Construction (EPC) contracts, which require precise coordination and clear communication among all parties. BIM enhances contractual management by providing a centralized platform where all stakeholders can access up-to-date project information, collaborate effectively, and ensure that contractual obligations are met [6].
6. **Risk Management:** Given the scale, duration, and environmental impact of hydropower projects, effective risk management is crucial. BIM facilitates real-time monitoring and early warning systems that can detect potential risks and enable proactive management. The integration of UAVs and photogrammetry with BIM, for example, allows for the continuous monitoring of construction progress and the identification of deviations from the plan, which can mitigate risks associated with construction delays and cost overruns [15,16].

The unique nature of hydropower projects, characterized by their size, budget, long duration, environmental impact, and contractual complexity, underscores the importance of adopting advanced project management tools like BIM. By leveraging BIM’s capabilities, stakeholders can improve the efficiency, accuracy, and sustainability of hydropower projects, ultimately contributing to the successful delivery of these critical infrastructures.

Nawari [17] utilized BIM techniques for the construction of hydro-supportive structures, enhancing the design and construction processes. Similarly, Rong, Zhang [18] introduced an efficient BIM workflow for the design of hydraulic structures, offering a theoretical basis for digital modelling. Liu, Jia [19] addressed the problems of many participating professions, low communication efficiency, the consideration of conflicting problems, many design drawings, and the poor information management of design results. Liu, Jia [19] carried out research on parametric and collaborative design using BIM, which improved the efficiency of underground powerhouse design. Zhang, Zhang [20] applied the BIM technology to carry out online collaborative design, achieving the design of multi-specialty in the same platform by using the geological model, hydraulic model, and electrical equipment model. In the construction phase, Zhang, Zhang [20] developed a collaborative management system for the construction period of hydropower engineering using BIM and Geographic Information System (GIS) fusion technology. Overall, the application of BIM technology in hydropower engineering has indicated great opportunities for enhancing the efficiency and quality of design, engineering, and construction.

Hence, the adoption and application of BIM in hydropower projects are emerging as critical areas of research due to the increasing complexity and sustainability challenges associated with these infrastructures. While numerous studies have explored the utility of BIM in construction projects, there is a notable gap in the comprehensive application of BIM across the lifecycle of hydropower projects. This study aims to fill this gap by providing a holistic review and analysis of BIM adoption in hydropower infrastructures. Table 1 summarizes the contributions of previous studies and highlights the specific gaps that this study seeks to address.

**Table 1.** Contributions of previous studies and identified gaps.

Study	Key Contributions	Identified Gaps
[2]	Discussed BIM’s role in improving the design and operation of infrastructures.	Lack of integration with hydropower project lifecycle.

[21]	Improved efficiency in underground powerhouse design using parametric and collaborative design with BIM.	Insufficient exploration of BIM in other hydropower components like dams and power plants.
[22]	Reviewed BIM adoption in dam construction in Indonesia.	Limited to the planning and construction phases, with no comprehensive lifecycle analysis.
[3]	Assessed BIM awareness among hydropower professionals in Nepal.	Highlighted lack of training but did not propose specific integration frameworks for BIM in hydropower projects.
This Study	Comprehensive review of BIM adoption across the entire lifecycle of hydropower projects, integrating digital twin, UAV, GIS, and simulation tools.	Addresses the need for holistic application and explores benefits and challenges, guiding future research and practical adoption strategies.

Therefore, it is imperative to fully adopt and grasp this technology in the design and engineering of hydropower infrastructures, with reference to higher integration, superior collaboration, and more efficient project development. Moreover, the complete application and adoption of BIM in hydropower projects has not been conducted because the process and engineering standards of building and hydropower are entirely different [23]. As to the database search in finding papers of BIM adoption in hydropower, it can be inferred that the work carried out in this area is very limited, to only a handful of studies. This is due to the complex nature of hydropower projects in terms of requiring intricate engineering design, uncertain geological considerations, environmental factors, and regulatory requirements. The existing literature is mainly focused on BIM application on a particular phase of any hydropower component, which does not elucidate the insights on total workflow of BIM on hydropower. In addition, the case studies in the current literature have been mainly focused on a specific country and the concept is not covered in its entirety. To this end, there is still a lack of comprehensive review and analysis on BIM adoption for design, engineering, collaboration and communication in the entire lifecycle of hydropower projects where state-of-the-art technologies like BIM still remain a myth.

Therefore, this study aims to critically and systematically review the literature and evaluate the feasibility, application and adoption of BIM to the whole lifecycle of hydropower structures. Moreover, the benefits and challenges of adopting BIM in hydropower are critically analyzed to identify the existing research gaps in these fields. This study provides a comprehensive view on how BIM can be leveraged to enhance the resilience of hydropower projects and ensure that these structures can withstand, adapt to, and recover from disruptions while maintaining sustainable and efficient operations.

In more detail, this study has the following objectives:

- To explore the current body of knowledge on the identification and consideration of BIM in hydropower projects.
- To analyze how BIM has been applied in hydropower projects, what components of hydropower have been used for BIM application, and the type of methodological perspective in the literature.
- To assess the status of BIM adoption in hydropower projects.
- To define potential future research directions.

## 2. Review Methodology

This study’s methodological framework is based on a critical review and a systematic search approach using the classification described by Grant and Booth [24]. In order to conduct a thorough and systematic search, a PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) approach was used to retrieve the literature pertaining to BIM and its application in hydropower infrastructures. In this regard, a set of keywords was selected which were extracted from various review articles and the literature.

Keywords were grouped into two main categories, (a) BIM and (b) hydropower, as shown in Table 2. In the BIM set, the common terms related to BIM technology and their processes were mentioned. In the case of hydropower, the terms associated with the key components of hydropower projects were identified. Each category’s keyword relationships are based on the logical relationship of “OR”, and the two principal clusters are related using the relationship of “AND”. This implies that each category’s designated keywords must appear at least once in the chosen literature.

**Table 2.** Keywords selected for a systematic search of the literature.

Keywords Related to BIM	Relationship	Keywords Related to Hydropower
3D Design		Power Plant
Collaboration and Communication		Dam
Model Simulation		Powerhouse
Management	AND	Switchyard
Scheduling		Hydraulic Engineering
Sustainability		Lifecycle
Analysis		

The PRISMA framework comprises 27 reporting items that enhance the clarity and quality of systematic reviews. Our methodology encompasses four main phases: identification, screening, eligibility, and inclusion. Figure 1 demonstrates the process of appropriate literature selection for this study. In the identification stage, two scholarly bibliographic databases, Scopus and Google Scholar, were selected. Scopus is known for its extensive coverage of the engineering, technology, and construction-related literature, including a wide range of high-quality, peer-reviewed journals and conference proceedings that are pertinent to the field of BIM and hydropower infrastructure [25]. Google Scholar offers a broad multidisciplinary database that includes articles, theses, books, conference papers, and patents across various fields. It complements Scopus by providing access to the grey literature and other scholarly content that might not be indexed in specialized databases. Furthermore, the chosen databases have demonstrated strong relevance in the fields of BIM, infrastructure, construction technology, and hydropower engineering. They are frequently used in academic and industry research to source the latest studies and developments in these areas [26].

The following criteria were then used to find high-quality research studies:

- Language: English was selected as the language of publications.
- Time Range: The publication range that was chosen was roughly the past ten years, from 2013 to 2023, and the search was completed in December 2023. The 10-year timeframe was chosen in order to control the content of final papers. The decision to focus on the literature from the past ten years was based on several key considerations aimed at ensuring the relevance, currency, and applicability of the findings to contemporary hydropower infrastructure projects.
- Technological Advancements: The field of BIM and its integration with advanced technologies such as digital twins, UAVs, GIS, and simulation tools have seen significant advancements in the past decade. Focusing on the recent literature allows us to capture the latest innovations and their practical applications in hydropower projects.
- Industry Practices and Standards: The construction and hydropower industries have undergone substantial changes in terms of standards, practices, and regulatory frameworks in recent years. By reviewing the literature of the past ten years, it is ensured that the study reflects the current state of the industry, including the adoption of new methodologies and compliance with updated standards.
- Relevance and Applicability: Contemporary research is more likely to address the current challenges and opportunities faced by the hydropower sector. This includes

the latest sustainability initiatives, resilience planning, and digital transformation strategies that are crucial for modern infrastructure projects.

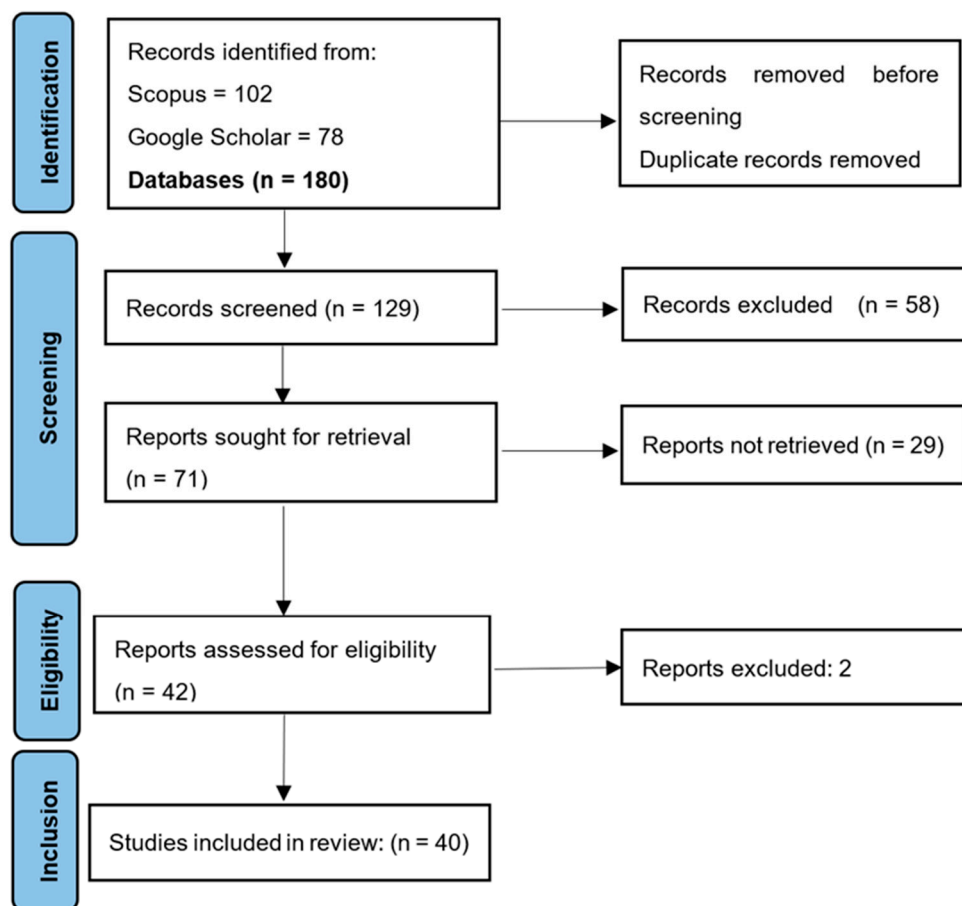
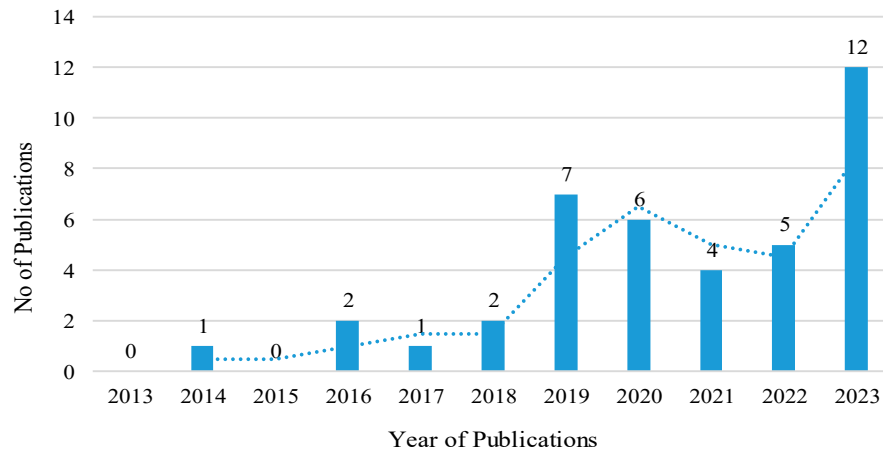


Figure 1. The PRISMA flow diagram of the study.

By specifying the search parameters (title, abstract, and keywords), the exploration through Scopus and Google Scholar resulted in the identification of 102 and 78 publications, respectively. The initial phase of screening involved the removal of duplicates, grey literature, and book chapters by reviewing article titles, leaving 129 records for further examination. The analysis of the abstracts led to the exclusion of 58 papers due to their lack of relevance to building-related topics. This refinement process resulted in 71 articles, of which 29 were further eliminated because their full texts were not accessible. Full-text articles were then assessed for eligibility based on a detailed evaluation of their content. A risk of bias assessment was conducted using standardized criteria to evaluate the methodological quality of the selected articles. Criteria included the clarity of research questions, the appropriateness of study design, the robustness of data analysis, and the relevance of findings to the research objectives of this study. The risk of bias assessment was a critical component of the methodology to ensure the reliability and validity of the findings. Each study was evaluated independently by two authors to minimize subjectivity. Discrepancies were resolved through discussion or consultation with a third author. Studies were assessed for potential biases related to selection, performance, detection, and reporting. The overall quality was categorized as low, moderate, or high risk of bias [27].

Then, 2 more papers were discarded after a thorough eligibility review, resulting in a total of 40 records meeting the criteria for inclusion. This selection comprised 25 journal articles, 11 conference papers, 3 books, and 1 review paper, all pertinent to the study’s focus for in-depth review. Figure 2 illustrates the distribution of these selected publications over the past decade, highlighting a notable increase in BIM-related publications in

the hydropower sector by 2023. This surge can be attributed to several factors, including the rapid technological advancements in digital twins, UAVs, GIS, and simulation tools [8,28], government and industry initiatives on BIM adoption in the infrastructure sector [6,22], lessons learned from early adopters [4], an increase in collaborative research, and the higher number of co-authored papers and collaborative projects published in recent years [3,23].



**Figure 2.** Research trend from 2013 to 2023.

In order to provide a theoretical overview of the collected literature, studies were classified into categories according to BIM implementation and adoption, specific use cases of BIM in hydropower (design, collaboration and communication, monitoring, scheduling, cost analysis, sustainability assessment, and geotechnical investigation), and hydropower component types (dam, powerhouse, power plant, switchyard, and water diversion). This classification is summarized in Table 3. References were chronologically organized, from the latest to oldest. In terms of the type of hydropower component, dam was assessed as the most studied in the literature followed by hydropower as a whole. The possible reason for this is that dams are complex structures with a significant impact on the environment and public safety. Evaluating the adoption of BIM in dams for effective design and analysis can help in risk assessment, safety evaluation, and the development of emergency response plans. In the case of BIM use in hydropower, design was a prominent area of focus for researchers as it is considered one of the very critical phases of the project. The least prominent areas of investigation for various BIM uses in hydropower were collaboration/communication and cost estimation. In the same vein, very few studies have been carried out on the assessment of BIM adoption in hydropower projects, and it can be implied that the adoption of BIM in hydropower is still in its early stages.

**Table 3.** Literature classification based on hydropower components, BIM uses, and BIM adoption.

Reference	Hydropower Component	BIM Use Cases					Assessment of BIM Adoption	Methodological Review		
		Design	Collaboration/Communication	Monitoring	Scheduling	Cost Estimation			Sustainability Assessment	Geotechnical Investigation
(Sentosa et al., 2023)	Dam			X	X			Simulation		
(Arbad et al., 2023)	Dam			X				Case Study		
(Shishehgar-khaneh et al., 2023)	Dam				X			Case Study		
(Zhang et al., 2023)	Dam						X	Case Study		
(Giavoni et al., 2023)	Power Plant	X						Case Study		
(Habibagahi et al., 2023)	Dam			X				Simulation		
(Hasan et al., 2023)	Dam					X		Case Study		
(Liu et al., 2023)	Powerhouse	X						Content Analysis		
(Liu et al., 2023)	Powerhouse	X						Qualitative Analysis		
(Liu et al., 2023)	Hydropower	X						NA		
(Zhang et al., 2023)	Hydropower	X						NA		
(Yang et al., 2023)	Hydropower						X	NA		
(Zhou et al., 2023)	Dam						X	Case Study		
(Bhattarai et al., 2022)	Hydropower							X	Survey Questionnaire	
(Shishehgar-khaneh et al., 2022)	Dam				X				Case Study	
(Azzam et al., 2022)	Power Plant							X	Case Study	
(West et al., 2021)	Hydropower								X	Survey Questionnaire
(Zhang et al., 2021)	Dam									Case Study
(Hermawan et al., 2021)	Dam	X						X		Case Study
(Djelic et al., 2021)	Power Plant/Turbine Rehabilitation									Case Study
(Chen et al., 2020)	Dam				X					Case Study
(Zhang et al., 2020)	Hydropower							X		Case Study
(Arbad et al., 2020)	Dam			X						Case Study
(Li et al., 2020)	Powerhouse	X								Case Study
(Wahyuningrum et al., 2020)	Dam	X								NA
(Niraula, 2020)	Hydropower								X	Descriptive Research
(Guevremont et al., 2019)	Hydropower				X					Case Study
(Guevremont et al., 2019)	Hydropower				X					Case Study

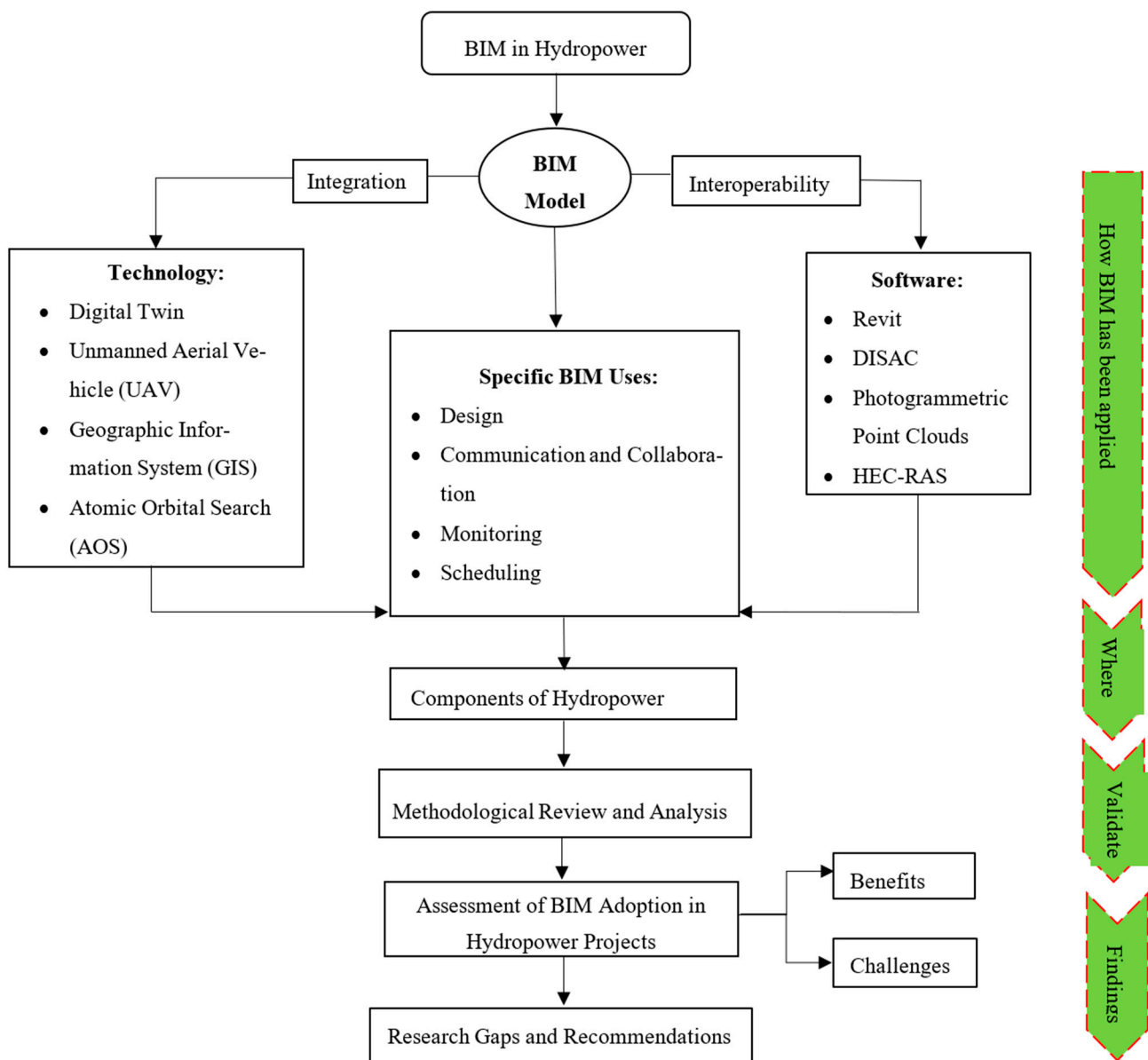


(Ji et al., 2019)	Dam		X		Simulation
(Liu et al., 2019)	Water Diversion		X		Case Study
(Dahal, 2019) [13]	Hydropower	X			Case Study
(Rong et al., 2019)	Dam	X			Case Study
(Hiratsuka et al., 2019)	Dam			X	Case Study
(Zhang et al., 2018)	Hydropower Station			X	Case Study
(Buffi et al., 2018)	Dam		X		Case Study
(Fougner et al., 2018)	Hydropower			X	NA
(Zhang et al., 2017)	Hydropower	X			Case Study
(Zhang et al., 2016)	Hydropower Station			X	Case Study
(Huang et al., 2016)	Hydropower	X			NA
(Correa et al., 2014)	Sub-station	X			NA

### 3. Thematic Analysis

Thematic analysis stands as a method for qualitative research, focusing on identifying and analyzing themes within qualitative data [29]. This technique is valuable for condensing extensive datasets, underlining variances and commonalities within the data, conceptualizing patterns of meaning, identifying consistent themes throughout a dataset, and generating insightful, reliable outcomes [30].

For this study, the themes were identified based on the insights and description provided by the literature. The selected literature significantly outlines the specific use of BIM in hydropower projects. Hence, based on the 40 final papers fixed for the analysis, it was found that BIM has been utilized in hydropower projects mainly for design (3D modeling), collaboration, monitoring, scheduling, cost estimation, sustainability assessment, and geotechnical investigation. Researchers have applied the BIM technology in various hydropower components, and, accordingly, the type of hydropower components like dam, hydropower (as a whole), power plant, sub-station, and powerhouse, which are also the areas of focus, have been critically considered for the study. Another key consideration for the analysis is the methodology used by the researchers in their studies to review and validate their findings. Finally, this analysis also included an assessment of the state of BIM adoption in hydropower infrastructures in order to address the research gaps and deliver future research recommendations. Based on all these considerations, a comprehensive theoretical framework was developed to present the thematic and content analysis structure, as shown in Figure 3.



**Figure 3.** Theoretical framework of the study.

### 3.1. BIM Use Cases in Hydropower

#### 3.1.1. Design

With respect to the analysis made, a landmark application of BIM in hydropower projects was undertaken with a specific focus on the design phase (Table 4). The literature has considered a collaborative and data-driven approach in designing hydropower facilities, resulting in improved efficiency, accuracy, and sustainability. With the BIM-based design in this practice, the amount of data loss between the owners and supervisors working on the site was significantly reduced. The quality and design of any project that uses BIM are beyond comparison as many analytical applications including energy calculation, site orientation, and structural analysis are carried out with this platform [4].

According to the published literature, numerous BIM-integrated tools and technologies were adopted in data collection for site analysis and selection (Table 4). Laser scanner is one of the technologies applied. Applying laser scanner to create a BIM model is a common practice in construction industry (and is new to the hydro industry) because it gathers accurate and detailed data of a building or area of interest [8]. Laser scanning involves the use of equipment that emits a beam of light reflected on the surfaces of buildings,

allowing the creation of a 3D point cloud that can be converted into a digital model. In the academic field, the methodology of creating a BIM model from scanning is called Scan-to-BIM [31]. In the study conducted by Giavoni, Caetano [8], the aerial scan was performed with a DJI Phantom 4 Pro drone coupled with a lidar RIEGL minVUX-1UAV laser scanner. The runtime was one day, with an accuracy of 50 points per square meter, enough to complement the ground scan data.

In a study by Hermawan and Monica [32], design data were collected by performing numerical analysis calculation with the help of 6D BIM analysis to design the discharge of diversion channel. In fact, the data collection is an important step after BIM planning/BIM Execution Plan drafting for hydropower infrastructures as most of the hydropower project sites are located in remote areas. Huang [33] employed Autodesk Infra-works to merge GIS data for the planning and feasibility analysis of hydropower projects in their initial design stages. This method facilitated the integration of traditionally isolated data into a coherent, 3D intelligent site model that enhances project visualization and supports comprehensive decision-making processes. A project site model for the power plant with most information like ground imagery and 3D terrain was generated using Infracore Model Builder, and GIS shape files were imported for data visualization. In their 2020 study, Li et al. conducted an in-depth analysis to ascertain the impact of the aspect ratio and the spacing between the underground main powerhouse and the transformer chamber. Central to their methodology was the creation of a detailed topographic geological model, utilizing CATIA software. This model played a crucial role in extracting and interpreting geological data, which was subsequently integrated into the design considerations. Their approach exemplifies the application of advanced modelling techniques in assessing critical design parameters in subterranean power infrastructure projects.

For the design of hydropower using BIM, the analysis of the literature indicates that Autodesk BIM 360 and Revit are the most common software used for 3D modelling (Table 4). Autodesk BIM 360 enhances the 3D BIM construction system by offering a dynamic, up-to-date platform. Designers can swiftly update BIM, drawings, and relevant documentation on the cloud based on the newest design alterations and notifications of onsite changes [34]. Similarly, clients have access to the latest design data in real time via the cloud server, allowing for the immediate updating of onsite construction details through an internet connection [33]. A review on the design of the Paulo Afonso IV power plant by Giavoni, Caetano [8] revealed that the planning phase of the model was executed with the objective of delineating the systems, establishing their respective levels of details, and defining their intended functions, all while focusing on the ultimate utilization within the BIM framework. Autodesk Revit 2021 was the chosen software for this endeavor. Subsequent to the initial phase, which encompassed 3D modelling, parameters such as the direct link to the client's information repository were integrated into the model for each system. Additionally, location parameters were input, slated for future geo-referencing. The employed BIM tool demonstrated remarkable flexibility in the addition and removal of parameters, a feature attributable to the model's strategic organization by discipline. Liu, Jia [19] constructed a knowledge graph and combined it with the BIM model design of the underground powerhouse to calculate the spatial topology model data by inputting the number of units, unit installation elevation, unit spacing, sub-powerhouse installation room layout, and main plant width.

Liu, Su [21] explored digital twin technologies in hydraulic engineering, emphasizing that the BIM technology's benefit during the planning and design phases is its capability to generate a detailed project model for visualizing design outcomes. GIS technology plays a crucial role in the management and analysis of geographic data for extensive areas, offering designers comprehensive GIS data and spatial information for macroscopic project planning. Progressively, Liu and Luo [28] identified intelligent design as the application of BIM technology in 3D digital modelling, facilitating the entire lifecycle management of water conservancy and hydropower projects, thus enhancing design precision and efficiency. BIM was also utilized to construct a sophisticated hydrodynamic model

for simulating the discharge and flood routing at the Wudu reservoir, aiming to assess hydraulic parameters in the dam discharge design and their effects on downstream areas, incorporating complex terrain and detailed dam structures [18].

The concept of HydroBIM was addressed by Zhang, Zhang [20], who explained that in the bidding and construction design phases of Nuozadu hydropower, the team developed NZD-VisualGeo, a system for 3D visualization modelling and the analysis of geological information. This system allowed for the dynamic updating of the geological information model based on the latest geological conditions, providing an interactive platform for design and construction and improving work efficiency and quality. Using the reverse engineering technology, the GIS 3D geological model was materialized. The team then used software packages such as Civil3D, Revit, and Inventor to carry out 3D design directly, and Navisworks software for intuitive model integration review, support design, model profiling, and 4D construction. This provided a complete 3D design review scheme for the hub and electromechanical engineering design. By combining the geological conditions during construction, discovered by 3D CAD/CAE-integrated analysis and monitoring information feedback, the team was able to dynamically adjust and optimize the underground cavern group and high slope support parameters, ensuring the safety and economy of the project engineering.

**Table 4.** Literature analysis on the BIM use cases for hydropower design.

Reference	Components of Hydropower	BIM Use	Software/Technology Used	Case Study	Country	Results/Benefits
[8]	Power Plant	<ul style="list-style-type: none"> <li>• Conversion of point cloud into 3D model.</li> <li>• Evaluation of level of detail.</li> <li>• Parameter analysis.</li> </ul>	<ul style="list-style-type: none"> <li>• Scan-to-BIM</li> <li>• Autodesk Revit 2021</li> </ul>	Paulo Afonso IV Power Plant	Brazil	<ul style="list-style-type: none"> <li>• Future asset management.</li> <li>• Assembly and disassembly of equipment.</li> <li>• Equipment upgrades.</li> </ul>
[19]	Powerhouse	<ul style="list-style-type: none"> <li>• Spatial analysis of BIM model.</li> <li>• Knowledge graph construction for design parameters.</li> </ul>	<ul style="list-style-type: none"> <li>• Optical Character Recognition (OCR)</li> </ul>			<ul style="list-style-type: none"> <li>• Provided the following design information:</li> <li>• Internal structure of powerhouse.</li> <li>• Composition of structural parameters.</li> <li>• Basis of parameter calculation.</li> </ul>
[21]	Hydraulic Engineering	<ul style="list-style-type: none"> <li>• 3D Visualization.</li> <li>• BIM and digital twin for design coordination.</li> </ul>	<ul style="list-style-type: none"> <li>• Digital Twin</li> </ul>			<ul style="list-style-type: none"> <li>• Provided uniform platform for data integration and analysis.</li> <li>• Enabled decision-making and sustainable water resource management.</li> </ul>
[28]	Hydropower	Collaborative design, visualization, high simulation, and convenient project optimization.				<ul style="list-style-type: none"> <li>• Improved design efficiency and quality.</li> </ul>
[20]	Hydropower	Hydro-BIM collaborative design and analysis-integrated	<ul style="list-style-type: none"> <li>• Civil 3D</li> <li>• Revit</li> <li>• Inventor</li> </ul>	Nuozado Hydro-power	China	<ul style="list-style-type: none"> <li>• Improved the cooperativity of stakeholders, productivity</li> </ul>

		platform enabled BIM model collaborative design, BIM-integrated analysis, and feedback optimization design.	<ul style="list-style-type: none"> <li>• Navisworks</li> </ul>			<p>and information integration.</p> <ul style="list-style-type: none"> <li>• Ensured the quality and safety of the lifecycle of hydro-power engineering.</li> </ul>
[32]	Dam	<ul style="list-style-type: none"> <li>• Simulation using 6D BIM numerical analysis.</li> <li>• Design of discharge.</li> </ul>	<ul style="list-style-type: none"> <li>• HEC-RAS</li> </ul>	Margatiga Dam	Indonesia	<ul style="list-style-type: none"> <li>• BIM-based design discharge = 1075.66 m<sup>3</sup>/s (higher and safer).</li> <li>• Actual discharge observed = 884.69 m<sup>3</sup>/s.</li> <li>• Initial design discharge = 789.10 m<sup>3</sup>/s.</li> </ul>
[35]	Powerhouse	<ul style="list-style-type: none"> <li>• BIM and numerical analysis to find the effect of aspect ratio (height/width) and interval between powerhouse and transformer chamber.</li> <li>• Definition of design parameters.</li> </ul>	<ul style="list-style-type: none"> <li>• CATIA</li> <li>• ABAQUS</li> </ul>	Suki Kinari Under-ground Powerhouse	Pakistan	<ul style="list-style-type: none"> <li>• Increase in aspect ratio reduces crown settlement but increases sidewall deformation.</li> <li>• Total deformation of powerhouse has polynomial relationship with aspect ratio.</li> <li>• Overall deformation decreases with the increased interval.</li> </ul>
[4]	Hydro-power Infrastructure	<ul style="list-style-type: none"> <li>• 3D modelling.</li> <li>• Design change.</li> <li>• Structural analysis.</li> </ul>	<ul style="list-style-type: none"> <li>• Tekla Structure</li> <li>• ArchiCAD</li> </ul>	Lower Piluwa Small Hydro-power Project	Nepal	<ul style="list-style-type: none"> <li>• Improved 3D visualization.</li> <li>• Collaborative design minimized errors.</li> <li>• Clash detection prevented reworks.</li> </ul>
[18]	Dam	<ul style="list-style-type: none"> <li>• Generate 3D modelling dam discharge.</li> <li>• Assess dam discharge energy dissipation rate.</li> <li>• Analyze dam operation rules and conduct downstream flood risk assessment.</li> </ul>		Wudu Reservoir	China	<ul style="list-style-type: none"> <li>• Dam discharge and flood routing framework provided accurate details of the complex flow patterns for design consideration.</li> <li>• Transient characteristics were optimized to achieve maximum discharge capacity for downstream safety.</li> </ul>
[33]	Power Plant	<ul style="list-style-type: none"> <li>• Site information modelling.</li> <li>• Design simulation.</li> <li>• Integration of GIS data with BIM model for planning and feasibility study.</li> </ul>	<ul style="list-style-type: none"> <li>• Autodesk Infra-works 360</li> </ul>			<ul style="list-style-type: none"> <li>• Collaborative design facilitated effective communication.</li> <li>• Improved project visualization and enabled broader decision-making.</li> </ul>

### 3.1.2. Communication and Collaboration

The literature analysis indicates that the communication and collaboration aspects of BIM use in hydropower have received less attention from researchers. Communication and collaboration remain the broader domain due to which research efforts might have been diverted towards discipline-specific applications [36].

The introduction of BIM marks a significant evolution in the management of information throughout the entire lifecycle of construction projects. It serves as a sophisticated digital instrument and a platform for sharing information, facilitating comprehensive process management in large-scale infrastructure endeavors, including those following the Engineering, Procurement, and Construction (EPC) model. This approach introduces a novel strategy for executing integrated project management. According to the research conducted [7], a model for collaborative work utilizing BIM technology was developed specifically for hydroEPC projects. This led to the creation of a BIM-based collaborative platform employing a three-tier structure and web technologies. The platform's capabilities are distributed across five modules: model creation, model management, collaboration management, workflow management, and system administration. Additionally, Van Berlo, Beetz [37] designed a prototype system for communication and collaboration at the Huaneng Jueba Hydropower Station. This system achieved communication and coordination between local software and a web server for BIM models through a plug-in mechanism. It also realized the integration of BIM technology with enterprise systems via a database, enabling information retrieval and data mapping. The backbone of this collaboration platform operates on Linux, with Apache serving as the web server. Additional servers include a workflow server, Primavera Project Planner for Enterprise for Construction (P3E/C) server, an open-source BIM server, and Microsoft SQL Server.

### 3.1.3. Monitoring

Recent research has increasingly concentrated on the application of BIM in the monitoring of dam construction, encompassing both the construction and post-construction phases (Table 5). Arbad, Arifin [15] provided an example, demonstrating the monitoring of the Margatiga Dam during its construction phase. This was achieved through the integration of photogrammetric point clouds with BIM technology. The photogrammetric data, acquired and processed using Agisoft Metashape software, facilitated the creation of a detailed 3D mesh model. This model, derived from the 3D point cloud, was subsequently imported into the BIM framework. Such integration enabled a comprehensive comparison between the 3D mesh and BIM models, enhancing the accuracy and efficiency of the monitoring process.

In a study by Buffi, Manciola [16], Unmanned Aerial Vehicles (UAVs) were employed to conduct a comprehensive survey of the Ridracoli Dam. The UAVs captured interactive photos and videos, generating a dense point cloud representation of the dam's structure. The data points extracted from this cloud were then converted into .txt format for compatibility and subsequently imported into a commercial 3D modelling software. This approach exemplifies the integration of UAV technology with 3D modelling for dam structural analysis.

In a separate study, Ji and Hu [38] developed a BIM model of the Qianming Reservoir Dam using Autodesk Revit. This model was not only a structural representation but also included detailed information on monitoring instrument placement and construction methodologies. The concrete pouring process was simulated using Navisworks software. Furthermore, they employed a 3D finite element application to simulate both the temperature and the stress field of the dam during its construction phase. Their work demonstrates the synergy of BIM with simulation tools, allowing for the real-time monitoring of critical factors such as concrete temperature and stress during the reservoir construction process.

This review includes a BIM-based dam safety monitoring system introduced by Zhou, Bao [39]. Their approach combined BIM with domain ontologies, a process which involved an extensive collection and analysis of domain-specific knowledge alongside the

extraction of contextual information from the dam information model. Furthermore, they implemented a rule-based reasoning framework and utilized SPARQL queries to facilitate this integration. This methodology significantly improved the efficiency of integrating dam safety monitoring data and reduced data retrieval times when compared to conventional database systems. In another study, Habibagahi, Varamini [40] focused on analyzing the displacement patterns of a rock-fill dam. They constructed a detailed model in Abaqus and performed a comprehensive creep analysis. This approach provided valuable insights into the structural behavior and potential risks associated with the dam’s stability.

Meanwhile, Liu, Chen [41] addressed dam safety from a different perspective by proposing a safety inspection tool integrating UAVs with dynamic BIM. This research resulted in the development of a comprehensive workflow for UAV-augmented dynamic BIM safety inspections. This workflow encompassed the data collection, the construction of a dynamic BIM, and the coupling of UAV and BIM technologies. The researchers achieved a dynamic BIM model by integrating continuously updated safety data within a web-based BIM environment. Additionally, they realized synchronous navigation between UAV video footage and dynamic BIM by aligning the parameters of the virtual camera with those of the actual UAV cameras.

**Table 5.** Literature analysis on BIM use in hydropower project monitoring.

Reference	Components of Hydropower	BIM Use	Software/Technology Used	Case Study	Country	Results/Benefits
[15]	Dam	<ul style="list-style-type: none"> <li>• Three-dimensional point clouds by photogrammetry are converted to 3D mesh model.</li> <li>• Mesh and BIM models are then aligned to compare as-built with the original design.</li> <li>• Any discrepancies or deviations are identified.</li> </ul>	<ul style="list-style-type: none"> <li>• Unmanned Aerial Vehicle (UAV)</li> <li>• Agisoft Metashape</li> </ul>	Margatiga Dam	Indonesia	<ul style="list-style-type: none"> <li>• Provided construction data including planned completion dates and quantities of materials required.</li> <li>• Visually represented and observed real-time advancement of the construction job.</li> <li>• Surface geometry provided a clear visual representation of the physical state of the construction site.</li> </ul>
[39]	Dam	<ul style="list-style-type: none"> <li>• BIM-based ontology technology for collecting dam safety monitoring information.</li> </ul>	<ul style="list-style-type: none"> <li>• Revit</li> </ul>	Concrete Dam	China	<ul style="list-style-type: none"> <li>• Effective integration of dam safety monitoring information.</li> <li>• Reduced retrieval time effectively compared with traditional databases.</li> </ul>
[40]	Dam	<ul style="list-style-type: none"> <li>• Three-dimensional modelling of rock-fill dam.</li> <li>• Rock-fill creep phenomenon is fed to the BIM model.</li> <li>• Sensitivity analysis is performed.</li> </ul>	<ul style="list-style-type: none"> <li>• Abaqus</li> </ul>	Crotty Dam	Australia	<ul style="list-style-type: none"> <li>• Increase in modulus of deformation of rock-fill reduced the total displacement.</li> <li>• Reducing embankment slope may reduce post-construction displacements.</li> <li>• Increase in dam height increases total displacement.</li> </ul>

[41]	Water version	Di-	<ul style="list-style-type: none"> <li>Workflow for dynamic BIM-augmented UAV safety inspection is developed.</li> <li>Navigation of UAV video and dynamic BIM is realized by matching virtual camera parameters with the real one.</li> </ul>	<ul style="list-style-type: none"> <li>Autodesk Forge</li> </ul>	Tianjin Water Diversion Project	China	<ul style="list-style-type: none"> <li>Improved safety inspection efficiency.</li> <li>Ensured timely and comprehensive safety evaluation through inspection video.</li> </ul>
[38]	Dam		<ul style="list-style-type: none"> <li>Monitoring instrument embedding and construction methods were incorporated into BIM model.</li> <li>Image-based information visualization.</li> </ul>	<ul style="list-style-type: none"> <li>Revit</li> <li>Navisworks</li> </ul>	Qianming Reservoir Dam	China	<ul style="list-style-type: none"> <li>Real-time temperature monitoring of dam construction was achieved.</li> <li>Four-dimensional temperature and stress strain prevention and control supervision was carried out.</li> </ul>
[16]	Dam		<ul style="list-style-type: none"> <li>UAV dense cloud is integrated with BIM.</li> <li>BIM model employed in finite element analysis including monitoring data.</li> <li>Storing and sharing survey information of dam.</li> </ul>	<ul style="list-style-type: none"> <li>UAV</li> </ul>	Ridracoli Dam	Italy	<ul style="list-style-type: none"> <li>Thorough inspection of dam was possible, including the inaccessible portion.</li> <li>Facilitated information sharing among maintenance and management technicians.</li> </ul>

### 3.1.4. Scheduling (4D)

Four-dimensional BIM (4D-BIM) modelling, also referred to as BIM-based scheduling, represents a sophisticated approach to the design and scheduling of construction activities [42]. This methodology extends the functionality of traditional planning by incorporating a wide array of operations, enabling 4D visualization across the project’s lifecycle and the detailed articulation of labor and resources. It utilizes diverse tools and technologies to define the geometry, spatial relationships, geographic context, quantities, and characteristics of construction elements, along with materials and timelines [43]. This approach effectively connects the conceptual model developed during the design phase with the detailed planning and scheduling required in the construction phase [44]. Moreover, its graphical visualization aids in the early detection of unforeseen issues and discrepancies, facilitating the identification of possible scheduling conflicts [45].

As to the 4D-BIM of hydropower infrastructures, Sentosa, Azzaqy [11] constructed a BIM model for the Semantok Dam using Revit at a level of detail (LOD) of 400, where components were detailed as specific assemblies, including comprehensive information on quantity, size, shape, location, and orientation. The construction schedule was developed through a work breakdown structure, with dates assigned to the respective activities associated with the structure. The model was fed into Autodesk Navisworks for simulation and analysis purposes. In another study, to monitor the progress of the Shandian Reservoir, Chen, Wu [12] developed a 4D schedule monitoring system using CATIA software and the SQL Server database to combine the 3D model and progress information within a central database. Guévremont and Hammad [46] examined the construction



schedule for the safety planning of hydroelectric projects applying 4D simulation to reduce accidents through the lifecycle (e.g., planning or construction) of a project, by applying LoDs (4D-LOD). Guevremont and Hammad [47] used 4D simulation for the schedule validation of rock excavation works in a powerhouse, which developed an upgraded decision tool in comparison with the traditional Gantt Charts. Baghalzadeh Shishehgarkhaneh, Fard Moradinia [48] integrated a BIM model with Atomic Orbital Search (AOS) algorithms to optimize the project time and cost. Thus, the literature analysis for this section (Table 6) concludes that 4D BIM-based scheduling can be effectively carried out for hydropower projects for the monitoring of progress, safety, and timely decision-making.

**Table 6.** Literature analysis on BIM use in hydropower project scheduling (4D) and cost estimation (5D).

Reference	Components of Hydro-power	BIM Use	Software/Technology Used	Case Study	Country	Results/Benefits
[11]	Dam	<ul style="list-style-type: none"> <li>• Three-dimensional BIM model is developed with LOD 400.</li> <li>• Construction scheduling (4D BIM), integration, and simulation.</li> </ul>	<ul style="list-style-type: none"> <li>• Revit</li> <li>• Navisworks</li> </ul>	Semantok Dam	Indonesia	<ul style="list-style-type: none"> <li>• Assisted in communicating and detecting scheduling errors.</li> <li>• As-planned database for monitoring the construction phases.</li> <li>• Informed and assertive decision-making.</li> <li>• On-time project delivery.</li> </ul>
[48]	Dam	<ul style="list-style-type: none"> <li>• Atomic Orbital Search (AOS) is employed in BIM model.</li> <li>• AOS's capacity to solve the minimization of time, cost and risk and ensure maximum quality is assessed.</li> </ul>	<ul style="list-style-type: none"> <li>• AOS optimization algorithms.</li> </ul>	Goocham Dam	Iran	<ul style="list-style-type: none"> <li>• Cost and time decreased by 7% and 40%.</li> <li>• Best and shortest computing time of 1.79 s was provided.</li> <li>• Project expenses were lowered.</li> </ul>
[12]	Reservoir	<ul style="list-style-type: none"> <li>• Use of 4D BIM to optimize construction progress.</li> <li>• Real-time perception and control of actual construction progress.</li> </ul>	<ul style="list-style-type: none"> <li>• CATIA</li> <li>• SQL Server Database</li> </ul>	Shandian Reservoir	China	<ul style="list-style-type: none"> <li>• Achieved comprehensive traceability of information.</li> <li>• Enhanced the dynamic oversight of the construction process on-site.</li> <li>• Enabled visual oversight of project time-lines.</li> </ul>

						<ul style="list-style-type: none"> <li>• Saved time and cost.</li> </ul>
[47]	Hydropower	<ul style="list-style-type: none"> <li>• Integration of safety planning with project schedule for 4D simulation.</li> <li>• Visualization of construction operations.</li> </ul>		Quebec Hydropower Project	Canada	<ul style="list-style-type: none"> <li>• Potential accidents were minimized at different project phases.</li> <li>• Project schedule was updated to protect workers from different hazards.</li> </ul>
[46]	Powerhouse	<ul style="list-style-type: none"> <li>• Four-dimensional simulation to determine feasibility of excavation methods.</li> <li>• Demonstrate schedule feasibility.</li> <li>• Evaluate schedule acceleration.</li> </ul>	<ul style="list-style-type: none"> <li>• CATIA</li> </ul>	Quebec Hydropower Project	Canada	<ul style="list-style-type: none"> <li>• Facilitated the verification of schedules for all project participants.</li> <li>• Offered a superior tool for decision-making.</li> </ul>
[9]	Dam	<ul style="list-style-type: none"> <li>• Use of 5D BIM for evaluating construction project budgets.</li> </ul>		Iraqi Dam	Iraq	<ul style="list-style-type: none"> <li>• BIM reduced considerable levels of time, effort, and budget required to evaluate project cost.</li> <li>• BIM significantly mitigated human errors and achieved better accuracy in cost calculations.</li> </ul>
[4]	Powerhouse	<ul style="list-style-type: none"> <li>• BIM-based quantity take-off of concrete for cost estimation.</li> </ul>	<ul style="list-style-type: none"> <li>• Tekla Structures</li> </ul>	Lower Puluwa Small Hydropower Project	Nepal	<ul style="list-style-type: none"> <li>• BIM-based method showed more accurate quantity estimation than the traditional design method.</li> <li>• Resulted in significant cost-saving for the project.</li> </ul>

### 3.1.5. Cost Estimation (5D)

The assessment of dam construction costs has also benefited from the adoption of intelligent methodologies, particularly the 5D BIM approach [49,50]. BIM authoring tools, such as the Revit package, enable accurate calculations of concrete volumes, required reinforcement steel, and other critical project aspects, significantly enhancing the precision of cost estimations for dam projects [10]. Dahal [4] undertook research highlighting the significant advantages of implementing BIM technology, using systematic review and

case study methods on a hydropower dam in Nepal. Applying 5D BIM principles, the study confirmed that BIM facilitated effective and practical cost management and quantity take-offs with greater accuracy. The use of BIM principles led to substantial savings in time, effort, and expenses associated with budget estimations for hydropower dam construction projects. Hasan, Naimi [9] performed a mixed-method study, including literature review and quantitative and qualitative research, to explore the vital role and contributions of BIM technology and its software tools in cost estimation for the development of dams in Iraq, noting their complex nature, detailed management requirements, long construction durations, and significant material needs (Table 6).

### 3.1.6. Role and Significance of Common Data Environments (CDEs)

Common Data Environments (CDEs) play a crucial role in the successful implementation of Building Information Modelling (BIM) in hydropower projects. CDEs provide a collaborative platform where project data are stored, managed, and shared among all stakeholders, ensuring that everyone has access to the most up-to-date information. CDEs such as Asite and ProjectWise facilitate improved collaboration and communication among project stakeholders by providing a centralized repository for all project-related data. This ensures that all team members, including designers, engineers, contractors, and clients, have access to the latest information, reducing the risk of errors and miscommunication [7]. For instance, Asite offers a cloud-based platform that supports document management, project control, and team collaboration, enabling seamless communication across different project phases. In large-scale hydropower projects, managing a vast amount of documentation can be challenging. CDEs streamline document management by organizing and storing all project documents in a structured manner, making it easy to retrieve and update information. ProjectWise, for example, provides robust document management capabilities, including version control, access permissions, and audit trails, ensuring that all project documentation is accurate and up-to-date [37].

The integration of BIM with CDEs enhances the overall efficiency and effectiveness of project management. By combining BIM models with a CDE, stakeholders can visualize project data in a 3D environment, conduct clash detection, and simulate construction processes. This integration supports better decision-making and reduces the likelihood of rework and delays [36]. ProjectWise, for instance, integrates seamlessly with BIM software like Autodesk Revit, enabling real-time collaboration and model coordination.

Several hydropower projects have successfully implemented CDEs to enhance project management and collaboration. For example, the use of ProjectWise in the management of the Xiluodu Dam project in China demonstrated significant improvements in document control, project tracking, and stakeholder collaboration. Similarly, Asite was used in the Lower Thames Crossing project in the UK, showcasing its ability to manage complex project data and facilitate collaboration among a large number of stakeholders.

### 3.1.7. Security Concerns in Hydropower Projects

Hydropower projects, due to their critical infrastructure status, are subject to significant security concerns that can affect information access and management. These concerns include protecting sensitive data from unauthorized access, ensuring the integrity of project information, and maintaining the confidentiality of operational details.

1. **Protection of Sensitive Data:** Hydropower projects generate a vast amount of sensitive data, including design specifications, operational parameters, and environmental impact assessments. Unauthorized access to this information can pose security risks, including sabotage, the theft of intellectual property, and exposure to cyber threats. BIM and CDEs must incorporate robust security measures to protect sensitive data. For instance, CDEs like Asite and ProjectWise offer advanced encryption protocols and access control mechanisms to ensure that only authorized personnel can access critical project information [7].

2. **Ensuring Data Integrity:** Maintaining the integrity of project data is essential to ensure the accuracy and reliability of information used in decision-making processes. Hydropower projects must implement measures to prevent data tampering and unauthorized modifications. CDEs provide version control features that track changes made to documents and BIM models, ensuring a clear audit trail and enabling the restoration of previous versions if necessary. This helps in maintaining data integrity and ensuring that all stakeholders are working with accurate and up-to-date information [37].
3. **Confidentiality and Information Access:** Confidentiality is a major concern in hydropower projects, especially when dealing with proprietary designs, financial data, and strategic plans. CDEs address this by implementing role-based access controls (RBACs), where users are granted access based on their roles and responsibilities. This ensures that sensitive information is only accessible to those who need it for their specific tasks, thereby minimizing the risk of data breaches and unauthorized access [36].
4. **Cybersecurity Threats:** Hydropower projects are increasingly targeted by cyberattacks due to their critical role in national infrastructure. Cybersecurity measures must be integrated into BIM and CDE platforms to protect against such threats. This includes implementing firewalls, intrusion detection systems, and regular security audits. CDEs like Asite and ProjectWise continuously update their security protocols to address emerging threats and vulnerabilities, ensuring that project data remain secure [22].

Several hydropower projects have successfully addressed security concerns through the implementation of secure CDEs. For example, Hoover Dam in the United States has implemented stringent cybersecurity measures to protect its operational data and infrastructure. Similarly, the Three Gorges Dam in China employs advanced security protocols within its BIM and CDE systems to safeguard against unauthorized access and cyber threats.

### 3.1.8. Sustainability Assessment

To evaluate the sustainability performance of power plants, Azzam, El Zayat [13] introduced a BIM-integrated tool known as the Power Plant Sustainability Metric (PPSM). This tool features various user interfaces for interacting with the PPSM plugin, enabling users to select the type of power plant project, access sustainability criteria within the BIM environment, and input necessary data for the evaluation process. Fougner and Sandvik [14] highlighted Norconsult's innovative approach to sustainable hydropower design by integrating their BIM models with the project's bill of materials using a custom Application Programming Interface (API) [51]. This integration provides a versatile and efficient means for analyzing both quantitative and qualitative material data, with potential for adjustments to evaluate sustainability metrics, including greenhouse gas emissions [52]. Zhang, Zhang [53] devised a lifecycle assessment (LCA) technique for comprehensive carbon footprint analysis in pumped storage hydropower (PSH) projects, leveraging industry foundation classes (IFCs) to facilitate direct carbon emission calculations during the design phase. This approach estimates emissions based on the consumption of diesel, electricity, and materials, using their respective conversion factors.

Evidence gathered from the literature indicates that BIM holds significant potential for aiding the sustainable design of hydropower projects. However, a primary challenge identified is the assessment of sustainability through BIM. This difficulty largely stems from the absence of universally recognized sustainability rating systems for hydropower infrastructures. The complexity of this challenge is compounded by the inherent ambiguity in defining and quantifying sustainability metrics specific to hydropower projects. Such variability in sustainability criteria across different regions and projects adds layers

of complexity to the development of a standardized, global framework for sustainability assessment in this context.

### 3.1.9. Geotechnical Investigation

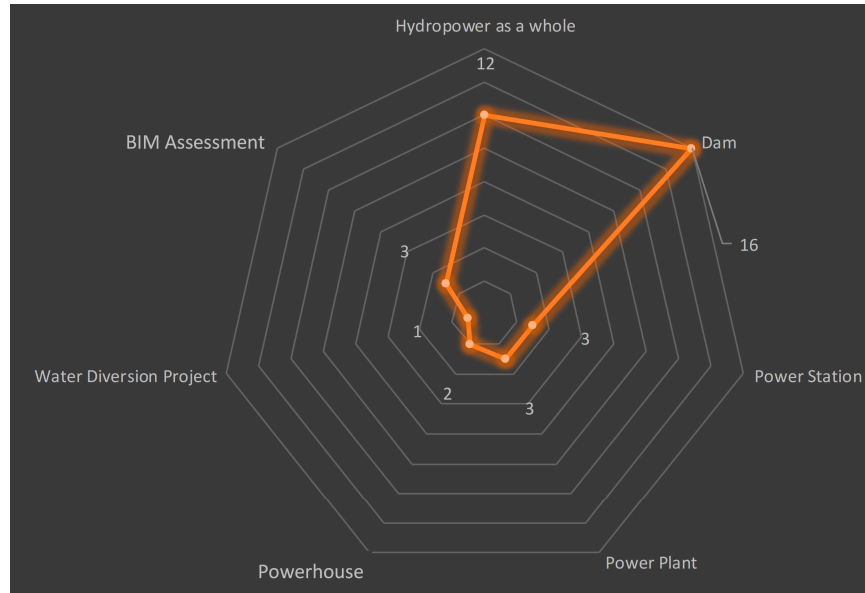
Geotechnical investigation encompasses a comprehensive and labor-intensive process involving the collection, processing, presentation, and analysis of geotechnical data. This multifaceted procedure includes the systematic gathering of geotechnical data, the compilation of geological maps, and the analysis of the collected information. The culmination of this extensive investigation is the production of a detailed investigation report. This report synthesizes all findings and insights derived from the various stages of the investigation, providing a critical foundation for subsequent decision-making and planning in infrastructure projects [54]. Zhang, Wu [55] designed an operational framework for the geotechnical investigation of a hydropower project using a geotechnical BIM model database in which a 3D geotechnical information model and a BIM-based database were integrated. The integration of a continuously updated model and database served as a dynamic platform for both operational tasks and analytical processes. This strategy, by linking each phase of the geotechnical investigation continuum, enabled all operations to be conducted within a 3D BIM model and database environment. Such an approach delivered the potential for significant enhancements in the overall efficiency of geotechnical investigations. Moreover, the synergy created by combining the BIM model with the database aimed to minimize data errors and reduce the need for data conversions. It also addressed the challenge of interpreting the often abstract nature of geotechnical data. Consequently, this integrated system was designed to improve the accuracy of data interpretation, thereby enhancing the reliability and effectiveness of geotechnical assessments for hydropower. Zhang, Wu [56] developed a management approach for hydropower geotechnical data, incorporating it into a centralized database and an informative model to merge geotechnical data with a project's BIM, thus enabling complete lifecycle geotechnical information management. Further extending the integration of BIM with GIS, Zhang, Hou [57] created a platform that amalgamates micro- and macro-scale information into a cohesive system, eliminating the need for standard conversions or plugin installations. [58] examined the application of BIM in green construction management in the context of green water conservancy projects.

The collective body of literature underscores a critical issue: the process of accumulating geotechnical information in hydropower infrastructures is often discontinuous. This discontinuity primarily arises from the loss of geotechnical data during their transfer to subsequent stages, such as design and construction. This challenge hampers the seamless integration of geotechnical data into the lifecycle production and management of these projects, leading to considerable inefficiencies and losses. However, when geotechnical information is systematically archived, combining a centralized geotechnical database with a detailed geotechnical model, the disconnect between the geotechnical investigation phase and subsequent professionals is substantially mitigated. Moreover, the integration of a 3D geotechnical model into the design and engineering model of a hydropower project fosters an environment conducive to collaborative work and multidisciplinary decision-making. This integration not only bridges the gap between different stages of the project but also enhances the overall efficiency and effectiveness of project management.

### 3.2. Components of Hydropower

A comprehensive review of the literature reveals that research on the application of BIM in hydropower has encompassed various components of hydropower infrastructure. Within the scope of the 40 selected studies, a remarkable distribution of focus areas was observed. Specifically, 12 studies [4,20,28,46,47,57] comprehensively addressed hydropower in its entirety, while 16 articles [9,11,15,22,32,39,40,48,53] specifically concentrated on dams. Additionally, the scope of this review included 2 studies [55,59] that focused on

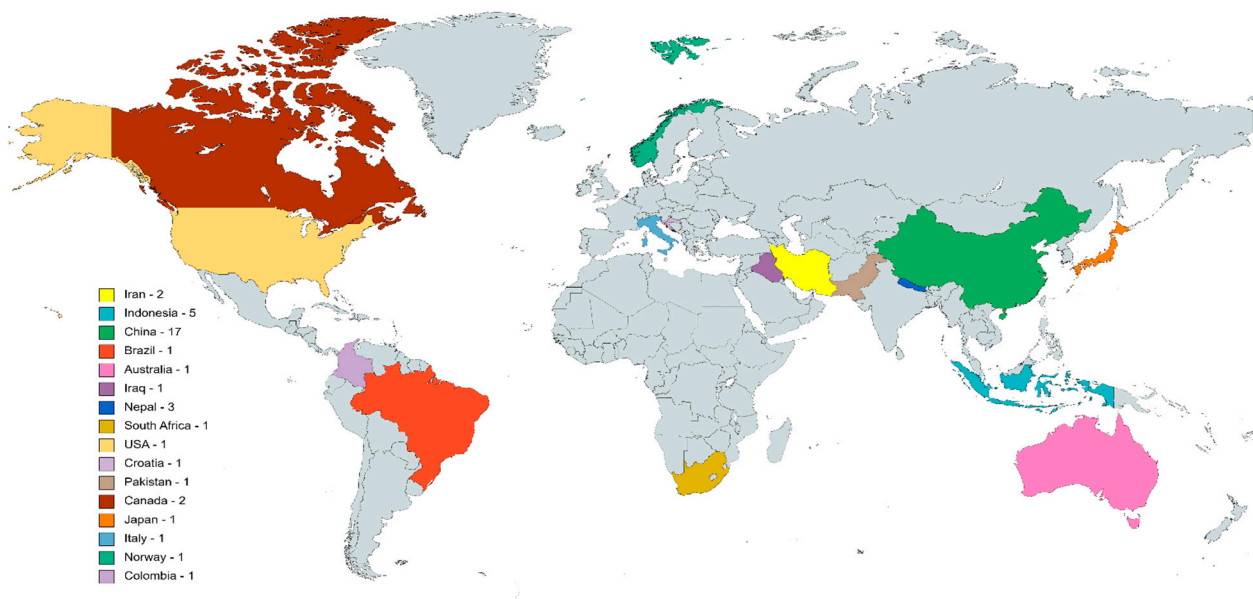
power stations, three papers [8,13,60] that examined power plants, 2 studies [19,35] that explored powerhouses, one [41] that considered a water diversion project, and three [3,6,61] that focused on the assessment of BIM adoption in hydropower. This distribution highlights that the areas of hydropower as a whole and dam infrastructure represent the primary focal points for the majority of researchers in the field, as shown in Figure 4.



**Figure 4.** Literature distribution of BIM in hydropower infrastructures.

The adoption of BIM technology in the field of hydropower engineering is proving to be a catalyst for enhancing the efficiency and quality of engineering design, construction, and operational management processes [20]. Figure 5 indicates the BIM-hydropower literature distribution by country. Many scholars discovered that the development and construction model for hydropower in China, for instance, has shifted from the traditional construction model, where design, construction, and operation are conducted independently, to the BIM-based platform. This new perspective emphasizes digital design, intelligent construction, and intelligent operation, with integrated control throughout the entire lifecycle [38].

In Indonesia [22], the application of BIM in dam construction is progressively being adopted by contractors, primarily in response to directives from the Directorate General of Water Resources. However, its implementation remains constrained by the absence of comprehensive regulations that mandate its use, particularly at crucial stages such as planning by consultants and construction execution by contractors.



**Figure 5.** BIM-Hydropower literature distribution by country.

ISO 19650 [62] is an international standard for managing information over the whole lifecycle of a built asset using BIM. In the context of hydropower projects, ISO 19650 is highly relevant as these projects involve multiple stakeholders, extensive data, and complex coordination. The standard facilitates a structured approach to managing information, ensuring that all parties work with accurate and up-to-date data. However, the adoption of ISO 19650 in hydropower projects varies. In some regions, there is a strong emphasis on following international standards, while in others, awareness and implementation are still developing. For instance, the UK government has been a strong proponent of BIM, mandating its use for all public sector construction projects since 2016. Such national policies not only promote BIM adoption but also encourage the standardization of BIM practices, including adherence to ISO 19650 [22,37]. In fact, the adoption of BIM in hydropower projects is influenced by a combination of project needs, organizational mandates, and national policies. ISO 19650 plays a critical role in standardizing BIM practices, ensuring effective information management and collaboration. While the demand for BIM is driven by the inherent complexities and requirements of hydropower projects, the influence of organizational strategies and national regulations cannot be overlooked. Hence, future research and policy development should continue to promote the adoption of ISO 19650 and other relevant standards to enhance the efficiency and success of hydropower projects.

Sari, Wahyuningrum [22] identified the importance of further research into the integration of BIM in the dam construction process, considering these existing limitations. Dams, being among the most complex and sizable structures in hydropower projects, are inherently associated with significant engineering and environmental risks. The paramount importance of safety in dam projects, given the potentially catastrophic consequences of dam failures, underscores the critical nature of these structures and their emergence as a primary focus in BIM application research.

Contrasting with broader applications in hydropower projects, BIM use in powerhouses has been the subject of only two studies [19,35]. This limited focus is considerable given the unique challenges posed by underground powerhouses, which are frequently situated in complex geotechnical conditions characterized by varied rock or soil properties. The accurate modelling and simulation of these conditions within a BIM framework are a significant challenge, primarily due to the often limited and uncertain nature of geotechnical data. Another observation from the existing literature is that many researchers in the field of BIM application in hydropower design tend to overlook the integration of

critical geotechnical data. This omission could be a contributing factor to the relatively limited research on BIM applications for powerhouses, as the lack of comprehensive geotechnical data integration might impede the full realization of BIM's potential in this specific context.

### 3.3. Methodological Review and Analysis

In terms of the methodological review, the case study methodology emerges as the predominant approach employed by authors to substantiate their findings. A significant number of scholars [11,12,15,38,46,57] in this field have applied their theoretical concepts and procedural innovations to actual hydropower projects, which were in the construction phase during their respective studies. This real-world application provides a practical context for evaluating the efficacy of their research. Interestingly, several researchers [20,32,39,40] have observed that incorporating case studies in their work significantly enhances the utility of the BIM-based approach. Specifically, it facilitates comprehensive assessments of various project aspects by streamlining the development of alternative solutions and providing enriched data representation. This, in turn, supports more informed decision-making processes in relation to the proposed alternatives. The tangible examples provided by these case studies serve to validate the practical applicability and benefits of BIM in the complex field of hydropower project management.

As to the real-life case studies, [7] created a BIM-based collaborative management platform specifically designed for hydroEPC project management. This platform was tested through a case study of an ongoing project in Southwest China, illustrating the platform's effectiveness in fostering collaboration within a BIM framework. The findings indicated that the platform serves as an effective visual and collaborative management tool in actual project settings, leveraging BIM technology for enhanced project management. Similarly, Hasan, Naimi [9] conducted an in-depth examination of the pivotal role BIM technology plays in the cost assessment of intricate dam construction projects. Their analysis included a case study on a specific dam in Iraq, revealing that BIM methodologies significantly reduce human errors in cost estimation and improve the precision and efficiency of dam cost analysis. In another research endeavor, Zhang, Wu [56] explored the integration of a BIM-based geotechnical database within a hydropower station setting. Their experimental study confirmed the effectiveness of their proposed management strategy, validating the integration approach for improved project management.

Only three papers [11,38,40] used a simulation method to practically analyze the findings of their research. All these papers applied the Autodesk Navisworks Timeliner module for the simulation of the hydropower construction process in order to monitor progress in terms of time, concrete temperature, and stress during construction and creep displacement during operation. The simulation methodologies showcased in these studies are anticipated to significantly promote the adoption of BIM in the realm of dam construction and management. This anticipated increase is not only expected to augment the overall effectiveness of these projects but also to serve as a catalyst for enhancing sustainable practices within this sector.

Survey questionnaire was the next method used by the works in the literature. Two studies [3,6] employing this method aimed at gaining a comprehensive and in-depth understanding of the status of BIM usage and of the knowledge, experience, and challenges associated with BIM adoption in hydropower projects.

### 3.4. Assessment of BIM Adoption in Hydropower Projects

As BIM gains widespread acceptance in the construction sector, scholarly attention has shifted towards examining its adoption in developed nations and understanding its perception in developing countries. The study by Bhattarai and Kisi [3] investigated BIM awareness among hydropower experts of Nepal. Their findings revealed that a mere 9% of respondents were aware of BIM's application in hydropower, highlighting a significant knowledge gap. The study also identified the lack of BIM training and awareness as



primary barriers to its implementation in Nepalese hydropower projects. However, it was observed that BIM awareness is on the rise in Nepal, with professionals in the hydropower sector increasingly advocating BIM's mandatory integration into projects.

In contrast, a study by West and Liu [6] revealed that the U.S. Army Corps of Engineers extensively utilizes BIM in hydropower projects, as mandated by policy. In the U.S., BIM is predominantly employed for visualizing designs, rapidly creating 2D plan sheets, and conducting preliminary quantity tabulations for cost estimates. The most significant value of BIM, as identified in the study, lies in its capability to facilitate the clear communication of complex project designs among engineers, stakeholders, and owners. Despite its extensive use, the full potential of BIM in U.S. hydropower projects has yet to be realized. The study pointed out resistance to change and a lack of training as the major challenges hindering its broader adoption.

In a work by Niraula [61], only 23.25% of the construction firms in the AEC industry used BIM among 68 construction companies surveyed in Nepal. The uses of BIM among the firms were all limited to the design phase only and BIM was not applied in the construction, operation, maintenance, and renovation phases. The findings also revealed that BIM technology was barely touched in the hydropower sector in Nepal as major challenges in BIM adoption inherently lay in a lack of new technology to support BIM, expensive software and setup costs, a lack of skilled human resources, and a lack of interest in clients.

#### 4. Discussion

The literature review indicates that prior research has predominantly focused on the application of BIM technology across various components and stages of hydropower projects. This focus is evidenced by the numerous BIM-based frameworks and workflows proposed by scholars, suggesting a growing interest in BIM within the hydropower sector such as dams, spillways, turbines, and powerhouses. These studies not only offer a theoretical analysis of BIM's role in geotechnical investigation, design, collaboration, cost estimation, monitoring, and sustainability assessment in hydropower projects, but also validate their findings through case studies, simulations, and survey questionnaires [3,19,22,23].

Comprehensive analyses of these studies reveal that the integration of robotic technology, automation tools, and 3D laser scanning technologies with BIM can lead to the creation of 3D models for hydropower projects, enhancing collaboration, communication, and information management, thereby improving design efficiency [4,28]. Furthermore, BIM integration with technology promises automation and digitization in hydropower construction, a reduction in human error and safety risks, and improvements in construction productivity and quality [8,32]. For monitoring purposes, BIM facilitates real-time problem detection and early warning processing, ensuring the project's safe and stable operation [15,16].

BIM techniques also significantly reduce human errors in cost calculations, leading to more accurate and efficient project cost evaluations [4,9]. This is particularly evident in studies focusing on 5D BIM, where cost estimation and budget management are enhanced through precise quantity take-offs and real-time updates [10,49]. The literature highlights the advantages of applying BIM to individual components of hydropower projects, such as dams, powerhouses, power plants, and sub-stations, suggesting substantial benefits if BIM is applied comprehensively throughout a project.

Despite these benefits, BIM adoption in hydropower projects is not yet widespread, characterized by a slow yet growing uptake. The literature suggests that BIM adoption in hydropower is in its nascent stages, primarily due to a lack of a pronounced understanding of BIM's potential within the hydropower sector [3]. In developing countries, the limited adoption is largely attributed to the lack of BIM knowledge, relevant skills, and training. This is echoed in the findings of Bhattacharai and Kisi [3], who reported that only 9% of hydropower professionals in Nepal were aware of BIM applications in their field.

In contrast, in developed countries, the slow pace of BIM adoption is often linked to the absence of specific legal and regulatory frameworks [6]. The U.S. Army Corps of Engineers, for example, mandates the use of BIM, but its full potential is yet to be realized due to resistance to change and a lack of training [6]. Additionally, adopting BIM requires a cultural shift within organizations, necessitating staff adaptation to new processes and workflows, which can encounter resistance or reluctance [22]. This resistance can impede the integration of BIM into existing infrastructure development workflows. Furthermore, the literature identifies significant initial costs, investments in software, training, hardware maintenance, a reluctance of stakeholders or subcontractors to use BIM or 4D planning, and a potential loss of proprietary information due to open sharing between disciplines as additional challenges to BIM adoption in hydropower projects [22].

In geotechnical investigations, the integration of BIM with GIS provides a comprehensive platform for managing geotechnical data, improving data accuracy, and enhancing decision-making processes [55]. The integration of 3D geotechnical models with BIM enables a detailed and accurate representation of subsurface conditions, which is critical for the design and construction of hydropower infrastructures [54].

Sustainability assessment using BIM is increasingly recognized for its potential to evaluate and enhance the environmental performance of hydropower projects. Azzam et al. [13] introduced the Power Plant Sustainability Metric (PPSM), a BIM-integrated tool for assessing sustainability criteria. This aligns with the findings of Fougner and Sandvik [14], who demonstrated the use of BIM in analyzing material data and greenhouse gas emissions. However, the lack of standardized sustainability metrics for hydropower projects remains a challenge, as noted by Zhang et al. [20], highlighting the need for further research and development in this area.

#### *Evolution Model*

The evolution model of BIM in hydropower infrastructures, as depicted in Figure 6, can be narratively discussed in the following structure.

*Initial Years (up to 2019)—The Nascent Stage:* The early adoption of BIM in hydropower projects was characterized by a fledgling stage with significant variances in how BIM was adopted across different developed economies. The key challenges during this phase were as follows:

- **Adoption Variance:** There was a lack of uniformity in BIM adoption standards and practices across regions, which led to inconsistencies in results and integration difficulties.
- **Developed Economy Concentration:** Initial BIM adoption was largely concentrated in developed economies, with developing regions lagging behind due to various constraints including technological, economic, and human resources.
- **Application Integration:** BIM was still not fully integrated into the entire lifecycle of hydropower projects, with its use being sporadic and often limited to certain phases of construction.
- **Interoperability:** There was a significant challenge in the interoperability of BIM with other systems, which is critical for seamless data exchange and collaboration among stakeholders.

*Turning Point (2019)—A Surge in Application:* The year 2019 marked a turning point, witnessing a surge in the application of BIM in hydropower structures. This surge was likely due to an increased awareness of BIM's benefits, technological advancements, and a push for industry-wide digital transformation. Key applications that emerged during this phase were as follows:

- **Design and Engineering:** BIM began to be more widely used in the design and engineering phase, facilitating better visualization, simulation, and collaboration.

- Four-dimensional and five-dimensional BIM: There was an expansion in the use of 4D (time-related information) and 5D (cost-related information) BIM, allowing for improved project management and cost estimation.
- Performance Monitoring and Analysis: BIM tools started to be used for ongoing performance monitoring and analysis, aiding in the proactive maintenance and management of hydropower infrastructure. This capability is particularly important for maintaining the safety and efficiency of large structures like dams and powerhouses, where the early detection of issues can prevent catastrophic failures [15].
- Geotechnical and Sustainability Analysis: BIM enabled more detailed geotechnical and environmental impact analyses, contributing to the sustainable development of hydropower projects.

*Operational Impact (2019–2023)—Methodological Enhancements:* Between 2019 and 2023, there was an enhanced methodological approach to the application of BIM in hydropower projects. This period was marked by the operational impact of BIM, as it began to change the actual practices and processes in place. Key technologies that were increasingly employed included the following:

- BIM: The core technology of BIM including BIM authoring tools and analytical applications became more refined, with better software solutions and a push towards standardization across the industry.
- Digital Twin: The digital twin concept took hold, allowing for virtual replicas of physical hydropower assets for simulation and analysis purposes.
- UAV (Unmanned Aerial Vehicle): Drones were used to capture real-time data from construction sites, which could be integrated into BIM models for monitoring and inspection.
- GIS (Geographic Information Systems): Integration with GIS enabled a spatial analysis of hydropower projects, facilitating better site selection and impact assessment.

*Quantum Leap (2023 onwards)—Exponential Growth in R&D:* Post 2023, the field of BIM in hydropower is expected to experience a quantum leap, with a staggering escalation in research and development. Hot topics during this phase include the following:

- Digital and Automation Integration: There is a significant push towards the integration of BIM with advanced digital automation tools, enhancing efficiency and accuracy.
- Uptake for Hydropower Structures: As BIM technologies mature, their uptake for the specific complexities of hydropower structures increases, leading to a more sophisticated modelling and management of such projects.

*Future Directions—Looking Ahead:* The model outlines several key future directions for BIM in hydropower infrastructures:

- Lifecycle Application: BIM is expected to be used across the entire lifecycle of a hydropower project, from conception to decommissioning, allowing for a holistic management approach.
- Geospatial Data Integration: Further integration of BIM with geospatial data is anticipated, which would provide enhanced context and situational awareness for projects.
- Risk Management Strategies: The development of risk management strategies using BIM will become critical, as it can provide predictive insights and proactive mitigation plans.
- BIM Standard for Hydropower Structures: The establishment of a BIM standard specific to hydropower infrastructures is likely to emerge, which would facilitate better quality and consistency across global projects.

The narrative of BIM evolution in hydropower infrastructure is one of progressive integration, innovation, and sophistication. The journey from nascent stages to the potential future of comprehensive lifecycle application indicates a trajectory of increased

efficiency, enhanced collaboration, and improved sustainability in hydropower projects. Each phase of the evolution model not only represents a chronological development but also a paradigm shift in how industry professionals perceive, implement, and leverage BIM technology (Figure 6).

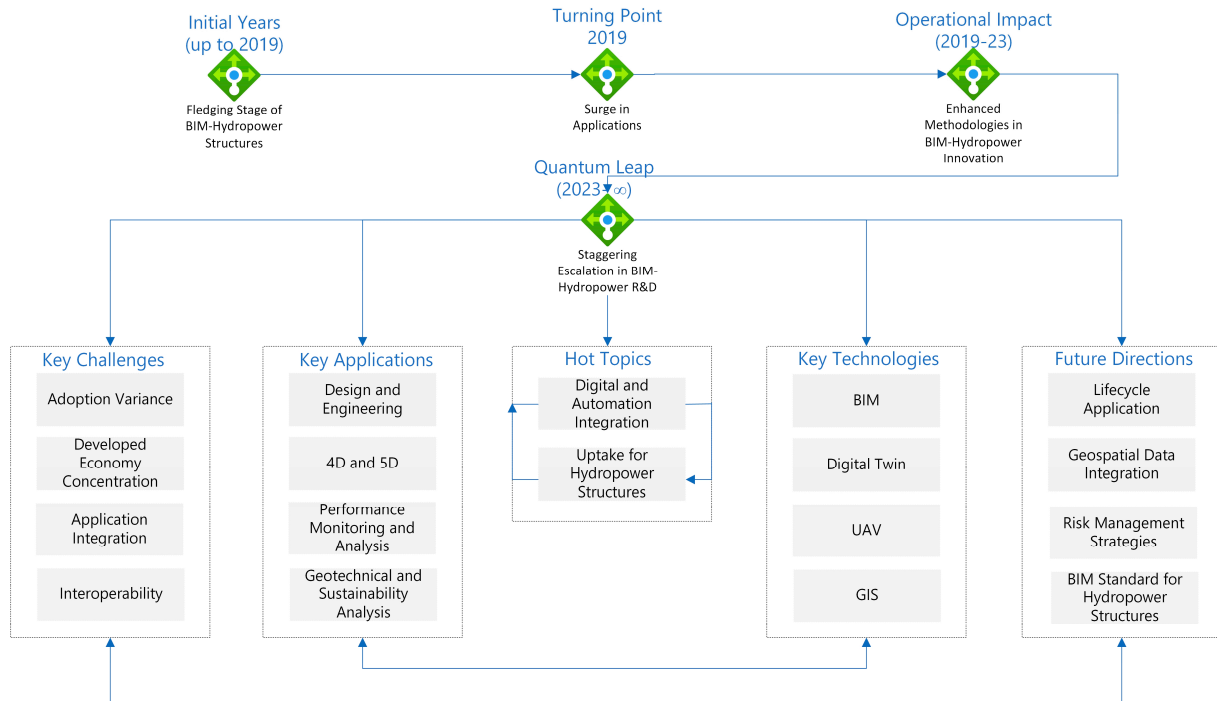
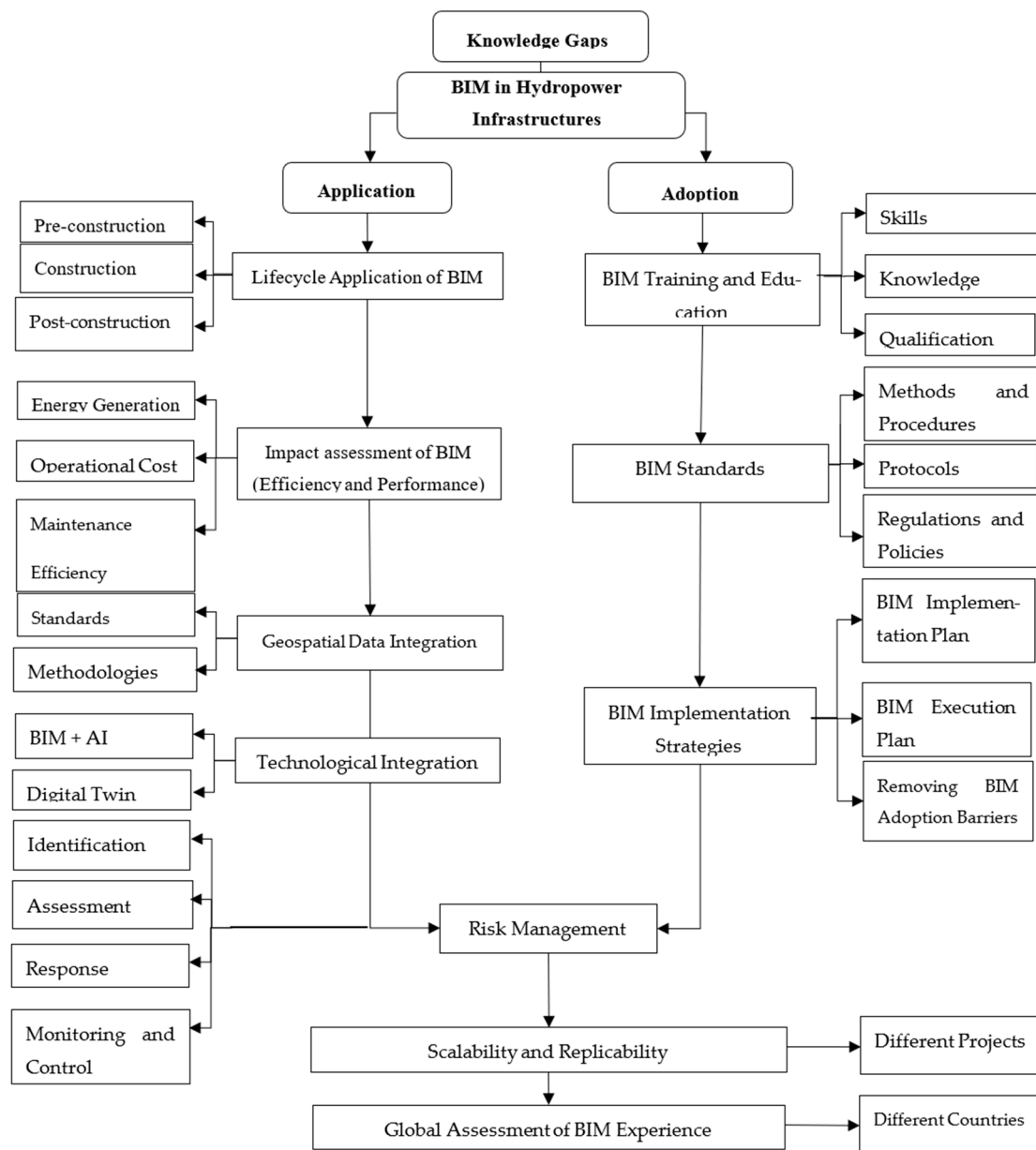


Figure 6. Evolution model of BIM-hydropower infrastructures.

### 5. Gaps and Future Research Directions

Based on the gaps identified in the existing literature on BIM in hydropower infrastructures, the following research avenues are proposed for future investigation (Figure 7):

1. **Comprehensive Lifecycle Application of BIM:** The existing literature primarily focuses on the construction stage of hydropower projects. Future research should broaden this scope to include BIM application across the entire lifecycle of hydropower projects, encompassing the pre-construction, delivery, and post-construction stages.
2. **Impact and Sustainability Assessment of BIM on Hydropower Efficiency:** There is a notable absence of studies quantifying the impact of BIM on the efficiency and performance of hydropower projects. BIM enables comprehensive sustainability assessments by integrating environmental impact data with project models. This is critical for hydropower projects, which must balance energy production with ecological preservation. BIM tools help in optimizing the environmental performance of hydropower plants by simulating various scenarios and assessing their impacts. Future research should evaluate how BIM influences key factors such as energy generation, operational costs, and maintenance efficiency.
3. **Integration of Geospatial Data/GIS with BIM:** The integration of GIS and geospatial data into BIM in hydropower projects has been overlooked, whereas this integration can be immensely useful in developing BIM-GIS models of hydropower infrastructures. Research should focus on developing standards and methodologies for effectively incorporating geospatial data into BIM models.



**Figure 7.** The knowledge gaps and future research framework for BIM-hydropower infrastructures.

1. **BIM Training and Education in the Hydropower Industry:** There is a lack of focus on BIM training and education within the hydropower sector. Future studies should investigate effective training and education programs to equip professionals with the requisite BIM skills and knowledge for successful adoption.
2. **Development of BIM Standards and Guidelines for Hydropower Projects:** Unlike building projects, there are no specific BIM standards and guidelines tailored for hydropower projects. This area warrants attention in future research to establish relevant standards and guidelines.
3. **Risk Management and Mitigation via BIM:** The role of BIM in risk management and mitigation throughout the lifecycle of hydropower projects remains unexplored. Research should examine how BIM can aid in identifying and mitigating risks.
4. **Scalability and Replicability of BIM Solutions:** The scalability and replicability of BIM solutions in different hydropower projects have not been addressed. Investigating how BIM models and processes can be scaled and replicated across various hydropower facilities is crucial.

5. **Comprehensive BIM Implementation Strategies:** There is a lack of research on comprehensive BIM implementation plans for hydropower. Future studies should focus on establishing detailed implementation strategies to streamline the BIM adoption process and overcome barriers.
6. **In-depth Interviews with Industry Experts:** Future research should conduct in-depth interviews with industry experts, project managers, and stakeholders in hydropower projects to gain practical insights into the challenges and benefits of BIM implementation. These interviews will help uncover specific barriers to BIM adoption and identify opportunities for improvement based on real-world experiences.
7. **BIM and AI Integration:** Integrating BIM with artificial intelligence (AI) offers significant potential for hydropower projects. AI can automate tasks, optimize project scheduling, and predict issues, enhancing BIM's functionality. Research should focus on practical applications of AI in BIM in hydropower, using machine learning to analyze data and improve decision-making processes.
8. **Role of Digital Twins:** Digital twins—virtual replicas of physical assets—can greatly benefit hydropower projects by enabling real-time monitoring, predictive maintenance, and performance optimization. Future research should explore the use of digital twins in hydropower, both as standalone tools and as part of a larger system of interconnected twins, to improve the coordination and management of project components.
9. **Global Assessment of BIM Experience in Hydropower:** Current findings on BIM experience in the hydropower sector are limited to a few countries. It is recommended to conduct broader assessments across a diverse range of countries for a more generalized understanding of BIM application in hydropower (Figure 6).

The discussions and evolution model along with the gaps and future research directions were systematically derived and presented to capture the progression and maturation of BIM applications in hydropower projects. By analyzing studies chronologically, identifying underexplored areas, critically assessing the methodologies, findings, and limitations, and mapping the existing research landscape, the specific gaps in knowledge were identified and the opportunities for future research, emerging trends, technological advancements, and shifts in research focus were recognized. The evolution model (Figure 6) and the presented knowledge gaps and future research recommendations (Figure 7) underscore the necessity for continuous education and training for professionals in the hydropower sector to keep abreast of technological advancements. It also highlights the importance of policy-making that encourages the adoption of such technologies and the development of global standards to ensure uniformity and interoperability.

## 6. Implications of Research Findings

### Implications for Practice

1. **Enhanced Design and Construction Efficiency:** The integration of BIM in hydropower projects significantly enhances design and construction efficiency. The ability to create detailed 3D models and integrate them with advanced technologies such as digital twins, UAVs, and GIS allows for more precise planning and execution. This leads to reduced errors, improved accuracy, and faster project completion times. Practitioners can leverage these capabilities to streamline workflows, reduce rework, and improve overall project outcomes.
2. **Improved Collaboration and Communication:** BIM facilitates better collaboration and communication among stakeholders through shared digital models and integrated platforms. This enhances coordination, reduces misunderstandings, and ensures that all parties have access to the latest project information. By adopting BIM, organizations can foster a more collaborative environment, leading to more effective teamwork and project management.

3. **Cost Savings and Budget Management:** The use of 5D BIM for cost estimation and budget management provides more accurate and efficient financial planning. By enabling precise quantity take-offs and real-time updates, BIM helps in reducing human errors and unforeseen expenses. This can lead to significant cost savings and more predictable budgeting for hydropower projects.
4. **Real-Time Monitoring and Risk Management:** BIM's capability for real-time monitoring and risk management ensures safer and more stable project operations. The integration of UAVs and photogrammetry for monitoring construction progress helps in the early detection of issues and timely interventions. This proactive approach can significantly mitigate risks and enhance project safety.

#### **Implications for Policy and Regulation**

1. **Development of BIM Standards and Guidelines:** This research highlights the need for developing specific BIM standards and guidelines tailored to the hydropower sector. Regulatory bodies can use these findings to establish frameworks that ensure the consistent and effective implementation of BIM across projects. Standardized guidelines can help in overcoming the current barriers to BIM adoption and promote uniformity in practice.
2. **Promotion of BIM Training and Education:** To address the knowledge and skill gaps identified in this study, policymakers and industry leaders should invest in comprehensive BIM training and education programs. These programs can equip professionals with the necessary skills to effectively use BIM tools and methodologies, thereby facilitating smoother adoption and integration.
3. **Incentives for BIM Adoption:** Governments and regulatory bodies can consider providing incentives for the adoption of BIM in hydropower projects. These could include tax benefits, subsidies for software and training, and recognition programs for early adopters. Such incentives can encourage more organizations to embrace BIM, leading to broader implementation and enhanced project outcomes.

#### **Implications for Future Research**

1. **Lifecycle Application of BIM:** Future research should explore the comprehensive application of BIM across the entire lifecycle of hydropower projects, from pre-construction to operation and maintenance. This holistic approach can provide deeper insights into the long-term benefits and challenges of BIM, guiding more effective implementation strategies.
2. **Integration with Emerging Technologies:** The integration of BIM with emerging technologies such as AI, machine learning, and IoT offers exciting possibilities for further enhancing project efficiency and innovation. Research in this area can uncover new applications and methodologies that push the boundaries of what BIM can achieve in hydropower projects.
3. **Global Assessment and Case Studies:** Conducting global assessments and detailed case studies of BIM implementation in diverse contexts can provide valuable lessons and best practices. This can help in understanding the factors that influence successful adoption and the ways in which BIM can be tailored to different project environments and regional requirements.
4. **Environmental Impact and Resource Management:** The ability of BIM to integrate sustainability metrics and perform lifecycle assessments (LCA) can greatly enhance the environmental performance of hydropower projects. This allows for more sustainable resource management, reduced environmental impact, and better compliance with environmental regulations.
5. **Resilience to Climate Change:** By incorporating environmental data and climate models into BIM, hydropower infrastructures can be designed to be more resilient to climate change and extreme weather events. This ensures that these critical infrastructures can withstand, adapt to, and recover from disruptions while maintaining efficient operations.

As we look ahead, the ongoing research and development of BIM in hydropower infrastructure suggests a future where digital twins, real-time data integration, and advanced analytics play pivotal roles in sustainable energy production. The progressive maturation of BIM applications is likely to lead to more resilient and efficient hydropower structures, capable of meeting the increasing demands for renewable energy sources while minimizing environmental impact.

This can serve as a roadmap for academics, industry practitioners, and policymakers in strategizing the future directions for BIM applications in hydropower projects. It is essential to foster a culture of innovation that embraces these technological changes, ensuring that the hydropower industry continues to evolve and effectively contribute to sustainable development goals.

## 7. Conclusions

In conclusion, this comprehensive review of BIM applications and adoption in hydropower projects delineated a clear trajectory of progress and outlined pivotal areas for future research. This study highlights a growing interest in BIM within the hydropower sector, evidenced by the development of various BIM-based frameworks and workflows. Remarkably, BIM integration with advanced technologies like robotics, automation tools, and 3D laser scanning has shown potential in enhancing design efficiency, construction automation, and operational management in hydropower projects. Hydropower infrastructures are increasingly challenged by climate change, environmental uncertainties, and the need for sustainable management. In this context, this article's exploration of BIM applications across the lifecycle of hydropower projects—from planning and design to engineering, operation, and maintenance—is crucial. BIM, integrated with technologies like AI and digital twin, allows for the real-time monitoring and simulation of hydropower infrastructures. This capability is invaluable in anticipating and mitigating risks such as equipment failure, water flow irregularities, and environmental hazards.

Moreover, this article's discussion of the challenges and adoption gaps, particularly in developing countries, underscores critical aspects of the human and institutional factors. It advocates capacity building, training, and the development of legal frameworks, essential for the effective implementation of BIM. These aspects contribute to building a resilient workforce capable of managing and adapting hydropower infrastructures to evolving challenges. However, the full potential of BIM in the hydropower sector remains largely untapped, with its adoption still in the early stages, particularly in developing countries. This is attributed to several factors, including a lack of comprehensive understanding of BIM's benefits, insufficient BIM knowledge and training, and the absence of specific legal and regulatory frameworks. Moreover, cultural resistance within organizations and the significant initial investment in software, training, and hardware maintenance are other considerable challenges impeding wider BIM adoption.

This research identified several key areas for future investigation, including the need for a comprehensive lifecycle application of BIM in hydropower projects, the integration of geospatial data with BIM, and the development of specific BIM standards and guidelines for hydropower projects. Furthermore, studies focusing on the scalability and replicability of BIM solutions, along with comprehensive BIM implementation strategies, are essential to enhance the adoption and efficiency of BIM in the hydropower sector globally. Alternatively, this study is subject to certain constraints. The conclusions drawn rely on the literature identified using a specific set of keywords and databases. Despite employing a broad initial search refined through a recognized method, it is possible that relevant studies may have been overlooked. The scope of publications reviewed was confined to the most recent decade, spanning the years 2013 to 2023, which was deemed an appropriate timeframe for evaluating the contemporary literature in this domain. All in all, this review provides a foundational platform for future research, with the potential to catalyze significant advancements in the application and adoption of BIM technology in hydropower infrastructures.



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