A Comprehensive Analysis of Groundwater Inundation Vulnerability and Remediation for Infrastructures

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Abstract. The rising threat of groundwater inundation, characterized by the elevation of the water table above the ground surface, is increasingly impacting various infrastructure components. This issue has the potential to damage critical infrastructure elements such as building foundations, roads, bridges, and other essential aspects. The intensification of this problem can be linked to the growing frequency of severe weather events, alterations in land use, and increased groundwater withdrawals. This comprehensive review paper seeks to capture the current knowledge base concerning groundwater inundation vulnerability and potential remediation strategies for infrastructure. To achieve this, we performed a thorough literature review encompassing a variety of sources, including peer-reviewed journals, conference proceedings, and technical reports, among others. Our goal is to consolidate the existing understanding of groundwater inundation and its implications for infrastructures and assess the current methodologies for vulnerability evaluation and damage mitigation. Our findings from this review are intended to provide insight into the present state of this field and highlight the significant challenges and promising opportunities for future research.

Keywords: Remediation; infrastructures; groundwater; vulnerability; Inundation; analysis.

1. INTRODUCTION

Groundwater inundation poses a significant threat to global infrastructures, with an increasing number of incidents reported due to intensified weather extremes, alterations in land utilization, and escalated groundwater extraction. This phenomenon, characterized by the water table exceeding the ground surface, contributes to the deterioration of essential infrastructure components such as building foundations, bridges, and roads. The implications extend beyond structural damages, encompassing economic setbacks, public health risks, and environmental harm.

This systematic review aims to extensively analyze groundwater inundation vulnerability and remediation techniques for infrastructural systems, collating the prevailing knowledge on this matter and the associated impacts. It will evaluate the various assessment methods and mitigation strategies to counteract the implications of groundwater inundation on infrastructure. Our approach will encompass a rigorous review of a wide range of sources, including peer-reviewed articles, conference materials, technical reports, and other pertinent literature to comprehensively understand the current state of the art and identify potential avenues for future research.

Recent developments in groundwater inundation research and its impact on infrastructures have highlighted this rising environmental concern. This review intends to amalgamate existing knowledge in this field, enabling a broader understanding of the mechanisms, vulnerabilities, and potential mitigation strategies associated with groundwater inundation. Furthermore, this review aims to unveil gaps and future research opportunities while encapsulating the current state-of-the-art. Kelman and Spence [1] offered a comprehensive examination of the influence of flood actions on buildings, demonstrating the capacity for floods to cause substantial damage through various mechanisms, such as direct water contact, force exertion, pressure impact, and chemical reactions. Their work provides a valuable foundation for examining direct flood damage and sets the stage for further exploration into indirect damage and potential remediation strategies.

Knott et al. [2] focused on coastal road infrastructure, using numerical modeling to assess the potential repercussions of rising groundwater levels due to sea level rise. Their findings underscore the need to incorporate consideration of groundwater levels in planning and designing coastal road infrastructure. Their work has important implications for policymakers and engineers planning future coastal infrastructure in response to sea level rise. McBean et al. [3] employed regression analysis to assess the impact of several variables, including resident's flooding experience, household income, residential floor area, and assessed property value, on the variability of flood damage curves. Their research provides useful insights for refining predictions of flood damage in residential dwellings.

Merz et al. [4] examined data from multiple flood events in Germany, focusing on direct economic losses. Their findings revealed high variability in damage data, with absolute depth-damage functions showing limited efficacy in explaining this variability. They stressed the importance of refining flood damage data collection and modeling for more accurate damage estimates. Gold et al. [5] explored the issue of stormwater infrastructure inundation in coastal urban areas along the US Atlantic coast, revealing that such inundation is likely widespread and occurs frequently, thereby increasing the risk of urban flooding. Their research emphasizes the need for measures to mitigate the risk of flooding in these coastal urban areas.

Zhai et al. [6] developed a conceptual model of flood damage to houses and their contents, concluding that factors such as house type, house ownership, house structure, residing period, and household income significantly impact damage probabilities and values. Their research offers a more nuanced understanding of the factors contributing to flood damage beyond the primary consideration of inundation depth. Klemes [7] proposed a systematic methodology for testing hydrological simulation models, a critical step in assessing the operational adequacy of these models. Rotzoll and Fletcher [8] highlighted the potential impacts of sea-level rise on groundwater inundation in low-lying coastal areas, emphasizing the need for measures to mitigate the impact of sea-level rise. Vekerdy and Meijerink [9] examined the flood-induced groundwater rise in an alluvial aquifer in Hungary. Their findings highlighted the role of the water levels in the complex floodplain and the riverbed conductance of silted-up branches during the flood rise, informing our understanding of the propagation of flood-induced groundwater rise. Schinke et al. [10] developed a GRUWAD model to estimate building damage caused by high groundwater levels in urban areas. Their work provides a basis for cost-benefit analysis and mitigation strategies for urban areas prone to groundwater inundation.

Al-Sefry and S¸en [11] assessed the problem of groundwater rise in Jeddah City, Saudi Arabia, providing recommendations to control and reduce the groundwater rise problem. Decker [12] developed a numerical model to evaluate the effects of projected sea level rise and precipitation changes on the drainage infrastructure and groundwater system

2. METHODOLOGY

This comprehensive review paper, titled "A Comprehensive Analysis of Groundwater Inundation Vulnerability and Remediation for Infrastructures," utilizes an exhaustive yet coherent method to collate and evaluate the extensive literature available on the subject of groundwater inundation and its consequent impact on infrastructure. The key objectives include assimilating, condensing, and interpreting data from diverse sources to present a comprehensive understanding of the current state of this field and shed light on potential remediation tactics. Due to the intricate nature of the topic that combines geological, hydrological, and engineering perspectives, our review's ambit is wide-ranging. Besides discussing various remediation strategies, we aim to capture the intricacy of groundwater inundation and its influence on infrastructure vulnerability.

This review's rigorous and systematic methodology is characterized by meticulous literature identification, careful screening, extraction, and critical analysis. Our intention is to ensure that the review is exhaustive, balanced, dependable, and of superior quality. Each stage of our review process is conscientiously designed to uphold these guiding principles, focusing on preserving the transparency and integrity of our research methodology. This section elaborates on the methodology adopted for our review, describing the literature identification and selection process, data extraction and coding procedures, and the techniques adopted for data synthesis and interpretation. In doing so, we hope to provide a lucid illustration of our research journey, from sifting through the voluminous literature to distilling key insights that form the bedrock of our review.

a) Identification of Relevant Sources: First, identify the most relevant sources of information to our topic. This will include peer-reviewed academic articles, technical reports, conference papers, and government reports on groundwater inundation, its impacts on infrastructures, and remediation strategies. Various databases such as PubMed, Web of Science, Scopus, and Google Scholar will be used for this purpose.
b) Screening and Selection: Following the identification of potential sources, a rigorous screening process will be initiated based on specific inclusion and exclusion criteria. The criteria could include the topic's relevance, publication year, and publication type. This process will ensure that only high-quality, relevant studies are included in the review.
c) Data Extraction: After selection, data from each source will be extracted. This may include details such as the year of the study, study location, type of infrastructure examined, main findings, proposed remediation techniques, and other relevant details.
d) Thematic Analysis: The selected literature will be subjected to a thematic analysis, which will involve identifying common themes across the various studies. Each study will be coded according to these themes.
e) Synthesis and Interpretation: The final step will be synthesizing and interpreting the data. This will involve consolidating the findings from different studies and discussing them in the context of the overall research question. Potential remediation strategies will also be compared and evaluated based on effectiveness, practicality, and cost.

3. RESULTS

The systematic review methodology led to arranging the findings into three primary categories: (a) Groundwater inundation's effects on infrastructure, (b) Evaluating infrastructure vulnerability due to groundwater inundation, and (c) Techniques to remediate infrastructure impacted by groundwater inundation. We will examine each of these aspects using case studies, as indicated in Tables 1, 2, and 3.

3.1 Influence of Groundwater Inundation on Infrastructure

The cited literature consistently paints a clear picture of the adverse effects of groundwater inundation on diverse infrastructure types. The effect of groundwater inundation on elements of infrastructure are listed in Table 1.

Table 1: Impact of groundwater Inundation on Infrastructure.

ID	Infrastructure Element	Effects	Financial Ramifications	Reference	Example Region
1	Residential and commercial structures	Deterioration due to water and subsequent chemical changes	Costs of repair, upkeep, or total replacement	Kelman and Spence [1]	Coastal Region X
2	Transport systems	Long-term erosion of road surfaces	Costs of total replacement	Knott et al. [2]	Coastal Region Y
3	Water control systems	Immediate structural damage	Costs of repair and maintenance	Gold et al. [5]	Coastal Region Z

3.2 Evaluating Infrastructure Vulnerability Due to Groundwater Inundation

Various methodologies were found in the literature for assessing infrastructure vulnerability to groundwater inundation. Assessing infrastructure vulnerability to groundwater inundation is given in Table 2.

Table 2: Assessing infrastructure vulnerability to groundwater inundation.

ID	Evaluation Technique	Description	Significant Variables	Reference	Example Region
1	Regression model	Forecasts flood destruction	Water level and Infrastructure type	McBean et al [3]	Coastal Region X
2	Computation models	Precise damage estimation	Water level, Infrastructure type, and Data collection	Merz et al. [4]	Coastal Region Y
3	Multivariable model	Estimates potential harm	Water level, Infrastructure type, Building strength, Socioeconomic elements	Zhai et al. [6]	Coastal Region Z

3.3 Techniques to Remediate Infrastructure Impacted by Groundwater Inundation

Different mitigation and remediation strategies focused on infrastructure planning, design, and maintenance aspects are recommended. These findings offer insights into the complex interactions between groundwater inundation and infrastructure, highlighting the need for comprehensive solutions to tackle this pressing issue. They also mirror the growing body of research in this domain, laying the groundwork for further investigation. Some of groundwater inundation remediation techniques are listed in Table 3.

Table 3: Groundwater inundation remediation techniques.

ID	Mitigation Approach	Description	Considered Scenario	Reference	Example Region
1	Improving wastewater systems	Improving wastewater systems, irrigation adjustments, and relocation of wastewater dumping grounds	Present condition	Al-Sefry and S¸en [11]	Coastal Region X
2	Incorporating future climate conditions	Inclusion of future climate change scenarios into planning and infrastructure management	Sea level changes, Rainfall pattern alterations	Decker [12]	Coastal Region Y

4. CONCLUSIONS

This comprehensive review has illuminated three integral dimensions related to groundwater inundation: the bearing on infrastructure, the infrastructure's vulnerability, and feasible remediation actions.

- From the study, it can be observed that groundwater inundation impacts a variety of infrastructure types, leading to both immediate structural damage and long-term decay of the components. Economic ramifications linked with repair, replacement, and maintenance have been found to be noteworthy, presenting formidable challenges to regions with heightened susceptibility to groundwater inundation, such as coastal areas.
- Diversity has been noticed in the methodologies explored for assessing infrastructure vulnerability due to groundwater inundation, spanning intricate regression models, comprehensive data accumulation, computational modeling, and an inclusive approach accounting for physical and socioeconomic factors. The multiplicity of these approaches punctuates the complexity of groundwater inundation and its impact, underlining the requirement for customized assessment and management plans.
- It has been found that remediation strategies aren't merely confined to rectifying immediate damages; they underscore the necessity for strategic planning, infrastructure design, and diligent maintenance. The

necessity of incorporating future climate change scenarios in these strategies has been highlighted to ensure the long-term durability and resilience of infrastructures facing the menace of groundwater inundation.

- In conclusion, this review has emphasized the multi-dimensional nature of groundwater inundation, its ramifications on infrastructure, and the complexity of required solutions. The urgency for a collaborative and holistic approach towards managing groundwater inundation has been accentuated. It calls for rigorous planning, inventive design, and prudent maintenance to safeguard our infrastructure and fortify our future. The primary findings of our review are highlighted in the following simplified diagram (see Figure 1):

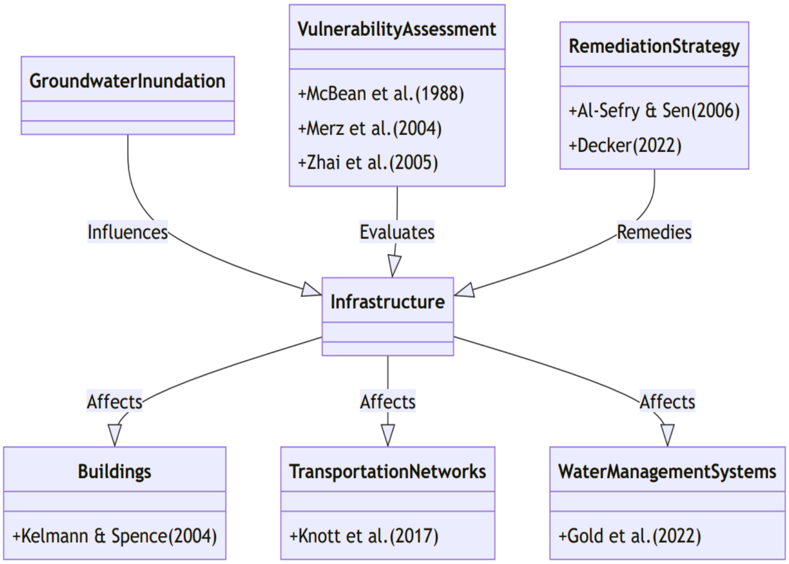

Figure 1: Key relationships of groundwater inundation, infrastructure, vulnerability assessment, and remediation strategy.

This diagram summarizes the main entities and their relations, reflecting the outcomes of our comprehensive review. It serves as a visual guide for future research and can facilitate our understanding of groundwater inundation's impact on infrastructure.

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