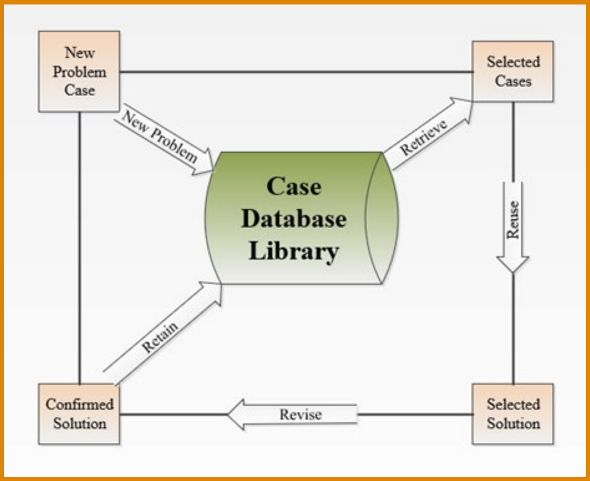
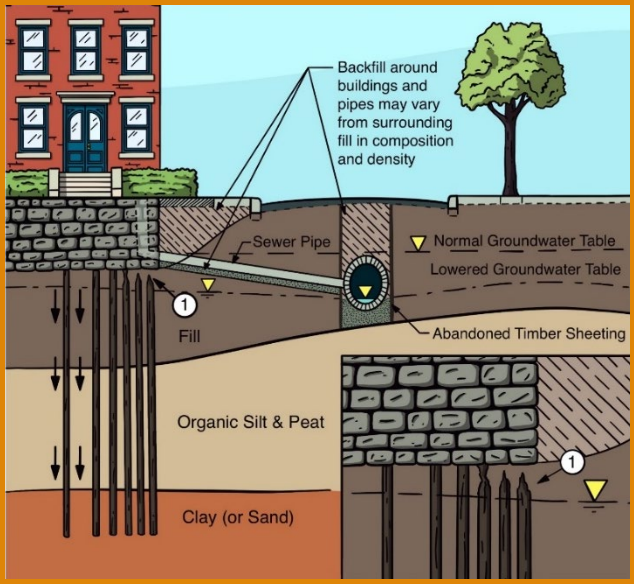
CIVIL ENGINEERING PRACTICE · JOURNAL OF THE BOSTON SOCIETY OF CIVIL ENGINEERS SECTION / ASCE

Winter 2025 VOLUME 32, NUMBER 1 ISSN: 0886-9685

Case Based Reasoning Bridge Deterioration Model



Boston's Groundwater Preservation Initiative: Groundwater Recharge System Analysis and Design



Instrumentation and Monitoring of a New FRP Composite Bridge using Sensing Textiles

Challenges and Innovations in Designing Underground Reservoirs for Urban Water Management

Volume 32, Number 1

CIVIL ENGINEERING PRACTICE · JOURNAL OF THE BOSTON SOCIETY OF CIVIL ENGINEERS SECTION / ASCE

CONTENTS

CIVIL ENGINEERING PRACTICE JOURNAL OF THE BOSTON SOCIETY OF CIVIL ENGINEERING SECTION / ASCE (ISSN 0886-9685) is published by the Boston Society of Civil Engineers Section / ASCE (founded 1848). Editorial, circulation, and advertising activities are located at: Boston Society of Civil Engineers Section / ASCE, The Engineering Center, One Walnut Street, Boston, MA 02108-3616; 617-227-5551. Known as the *Journal of the Boston Society of Civil Engineers Section / ASCE* until 1985, Vol. 71, Nos. 1 & 2.

Civil Engineering Practice seeks to capture the spirit and substance of contemporary civil engineering through articles that emphasize techniques now being applied successfully in the analysis, justification, design, construction, operation and maintenance of civil engineering works. Views and opinions expressed in Civil Engineering Practice do not necessarily represent those of the Society.

Civil Engineering Practice welcomes and invites the submission of unsolicited papers as well as discussion of, and comments on, previously published articles. Please contact our editorial office for a copy of our author guidelines. Please address all correspondence to the attention of the Editor.

Editorial, Circulation & Sales Office:

Civil Engineering Practice
Boston Society of Civil Engineers Section/ASCE
One Walnut Street
Boston, MA 02108-3616
www.bsces.org
bsces@engineers.org
617-227-5551

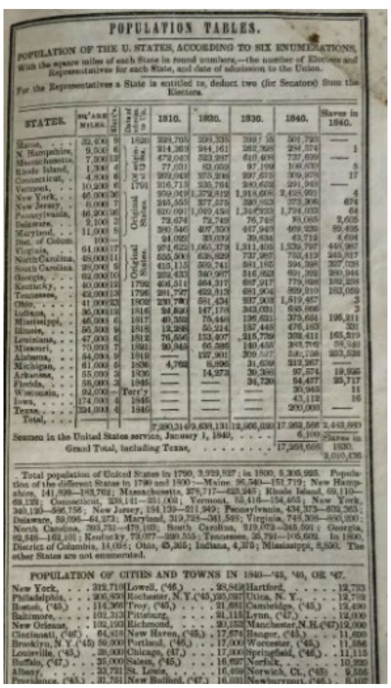
CIVIL ENGINEERING PRACTICE™ · JOURNAL OF THE BOSTON SOCIETY OF CIVIL ENGINEERS SECTION / ASCE

Message from the BSCES President

I am proud to announce the release of the Winter 2025 issue of the BSCES Civil Engineering Practice journal. During its nascence, BSCES publications leaned heavily toward railroad infrastructure, water supply, and coal and gas, which is understandable for the engineering climate in 1848 and is evidenced through the founding member occupations which skewed heavily toward these disciplines.

Joint standing committee on Boston Harbor, Map of Boston Harbor: showing commissioners' lines, wharves &c. (1852)

At this time, Boston had a population of a bit over 100,000 (654K in 2024) and Massachusetts as a state had a population around 750,000 (7.2M in 2024); its population had doubled since 1830 and industrialization, infrastructure and development in full effect at the city expanded its footprint substantially.



1848 FARMER'S ALMANAC Population Table

This was an area of exponential expansion and growth, which was apparent in the ongoing projects of the decade such as the Beacon Hill Reservoir, the Cochituate Aqueduct, railroad expansion (from 10 to 1,200 miles in MA between 1835-1855) and the ever-expanding shoreline of the city.

We find ourselves in a substantially different era today, when extensive engineering efforts are focused on the maintenance of our existing aging infrastructure and the preservation of the old as we build the new. Two of the articles in this journal address these distinct areas, *Case-Based Reasoning Bridge Deterioration Model* by Nasser Yari and *Boston's Groundwater Preservation Initiative: Groundwater Recharge System Analysis and Design* by Z.K. Boswell, J.A. Dominguez, and B.P. Strohman.

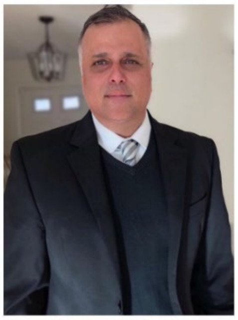
I am excited to see that a third article addresses the use and monitoring of FRP in composite bridges. In their article, *Instrumentation and Monitoring of a New FRP Composite Bridge Using Sensing Textiles*, Tzuyang Yu and his coauthors delve into utilizing FRP in new construction and retrofits. I firmly believe that it is advances such as these that will drive the innovation we need to address our infrastructure needs as we integrate the old with the new.

Lastly, this issue of the journal features an insightful article by Kishore Bandela, which is titled *Challenges and Innovations in Designing Underground Reservoirs for Urban Water Management*. This article examines whether subsurface reservoirs might be a sustainable solution for addressing water shortages in metropolitan areas and controlling flooding.

I would like to extend my sincere thanks to Dr. Gautham Das and BSCES Journal Editorial Board members for the immense work and dedication that goes into each journal issue. A Fall 1986 Civil Engineering Practice article titled, "BSCES: History and Heritage," by Gian S. Lombardo, details the founding and growth of BSCES starting in 1848. The original bylaws were based on the premise that "every member be required to present a paper, or make a gift of a scientific book, map, plan, or model each year." The journal and professional papers herein directly hearken back to the basest intent of BSCES. A special thanks to Nasser Yari, Z.K. Boswell, J.A. Dominguez, B.P. Strohman and Tzuyang Yu and his coauthors, and Kishore Bandela for their publications and their support of our Society's fundamental practice of civil engineering.

Christopher P. Hersey, LEED AP
BSCES President, 2024-2025

Message from the Editor-in-Chief



Welcome to this latest issue of *Civil Engineering Practice*, the flagship publication of the Boston Society of Civil Engineers Section (BSCES). As engineers, we are tasked with designing and maintaining infrastructure that is both innovative and enduring, and this issue reflects the dedication of our community to meet these challenges head-on.

In this edition, we bring you three outstanding contributions that showcase the transformative impact of research and collaboration on modern civil engineering practice.

The first paper, *Case-Based Reasoning Bridge Deterioration Model* by Nasser Yari, leverages artificial intelligence to revolutionize bridge asset management. This work introduces a predictive methodology using historical data to anticipate deterioration in bridge components, enabling precise maintenance planning and resource optimization. The findings have broad implications for enhancing the longevity and safety of vital transportation networks.

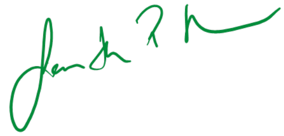
Our second paper, *Boston's Groundwater Preservation Initiative: Groundwater Recharge System Analysis and Design* by Z.K. Boswell, J.A. Dominguez, and B.P. Strohman, addresses the critical issue of preserving Boston's historic neighborhoods. The authors present a detailed study of groundwater recharge systems required under Article 32 – Groundwater Conservation Overlay District. This multidisciplinary work highlights the delicate balance between urban development and the preservation of historical foundations.

The third paper, *Instrumentation and Monitoring of a New FRP Composite Bridge Using Sensing Textiles* by Tzuyang Yu and colleagues, showcases a groundbreaking approach to structural health monitoring. By employing advanced sensing textiles integrated with fiber optic technology, the authors offer an innovative solution for real-time monitoring of FRP composite bridges, with implications for both new construction and retrofits. This collaboration between academia and industry highlights the potential of interdisciplinary partnerships to drive progress in our field.

Each paper in this issue exemplifies the creativity, rigor, and collaborative spirit that are hallmarks of our profession. Whether addressing the challenges of aging infrastructure, preserving historical landmarks, or exploring innovative materials and technologies, these authors remind us of the vital role civil engineers play in shaping our world.

I extend my heartfelt thanks to the authors for their contributions, the reviewers for their invaluable insights, and the editorial team for their dedication to producing this issue. As always, we aim to provide a platform for ideas and research that inspire innovation and foster professional growth.

We hope these articles will spark new ideas and encourage meaningful discussions among our readers. Together, let us continue advancing the practice of civil engineering and strengthening the foundations of our society.



Gautham P. Das
Editor in Chief
Journal.board@bsces.org

Volume 32, Number 1

Case Based Reasoning Bridge Deterioration Model

Nasser Yari[1]

[1] Department of Civil Engineering Wentworth Institute of Technology, Boston, Massachusetts
E-mail: yarin@wit.edu

Published December 15, 2024

Abstract

Today's increasing average truck/vehicle miles per gallon is significantly decreasing transportation infrastructure budgets making it more difficult to sustain desirable network bridge inventories above minimum condition assessments. A bridge forecasting model is a vital part of decision making within any Bridge Management System (BMS) and the quality of decision making depends greatly on the ability to predict the future condition of bridge components accurately. The deterioration model based on artificial intelligence (AI) techniques using a Case-Based Reasoning (CBR) method was developed to support proposed GIS Based Bridge Management System (GBMS) using the data provided by New Hampshire Department of Transportation (NHDOT). CBR methodology solves new problems based on the solutions of similar past problems. The proposed model is based on the following: 1) A case library is developed based on classifications outlined in this paper, this method uses the similarity in the performance among bridges under same environmental condition, similar traffic volume, similar level of maintenance procedures within a district, analogous operating condition, and matching bridge type and material; 2) The problem bridge is evaluated to predict future deterioration rates, the system retrieval searches the database for similar case bridges then the system proceeds to a final solution.

Development and implementation of a Case-Based Reasoning (CBR) method provide states and municipalities with a tool to help identify maintenance repair, prioritize bridge rehabilitation and replacement, develop preservation strategies, and allocate available funds accordingly.

Keywords: Bridge Management, Deterioration, Bridge Components, Prediction

1. Introduction

A deterioration model is one of the minimum requirements of any Bridge Management System (AASHTO 1993). Infrastructure deterioration is caused by climatic exposure, traffic volume, insufficient financial resources, and absence of a network management system. State DOTs and municipalities are recognizing the need to implement effective tools to better manage transportation infrastructure networks and are now demanding decision-support tools (Vanier 2000). In bridge asset management, knowledge of deterioration rates is crucial for forecasting and long-term planning. Bridge deterioration is the progression of bridge components deteriorating over time due to normal operation not including natural disaster and impact damage (Chen 2022). The deterioration process due to normal aging under different environmental conditions consists of very complex occurrences of physical and chemical changes in bridge components. Each bridge component- deck, superstructure, and substructure consists of many different elements and each element has its own unique deterioration rate (Thompson, 2001). In the early 1970s some deterioration models were developed to provide a tool for decision-makers by predicting the future condition of a pavement. This approach has been employed to develop a deterioration model for BMS (Agrawal et al, 2010).

Bridge element deterioration is caused by many different factors comprising of age, material quality environment, design characteristics, construction methods, traffic conditions etc.

A number of Probabilistic Deterioration Markov-Based Methods, both state-based and time-based, were developed in the past to forecast deterioration rate. The state-based model which forecasts long-term bridge conditions using transition probabilities is computed from the difference between the two condition states at a given discrete time interval. The time-based model or duration model is based on element deterioration from initial state to next lower condition state. Some of the models that were developed are Markov-Based Method (Bu et al 2014), integrates state based/time-based probabilistic, and Poisson regression (DeStefano and Grivas 1998). However, these models have limitation issues such as stationary transition probability, state-independence assumption (Bu et al 2014), and failure to account for routine preventive bridge maintenance such as annual water proofing and bridge washing. Some of these models only predict the concrete bridge deck deterioration. Furthermore, the relationship between superstructure and the deck is overlooked including deck type, membrane, bridge joint, and deck geometry. This paper presents the latest advanced deterioration model for the reliable prediction of future bridge performance including deck, superstructure, and substructure.

There are approximately over 610,000 public bridges in the United States with an average age of 42 years (ASCE 2017).. The National Bridge Inventory (NBI) is the aggregation of structure inventory and appraisal data which was initially developed in 1971 to observe bridge operations and safety. The NBI inventory data consisting of 116 items provides information for each bridge. These items are specified in the Recording and Coding Guide for the structure inventory and appraisal of the Nation's Bridges (FHWA-PD-96-001). The National Bridge Inspection Standards (NBIS) were established in 1971 to require that all bridge inspection processes, frequency of inspections, qualification of the bridge inspectors, bridge inspection reports and the maintenance of bridge inventories meet the National Bridge Inspection Standards. All bridges longer than 20 feet (6.1 meters) must be inspected per (NBIS; 23 CFR 650 subpart C) and reported by the states and federal agencies to the Federal Highway Administration. Therefore, each State DOT in the United States have a large number of historical bridge-condition ratings since 1979. This massive data system can be used for CBR case library to develop an advanced deterioration model for the reliable prediction of future bridge performance. The conditions are measured visually or by using instruments based on the guidelines and standards established by the Federal Highway Administration (FHWA) and the American Association of State Highway and Transportation Officials (AASHTO) Guide for Commonly Recognized (CoRe) Structural Elements (SE).

NBI condition ratings for various bridge components are designed based on the NBI guidelines and are listed in Appendix A. The AASHTO Guide for Commonly Recognized (CoRe) Structural Elements (SE) is an alternative to NBI condition rating. The AASHTO rating should be converted to an NBI rating using FHWA's computer program NBI translator. The FHWA National Bridge Elements (NBEs) are intended to provide consistency countrywide to standardize element condition.

Case-Based Reasoning (CBR) is an AI model developed in 1980s. Latest advancements in AI models, machine learning and deep learning, many applications in a wide range of engineering and technology fields are utilizing the benefits of AI models. In addition, large datasets from various fields are available, and such datasets are used to train and test AI models to successfully predict outcomes with sufficient accuracy (Althaqafi 2022). The approach is solving new problems based on the solutions of similar past problems. The CBR field has grown rapidly over the past three decades and is a powerful technique for computer reasoning. CBR approach uses detailed knowledge of previous experiences and tangible problem circumstances instead of relying only on general knowledge of a problem. The primary knowledge source is not generalized rules but a memory of stored cases detailing previous experiences. A new problem is solved by finding a comparable past case and applying it to the new problem. Every time a new experience is stored, it is immediately made available for future problems. Much of the original inspiration for the CBR approach came from the role of reminding in human reasoning (Schank, 1983 and Kolodner, 1985).

The proposed deterioration model is one of the five modules that were developed to support a GIS Based Bridge Management System (GBMS). In this model, a similarity measure of classification is developed to identify how close the characteristics of bridge components are to each other based on a scoring system. There are a number of steps required to predict the future condition of an existing bridge (the problem bridge).

CBR Model

This Case-Based Reasoning systems are based on a five-step process .

1. New problem bridge evaluated for future condition rating.
2. The CBR retrieves the "most similar" case or a set of similar cases which are called proposed solutions.
3. Reuse: Utilization of information and knowledge from selected cases and adapting the solutions to address a new problem.
4. Revise: Test the new solution and revise for future use. Learning in CBR systems is by adding new cases with sufficient detail to expand the information base.
5. Retain: Store the experience gained from all new cases, to continuously upgrade the database to include the use of new materials and procedures for use in future problem solving.

Figure 1 illustrates the CBR process based on the aforementioned steps. First, a new problem (new case) is solved by the CBR program by searching the case database library for one or more recorded similar cases to the new problem. Second, the CBR program reuses the retrieved cases and selects the solution of the best-matched problem and recommends a solution to an existing problem. Third, CBR through revised process evaluates this solution between the initial problem and the retrieved cases. The revised solution is, then, evaluated for potential success and modified if necessary. Fourth, CBR approach continually expands the case database library by adding new learned cases and supplementing existing cases when appropriate (These steps are explained in detail in later sections).

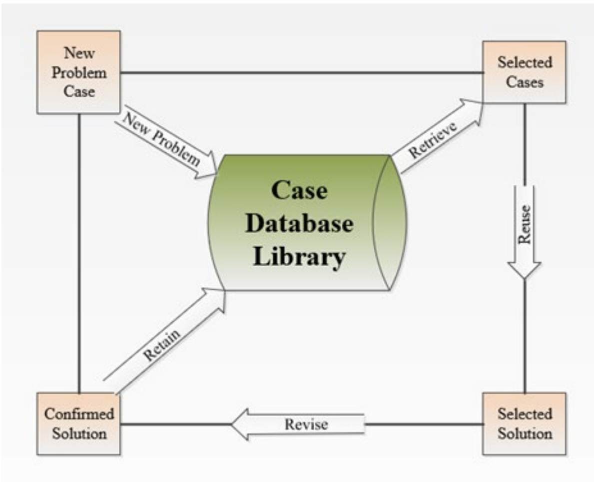


Figure 1. CBR Process.

Bridge components Case Development

The Retrieval process begins with an initial problem description and ends when best matching previous case/cases have been found. It is imperative that the CBR case library and analysis approach follows appropriate knowledge level modeling methods in defined cases, particularly the components of expertise methodology.

A similarity measure of classification is developed to identify how close the characteristics of bridge components are to each other based on scoring system values between 0 and 100, where 100 is totally similar and 0 is completely dissimilar. The CBR bridge deterioration model methodology is based on the similarity in the performance among bridges under similar environmental conditions, traffic volume, analogous operating condition, matching bridge type and material, and the equivalent level of preventive maintenance. The bridge components (deck, superstructure and substructure) case matching process is based on the following parameters for a bridge structure:

1. Bridge Structure Type, there are many different types of bridges, the most common ones in the State of New Hampshire are girder or beam type, culvert, timber, truss, and moveable.

2. Bridge Deck Types, A bridge deck is the most vulnerable component in a bridge. A severe environment, an increase in traffic volume, and aging are some of the main reasons for rapid bridge deck deterioration. There are three common materials used in the construction of bridge decks, including concrete, steel, and timber.

a. Concrete decks are the most common bridge deck type due to its workability to form in various shapes and sizes and are the most flexible alternative for the bridge designer and the bridge builder; it is most adaptive to a variety of construction techniques. However, concrete being weak in tension requires reinforcement and thus receptive to corrosive deterioration. There are several common types of concrete decks including reinforced cast-in-place (CIP), precast, prestressed deck panels, and precast prestressed deck panels with a cast-in-place topping. It is very important to identify the type of rebar used on the bridge deck. Concrete with black rebar deteriorates faster than coated and stainless-steel rebar and some fiber reinforced plastics.

b. Steel decks are composed of either solid steel plate or steel grids. There are three common types of steel decks which include corrugated steel flooring, orthotropic grid deck, and open, filled, or partially filled.

c. Timber decks are considered non-composite. This is due to inefficient shear transfer through the attachment devices between the deck and superstructure. There are some steel bridges with timber decking. Timber is relatively easy to fabricate, and timber can also withstand significant loads over a short period of time and is locally available. There are a few basic types of timber deck, plank decks, glued-laminated deck panels, nailed laminated decks, stressed-laminated decks, and structural composite lumber decks.

3. Wearing surface is a thin layer, less than 3 inches, placed on the bridge deck to seal and protect the bridge deck from traffic and weather conditions. The basic type of wearing surface classification for each bridge deck type includes, bituminous overlay, membrane and bituminous overlay, thin overlay, rigid overlay, timber planks, concrete and serrated steel.

4. District; most DOTs are divided into small districts and each district maintains their roads and bridges, as does each municipality at different condition levels which can have a significant effect on deterioration rate and must be classified accordingly to maintenance protocol. For example, Turnpike districts wash their bridges every year while other DOT districts and municipalities never wash their bridges. A primary issue is the application of de-icing chemicals typically used in urban areas.

5. ADT; the average daily traffic is subdivided into 3 case categories. Each category is based on volume of traffic. Case category 1 being ADT>25,000, case category 2 ADT of 10,000 to 25,000, and case category 3 with ADT< 10,000.

6. Road Classification; there are various types of roads (interstate, state routes, recreational road, town, and city streets, rural highways and unmaintained roads) within each highway network which receives different levels of maintenance.

An inspection history of over 2000 bridges provided by NHDOT is used to define cases based on the said requirements. The inspection history with NBI condition ratings is available from late 1970s to present.

Matching Process

The case matching process is based on a scoring system value between 0 and 100 where 100 is totally similar (problem bridge is similar to the case bridge) and 0 is completely dissimilar. The matching type for bridge deck is illustrated in Table 1 and the scoring system used to define cases is shown in Table 2. The case library database for this model consists of over 2000 bridges provided by NHDOT. The matching technique from the case library is based on three categories. Over 50% of the bridges in the case library have 70% similarities and this is used as a minimum baseline. The three categories include: A) Statewide Average Case Bridge (SACB) which is a group of bridges that have a 70% or more similarities based on criteria shown in table 2. B) Average Case Bridge (ACB) includes groups of bridges with 90% similarities and C) Refined Case Bridges are ACB bridges that are within the same district and have similar roadway geometric properties.

Table 1. Bridge Deck Matching Type

Deck Type		Bridge Type	
A	Cast in place with none coated rebar		Girder
B	Cast in place with coated rebar		Timber
C	Cast in place with stainless steel rebar		Culvert
D	Precast		Truss
E	Precast Prestressed deck panels		Ridged Frame
F	Precast Prestressed deck panels with cast in place toping		
G	Corrugated steel flooring	**ADT**	
H	Orthotropic deck	1	>= 25000
I	Grid Deck - open, filled, or partially filled	2	10000 to 25000
J	Plank deck Timber	3	<10000
K	Nailed laminated deck		
L	Glued-laminated deck planks	**Wearing Surface**	
M	Stressed-laminated decks	1	Membrane with Asphalt Bituminous
N	Structural composite lumber decks	2	Concrete
		3	Timber Planks
Road Classifacation		4	Serrated steel
Tier 1	Interstates, Turnpikes, and Divided Highways		
Tier 2	Statewide Corridors	**District**	
Tier 3	Regional Transportation Corridors	1	Highway Maintenance
Tier 4	Local Connectors	2	Turnpike
Tier 5	Local Roads	3	Municipality

Table 2. Matching Type Value

Category	SACB	ACB	RM
Matching Type	Point	Point	Point
Bridge Type	30	30	30
Deck Type	30	30	30
Wearing Surface	10	10	10
District	NA	NA	10
Road Class	NA	10	10
ADT	NA	10	10
Total	70	90	100

Case Bridge

The bridge deck deterioration rate is used to predict the future decline in the condition of the bridge deck; this information is used to prepare appropriate MR&R strategies (Kong, et al,2022).Every case bridge in the database is linked to an average case bridge. Average case bridges (ACB) are a group bridges that have 90 % or more similarities within the case bridge. The NHDOT's bridge data is used to determine on average how many years a bridge deck remains at the various NBI condition code states. The condition rating is based on NBI specifications which were developed by FHWA (FHWA 1989). A new bridge deck typically starts at a NBI condition code of 9 and declines throughout its life. The condition rating ranges from 0 to 9, 0 being the bridge deck has failed. A 4 rating is when the bridge is classified as structurally deficient and an NBI 3 rating warrants bridge closure. The process of building the average case bridge involves analyzing each bridge inspection history. The length of time in years that a bridge deck stays at NBI condition rating increments is recorded and combined with other 90% or better similar bridges to obtain an average table 3 and 4.

Each NBI rating must go through a complete cycle which includes the beginning and end dates for each condition rating cycle. Table 3 is an example of ACB (average case bridge) which includes a group of 25 bridges with 90% similarities. All these bridges are girder type bridges with type B deck (concrete cast in place with coated rebar), tier 1 road classification. and ADT greater than 25,000. Table 4 is an example of SACB (Statewide average case bridges) which includes a group of 103 bridges that are girder bridges with type B deck and have asphaltic membrane with 2 inches of bituminous pavement for wearing surface.

Table 3. Average Case Bridge(ACB) for Type B Deck

Girder bridge Type B Deck, Membrane, Tier 1 and ADT>25 K							
NBI Rating	**9**	**8**	**7**	**6**	**5**	**4**	
Bridge 1	4	9	18				
Bridge 2	2	4	14				
Bridge 3				10	7	5	
Bridge 4	2	6			7		
Bridge 5	2	4	21				
Bridge 6	2	4	23				
Bridge 7	2	2	23				
Bridge 8	3	12					
Bridge 9	5					6	
Bridge 10	4	4				10	
Bridge 11			19				
Bridge 12		8			6		
Bridge 13		9			6		
Bridge 14	4	11	23				
Bridge 15			23				
Bridge 16	4			12			
Bridge 17				11			
Bridge 18			14	12			
Bridge 19	2	10		11			
Bridge 20			24				
Bridge 21		14					
Bridge 22					10		
Bridge 23				14	8		Average expected
Bridge 24			22				lifespan to reach
Bridge 25	4				9		structurally deficient
Average(year)	3.1	7.5	20.4	11.7	7.6	7.0	57.1 Years

Table 4. Statewide Average Case Bridge (SACB) for Type B Deck

Girder bridge with concrete deck, concrete cast in place, (Type B), membrane, 2" pavement. Statewide (70)							
NBI Rating	9	8	7	6	5	4	
Bridge 1	4	8			6	14	
Bridge 2				6			
Bridge 3			24				
Bridge 4		20					
Bridge 5		18					
Bridge 6		6					
Bridge 7							
Bridge 8					12	4	
Bridge 9			20				
Bridge 10	2	16					
Bridge 11				14			
Bridge 100	2	12	12	13			
Bridge 101	1	7	6	3			Average expected
Bridge 102	2	12	16				lifespan to reach
Bridge 103	4	24					structurally deficient
Average	**3.25**	**11.51**	**16.54**	**11.58**	**10.00**	**8.71**	61.6 Years

Bridge conditions are assessed by trained DOT bridge inspectors through an inspection process per National Bridge Inspection Standards (NBIS), which involves the use of specific techniques to assess the physical condition of bridges. Visual inspection is conducted on a routine or scheduled basis; however, the reliability and accuracy of the inspection can be within +/- 1 NBI rating. Because the condition assessment of NBI rating of 8 and 7 are similar, same bridge decks can be rated 7 by one bridge inspector and 8 by another. However, combining the number of years the bridge deck condition remains at NBI 8 and 7 will result in a more accurate assessment. Analyzing the data provided by NHDOT, as illustrated in Table 3, the total years in NBI 8 and 7 is 27.9 years and from Table 4 is 28.05 years, as shown in Figure 2.

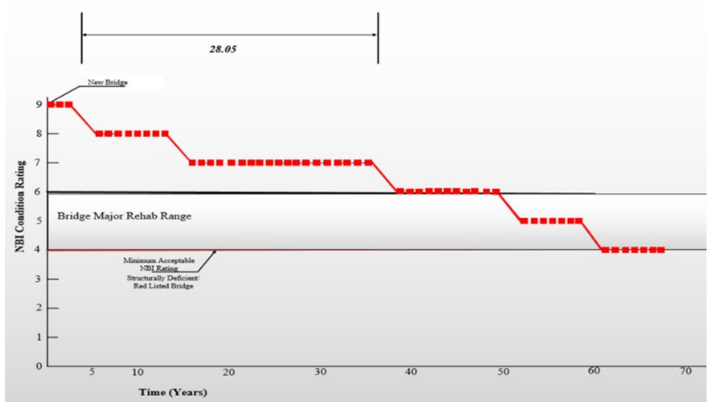


Figure 2. Deterioration Rate for Concrete CIP Deck

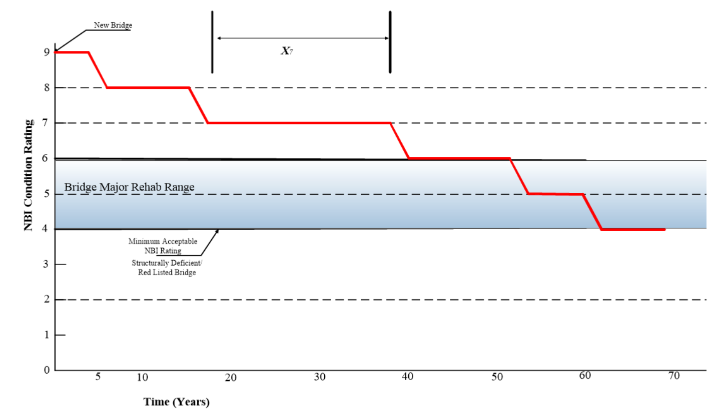


Figure 3. Average Case Bridge (ACB) Deterioration Rate for Type B Deck

Figure 3 demonstrates the deterioration rate for type B case bridge where Xi is the length of time in years that the bridge deck remains at a specific NBI condition rating.

The deterioration rate of bridge components (deck, superstructure, and substructure) is determined by the rate of deterioration between two consecutive NBI ratings calculated by the following equation:

$$D_i = \frac{CC_i - CC_{i+1}}{T_{i+1} - T_i}$$

Where,

Di is Deterioration rate at NBI *i*

CCi is Components condition rating at NBI *i*

Ti is Time at NBI *i*

Retrieval Process

The problem bridge is evaluated by the model on an individual basis and classified based on criteria shown in table 1 framework. The system retrieval will analyse the problem bridge using the matching process to search for the most similar bridge case in the case library database as outlined in Figure 4.

1. The system retrieval searches the database for ACB (bridge similarity greater than or equal to 90 points) based on the matching process. If a match is found, the system retrieval searches for a Refine Match (RM) based on condition history. The RM search on the identified ACB matches seeks bridges within a 10% differential over a designated number of years. Once RM matches are found the system continues to predict the problem bridge future deterioration rate.

2. If ACB is found and there are no RM bridges then the system proceeds to a final solution.

3. If ACB is not found, then the system will search the SACB data file through matching process to locate a matching set of bridges then proceeds to final solution.

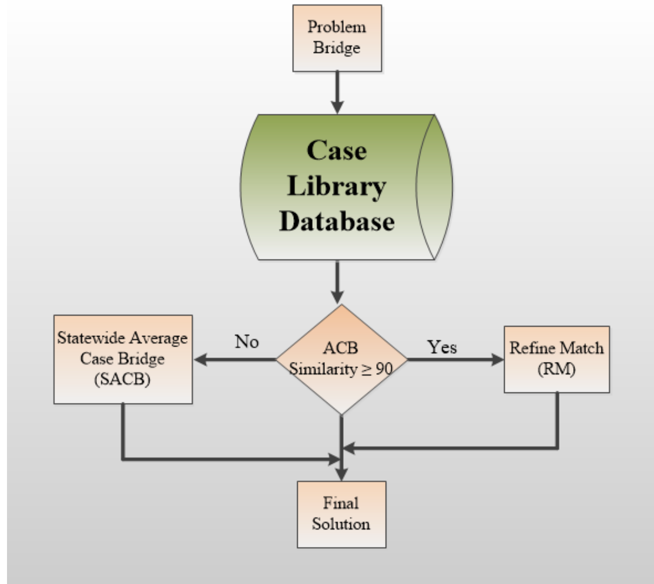


Figure 4. Retrieval Process

Example: a problem bridge (bridge # 145/060) with the given following information requires a deck condition rating be determined in 2028.

Bridge Type	Girder	NBI Rating	
Deck Type	Concrete CIP w epoxy coated rebar	1996	9
Wearing	Membrane, and 2" Pavement	1998	8
District	TPK	2000	8
Road Class	1	2002	8
ADT	> 25 K	2004	7
Year Built	1993	2006	7
		2008	7
		2010	7
		2012	7
		2014	7
		2016	7
		2018	7
		2020	7
		2022	7

Using the matching retrieval process for the given information this bridge classifies as a type B case bridge. The ACB type B is used to predict the future condition of the bridge deck. From the ACB data file there are two bridges (Bridge 5 and 6) that are very similar to the problem bridge. These two bridges are classified as Refine Match (RM).

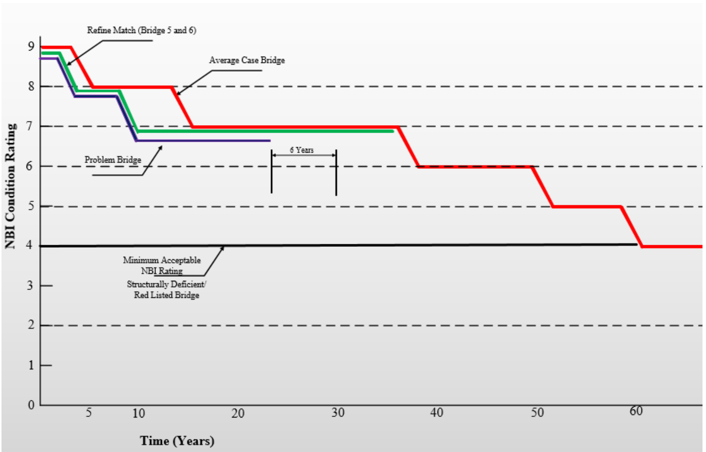


Figure 5. Problem Bridge

The Problem bridge is deteriorating at a faster rate than the average deterioration rate for the matching case bridges (Figure 5) even though the problem bridge mirrors two other bridges in the ACB file. In this case, the governing deterioration rate is the refined match (RM). The predicated condition rate for the problem bridge at age 32 is NBI 7, as shown in Figure 5.

Evaluation of Accuracy

Table 5 is one of the examples of one hundred blocks of randomly selected bridges which were used to evaluate the performance of the CBR model in terms of predicting the condition ratings of different bridge components. In this group of randomly selected bridges, the model predicted 91% accuracy for the deck, superstructure, and substructure combined based on retrieved refined match. However, the result was much different when the model couldn't find refined match. Figure 6 shows the summary of the results' percent retrieval. When a bridge was randomly selected, 73% of the time the CBR model was able to find a refined match with an average of 91% accuracy. However, if the refined match was not available, the CBR model was able to find average case bridge 93% of the time with reduced accuracy of 79%. Consequently, when both refined match and average case bridge were not available, the statewide average was available 100% of the time with low accuracy of 67%. The reason for reduced accurateness is undocumented repair work; the provided data from NHDOT has date of year built and year reconstructed. If the bridge was rehabilitated through bridge design and work was contracted out, then it is documented. However, each district maintenance has their own bridge crew for routine maintenance. Some of the repairs could be major like deck replacement and these types of work by bridge maintenance are not documented.

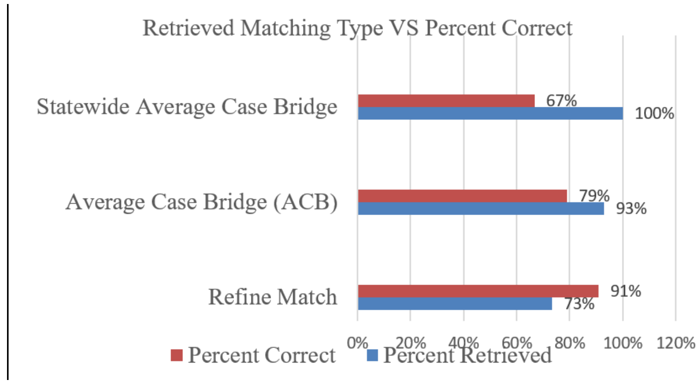


Figure 6. Accuracy Based on Retrieval Category

Table 5. Predicted Condition Vs Actual Condition

Predicted Condition vs Actual Condition for Year 2022												
#	Bridge Number	Predicted Condition			Actual Condition			Year Built	Year Rebuilt	Bridge Type	Deck Area (SF)	District
		Deck	Superstructure	Substructure	Deck	Superstructure	Substructure					
1	Bartlett 120/104	7	7	7	7	7	7	1926	1986	Girder	464.1	1
2	Bath 123/070	7	7	7	7	7	7	1990		Girder	16741.4	1
3	Bedford 151/152	7	5	6	7	5	6	1964	1995	Girder	4549.9	5
4	Bedford 184/132	7	7	6	7	8	6	1959	1993	Girder	6824.4	TPK
5	Bedford 189/122	8	8	8	8	8	8	2013		Girder	18279.9	TPK
6	Bedford 195/085	8	8	8	8	8	8	2010		Girder	50093.8	TPK
7	Bedford 199/129	7	6	6	7	6	6	1960	1992-21	Girder	50309.5	5
8	Bedford 201/082	8	8	8	8	8	8	2011		Girder	4588.5	5
9	Bethlehem 099/152	7	4	6	6	4	6	1927	1998	Truss	2976.2	1
10	Bethlehem 100/050	7	7	6	7	7	6	1959	1991	Girder	3440.2	1
11	Bow 136/155	5	7	7	5	7	7	1978	2007	Girder	13142.5	TPK
12	Bow 136/158	8	8	8	8	8	8	2014		Girder	16758.7	TPK
13	Bow 136/161	7	7	7	7	7	7	1978	2002	Girder	13103.4	TPK
14	Bow 140/159	7	7	7	7	7	7	1800	1996	Girder	888.4	5
15	Brentwood 136/109	8	7	8	7	7	8	1997		Girder	6926.3	6
16	Brentwood 137/108	8	7	8	8	7	8	1997		Girder	3249.8	6
17	Brentwood 137/109	8	7	8	8	7	8	1997		Girder	7414.5	6
18	Brentwood 138/108	8	7	8	8	8	8	1997		Girder	3293.9	6
19	Bristol 097/069	6	6	7	6	6	7	1982		Girder	1142.4	2
20	Bristol 097/075	7	8	7	7	8	7	1999		Girder	2508.6	2
21	Bristol 100/082	4	4	4	4	4	4	1924	1965	Girder	1980.1	2
22	Bristol 100/095	7	7	7	7	7	7	1949		Girder	1701.2	2
23	Campton 115/126	7	7	6	7	7	6	1934	1985	Girder	634.8	2
24	Campton 117/076	6	6	7	6	6	7	1869	2014	Timber	4032.2	2
25	Campton 117/126	7	7	7	7	7	7	1900	1973	Girder	543.4	2
26	Campton 117/135	6	5	6	6	5	6	1927		Girder	2411.7	2
98	Newport 097/139	1	1	1	1	1	1	1989	-4	Girder	424.8	2
99	Newport 103/136	9	9	9	9	9	9	1937	1989	Truss	2137.3	2
100	Newport 116/142	6	6	5	6	6	5	1845	1994	Timber	1955.3	2
	Newport 129/115	6	7	7	6	7	7	1979	-4	Girder	3485.1	2

Summary

The quality of decision making depends on the ability to accurately predict the future condition of bridge components. The deterioration process due to normal aging under different environmental conditions is a very complex occurrence of physical and chemical changes in bridge components. To address this, a deterioration model based on the artificial intelligence (AI) technique, the case-based reasoning (CBR) method was developed. CBR methodology solves new problems based on the solutions of similar past problems. The proposed model is built on 1) The development of a case library based on classifications outlined in table 1.This method uses the similarity in the performance among bridges under analogous environmental conditions, similar traffic volume, similar level of maintenance procedures within a district, analogous operating conditions, and matching bridge type and material; 2) The evaluation of the problem bridge to project its future deterioration rates, and the system retrieval searches the database for similar Average Case Bridges (ACB). If the ACB is found, then the system retrieval searches for higher similarities and if there are none, then the system proceeds to a final solution, as shown in Figure 4. The developed deterioration model CBR is practical and uses detailed knowledge of previously experienced, tangible problem circumstances stored in the BMS library database. Every time a new experience is stored, it will be available immediately for analysing future problems. CBR has overcome the limitations of other deterioration models. The current condition state is utilized by CBR model searching through the case library database by matching the condition history, thus eliminating the uncertainty and randomness of other Markovian models. This CBR model works best with large-size networks; however, it can also be used on small networks by accessing neighbouring larger network databases.

The advantages of this method are: (1) At network level, CBR provides the BMS with reasonably accurate predictions; (2) CBR compares the current problem bridge deterioration rate with the average deterioration rates of similar bridges with the same structure type, traffic volume, maintenance level, and similar environmental and operation conditions; (3) CBR works well with a large networks by providing large database information that can be used to manage average case bridges; (4) The data from other large bridge networks can be used for smaller networks. For example, a city or town with a small network consisting of 5 to 100 bridges can use the state DOT's data or neighbouring state data since all bridge inspection history can be extracted from the NBI file. This method provides bridge deterioration rates based on their NBI condition ratings or by their structural element condition ratings. In the United States, NBI condition history for all publicly owned bridges has been available since the 1980s.

The drawbacks of a CBR system are: (1) CBR requires a large network of bridges, but as noted above, a neighbouring state or DOTs bridge data can be used; (2) In certain unique situations when a bridge structure is the first of its own type or made of new material, a matching type may not be available for use in determining the deterioration rate. In this case, the deterioration rate may be determined based on the expected lifespan recommended by the manufacture, and (3) The degree of similarity and weighting factors are based on engineering experience and judgment which can be biased.

References

1. AASHTO (1993). Guidelines For bridge management systems, American Association of State Highway and Transportation Officials, Washington, DC Washington, D. C.
2. Abed-Al-Rahim, I. and Johnston, W., (1995), "Bridge Element Deterioration Rates", Transportation Research Record, 1490, Transportation Research Board, pp.9-18.
3. Agrawal, Anil K., Akira Kawaguchi, and Zheng Chen. "Deterioration rates of typical bridge elements in New York." Journal of Bridge Engineering 15.4 (2010): 419-429.
4. Althaqafi, E., & Chou, E. (2022). Developing bridge deterioration models using an artificial neural network. Infrastructures, 7(8), 101.
5. ASCE, Reston Va, pp. 623-626.
6. Bu, G., Lee, J., Guan, H., Blumenstein, M., & Loo, Y. C. (2014). Development of an integrated
7. DeStefano, P. D., & Grivas, D. A. (1998). Method for estimating transition probability in bridge deterioration models. Journal of infrastructure systems, 4(2), 56-62.
8. Deterioration," Proceedings of 4th. Congress on Computing in Civil Engineering,
9. Federal Highway Administration (FHWA) (1989b), "Bridge needs and Investment process", Technical Documentation and User's Guide, U.S. Department of Transportation, Washington, D.C, version 1.2.
10. Graham, D., Smith, S. D., & Crapper, M. (2004). Improving concrete placement simulation with a case-based reasoning input. Civil Engineering and Environmental Systems, 21(2), 137-150.
11. Haque, M. E. (1997). Uniform Bridge element identification system for database management for roadway bridges. Journal of Bridge Engineering, 2(4), 183-188.

12. Kolodner, J. L., Simpson, R. L., & Sycara-Cyranski, K. (1985). A process model of cased-based reasoning in problem solving (p. 6). School of Information and Computer Science, Georgia Institute of Technology.

13. Kong, X., Li, Z., Zhang, Y., & Das, S. (2022). Bridge deck deterioration: Reasons and patterns. Transportation research record, 2676(7), 570-584.

14. Kumar, H. S., & Krishnamoorthy, C. S. (1995). A framework for case-based reasoning in engineering design. AI EDAM, 9(3), 161-182.

15. Leake, D. B. (1996). CBR in context: The present and future. Case-Based Reasoning, Experiences, Lessons & Future Directions, 1-30.

16. Roddis, W. K., & Bocox, J. (1997). Case-based approach for steel bridge fabrication errors. Journal of Computing in Civil Engineering, 11(2), 84-91.

17. Schank, R. C. (1983). Dynamic memory: A theory of reminding and learning in computers and people. Cambridge university press.

18. Thompson, P. (2001), "Decision Support Analysis in Ontario's New Bridge Management System", Proceedings of the 2001 Structural Congress and Exposition, ASCE, Washington, D.C.

19. Vanier, D. J. (2000, September). Advanced asset management: tools and techniques. In Innovations in Urban Infrastructure Seminar of the APWA International Public Works Congress (pp. 39-56).

20. Wang, J. (1992). Integrated case-based reasoning for structural design.

Appendix A

NBI Condition Ratings		
Concrete Deck Condition Rating		
Code	**Condition of Deck Item**	**Description of Condition**
N	Use for all culverts	
9	**Excellent Condition**	No noticeable or noteworthy deficiencies which affect the condition of the deck item. Usually new decks.
8	**Very Good Condition**	Minor transverse cracks with no deterioration, i.e. delamination, spalling, scaling or water saturation.
7	**Good Condition**	Sealable deck cracks, light scaling (less than 1/4" depth). No spalling or delamination of deck surface but visible tire wear. Substantial deterioration of curbs, sidewalks, parapets, railing or deck joints (need repair). Drains or scuppers need cleaning.
6	**Satisfactory Condition**	Medium scaling (1/4" to 1/2" in depth). Excessive number of open cracks in deck (5 ft intervals or less). Extensive deterioration of the curbs, sidewalks, parapets, railing or deck joints (requires replacing deteriorated elements).
5	**Fair Condition**	Heavy scaling (1/2" to 1" in depth). Excessive cracking and up to 5% of the deck area is spalled; 20 - 40% is water saturated and/or deteriorated. Disintegrating of deck edges or around scuppers. Considerable leaching through deck. Some partial depth failures, i.e. rebar exposed (repairs needed).
4	**Poor Condition**	More than 50% of the deck area is water saturated and/or deteriorated. Leaching throughout deck. Substantial partial depth failures (replace deck soon).
3	**Serious Condition**	More than 60% of the deck area is water saturated and/or deteriorated. Use this rating if severe or critical signs of structural distress are visible and the deck is integral with the superstructure. A full depth failure or extensive partial depth failures (repair or load post immediately).
2	**Critical Condition**	Some full depth failures in the deck (close the bridge until the deck is repaired or holes covered).
1	**Immenent Failure Condition**	Substantial full depth failures in the deck (close the bridge until deck is repaired or replaced).
0	**Failed Condition**	Extensive full depth failures in the deck (close bridge until the deck is replaced).

Volume 32, Number 1

Boston's Groundwater Preservation Initiative: Groundwater Recharge System Analysis and Design

Z.K. Boswell, P.E., BC.GE[1], J.A. Dominguez, G.E., P.E., BC.GE[2] and B.P. Strohman, G.E., P.E., BC.GE [3]

[1] Director, Secretariat Advisors LLC, 2400 District Avenue Suite 105, Burlington, MA, 01803; PH: 781-296-1119; email: zboswell@secretariat-intl.com
[2] Director, Secretariat Advisors LLC, 2400 District Avenue Suite 105, Burlington, MA, 01803; PH: 617-909-6844; email: jdominguez@secretariat-intl.com
[3] Managing Director, Secretariat Advisors LLC, 2400 District Avenue Suite 105, Burlington, MA, 01803; PH: 603-738-9706; email: bstrohman@secretariat-intl.com

Published December 15, 2024

Abstract

The Back Bay neighborhood in Boston, MA, has a unique history where high rises and brownstones sit in an area that was originally part of the Charles River basin. In the early 1800s, the City of Boston undertook a massive landfilling effort to create the Back Bay neighborhood using soils mostly consisting of marine silts and sand and gravel mixed with mud, trash, and other construction debris. Due to the presence of these soils, many structures built in the Back Bay in the late 19th and early 20th centuries were founded on untreated timber piles that bear in the stiffer clay soils below. For decades, the existing untreated timber piles were a popular foundation option due to material availability, the relative ease of installation, and relatively large pile capacities.

As development within the Back Bay has continued over time, groundwater levels have been negatively impacted in many locations. Specifically, urbanization, construction of impermeable surfaces, and the use of private roof and site drainage systems conveying water directly into the City's buried infrastructure have decreased the groundwater levels in many areas of the city. The depressed groundwater levels can expose the top of the untreated timber piles to air, subjecting them to accelerated deterioration due to fungal-attack, bacterial attack, and insect infestation thereby reducing the strength of the wood and the cross-sectional area at the top of the untreated timber piles. The reduced strength of the wood and cross-sectional area decreases the load-carrying capacity of the top of the pile which ultimately can cause settlement of the structure.

In 2006, the City of Boston adopted Groundwater Conservation Overlay District (GCOD) Article 32 Zoning requirements to protect untreated timber piles from damage due to the depressed groundwater levels within portions of the city. The purpose of Article 32 is to prevent the deterioration of and, where necessary, promote the restoration of, groundwater levels in the city of Boston, protect and enhance the city's historic neighborhoods and structures, and otherwise conserve the value of its land and buildings, reduce surface water runoff and water pollution, and maintain public safety.

This paper presents a summary of the Article 32 requirements, an overview of the roles and responsibilities for members of the design team, and a synopsis of approaches to analyze and design groundwater recharge systems.

Volume 32, Number 1

Keywords: Groundwater Preservation, Groundwater Recharge Systems

1. Introduction

The development of the City of Boston during the 1900s through the present has resulted in significant local, temporary, and/or permanent lowering of the stabilized groundwater levels across the city. The lowered groundwater levels can result in negative effects on the timber pile foundations that support most of Boston's historic structures sometimes leading to significant building settlement. To combat this problem, in 2006, the City of Boston with the assistance of the Boston Groundwater Trust and other local government agencies, adopted Article 32 – Groundwater Conservation Overlay District, which requires building owners to collect and recharge stormwater into the ground, thereby locally raising the stabilized groundwater levels to assist in protecting Boston's timber pile foundations. Additionally, Article 32 requires a certification of no harm letter. The applicant must provide certification that the proposed project will not negatively impact the groundwater levels within the parcel or adjacent parcels. The no-harm certification is submitted as a letter stamped by a professional engineer registered in the Commonwealth of Massachusetts.

Meeting the requirements of Article 32 requires in-depth knowledge and understanding of the intent of Article 32, the Massachusetts State Building Code, the Massachusetts Stormwater Handbook (Commonwealth of Massachusetts 2008), and experience to design, install, and integrate a groundwater recharge system as a part of a new construction project or into an existing building renovation project. The design of a groundwater recharge system requires careful coordination between multiple engineering disciplines and, at times, an architect. This paper will summarize the history of land development in Boston, the origination of the Boston Groundwater Trust, the establishment of Article 32 zoning requirements, and approaches for the design of a groundwater recharge system for Article 32 compliance.

2. Developing Boston

2.1 History

The history of Boston's landmaking is well-documented and known to Boston's construction and engineering community. Seasholes (2003) provides the most well-rounded account of Boston's landmaking history. For brevity, this paper provides an overview of Boston's land development history to set the stage for a discussion of the Article 32 requirements (i.e., the creation of Boston's Groundwater Conservation Overlay District) and how knowledge of past landmaking operations can inform compliance with its intent and requirements.

Due to Boston's bustling maritime trade economy and the need for more residential land, its residents quickly extended the shoreline by means of extensive landmaking projects. The majority of the landmaking projects started in the early 1800s and lasted into the 1970s with the construction of Boston's Logan Airport. This work primarily occurred within the Back Bay, East Boston, Beacon Hill, and South Boston neighborhoods. Boston's made land covers about 30,000 acres and is larger than the original peninsula, likely making Boston one of the largest cities in North America that is developed on made land (Seasholes 2003).

2.2 Backfilling Boston

Much of the made land that overlaps with Boston's GCOD is predominantly located in the Back Bay and South End neighborhoods. The landmaking operations for these neighborhoods occurred between 1830 and 1940 (Seasholes 2003). Other neighborhoods that were developed on made land include Bay Village, Chinatown, the Leather District, Bulfinch Triangle, the North End, Downtown Waterfront, Lower Beacon Hill and the Fort Point Channel.

Upon completion, the City of Boston quickly developed these neighborhoods, constructing low-rise housing, high-rise commercial buildings, subway tunnels and stations, and the necessary infrastructure to support the area. Due to the fill soils deposited above the natural soft organic marine silts below, the buildings in these neighborhoods, particularly Back Bay and the South End, were typically supported on deep foundations.

2.3 Timber Pile Foundations

Boston's subsurface stratigraphy, from ground surface down, generally consists of a granular fill (i.e., made land), overlying soft marine silts and organics, sand and gravel outwash deposits, Boston blue clay, sand, glacial till, and bedrock. Due to the fill and the soft marine silts and organic soils being unsuitable bearing materials, most of the historic buildings throughout Boston over made land are supported on driven untreated timber pile foundations. The timber piles were driven through the fill and the soft organic marine silt layer into the denser soils below. Untreated timber pile foundations have supported these historic buildings for over a century. It is well documented (i.e., Aldrich and Lambrechts 1986, Zelada et al. 2013, Zelada and Homem 2017, and others) that to mitigate deterioration of the untreated timber piles, they must remain continuously submerged in water. Historically, this was achieved by terminating the tops of the timber piles below the stabilized groundwater level, which, at the time of original construction in the 1800s and early 1900s, was at approximately

El. 5 ft Boston City Base (BCB) datum (Aldrich and Lambrechts 1986).

The Boston Groundwater Trust (BGwT) has reviewed historic building permits to understand the original timber pile cutoff elevations, and over time, which buildings were subsequently underpinned. Figs. 1 and 2 show examples of this information for the Back Bay and Lower Beacon Hill neighborhoods. Unfortunately, as Boston continued to expand and develop, the stabilized groundwater level generally lowered, sometimes locally, exposing the tops of the previously submerged untreated timber piles. Once the untreated timber piles are no longer submerged and become exposed to air, they begin to deteriorate and experience accelerated deterioration, causing building settlement. Below is a summary of the causes of the lowered groundwater levels in Boston and the timber pile deterioration mechanisms.

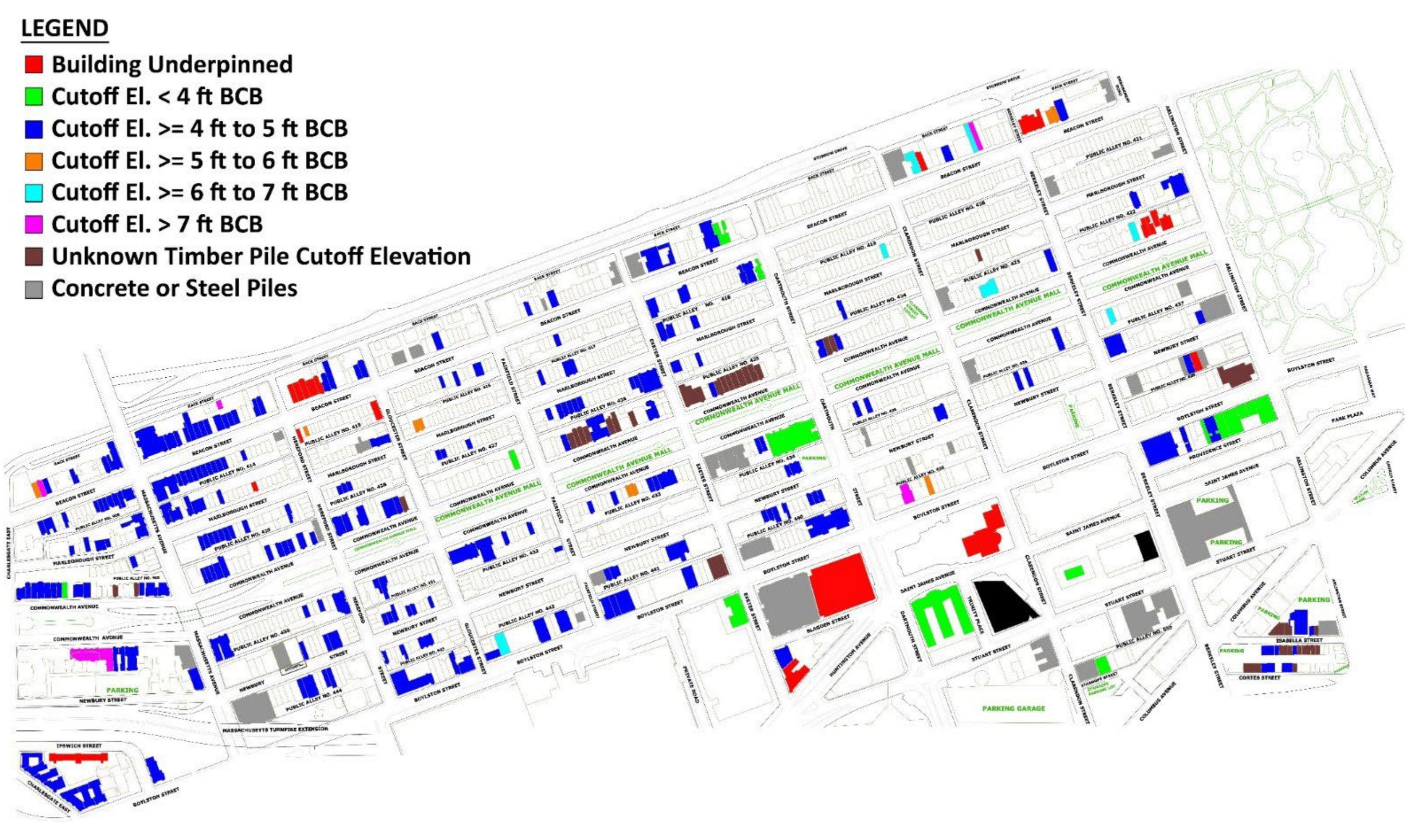


Figure 1. Timber Pile Cutoff Elevations and Underpinned Structures in Back Bay.

Source: Boston Groundwater Trust (2024)

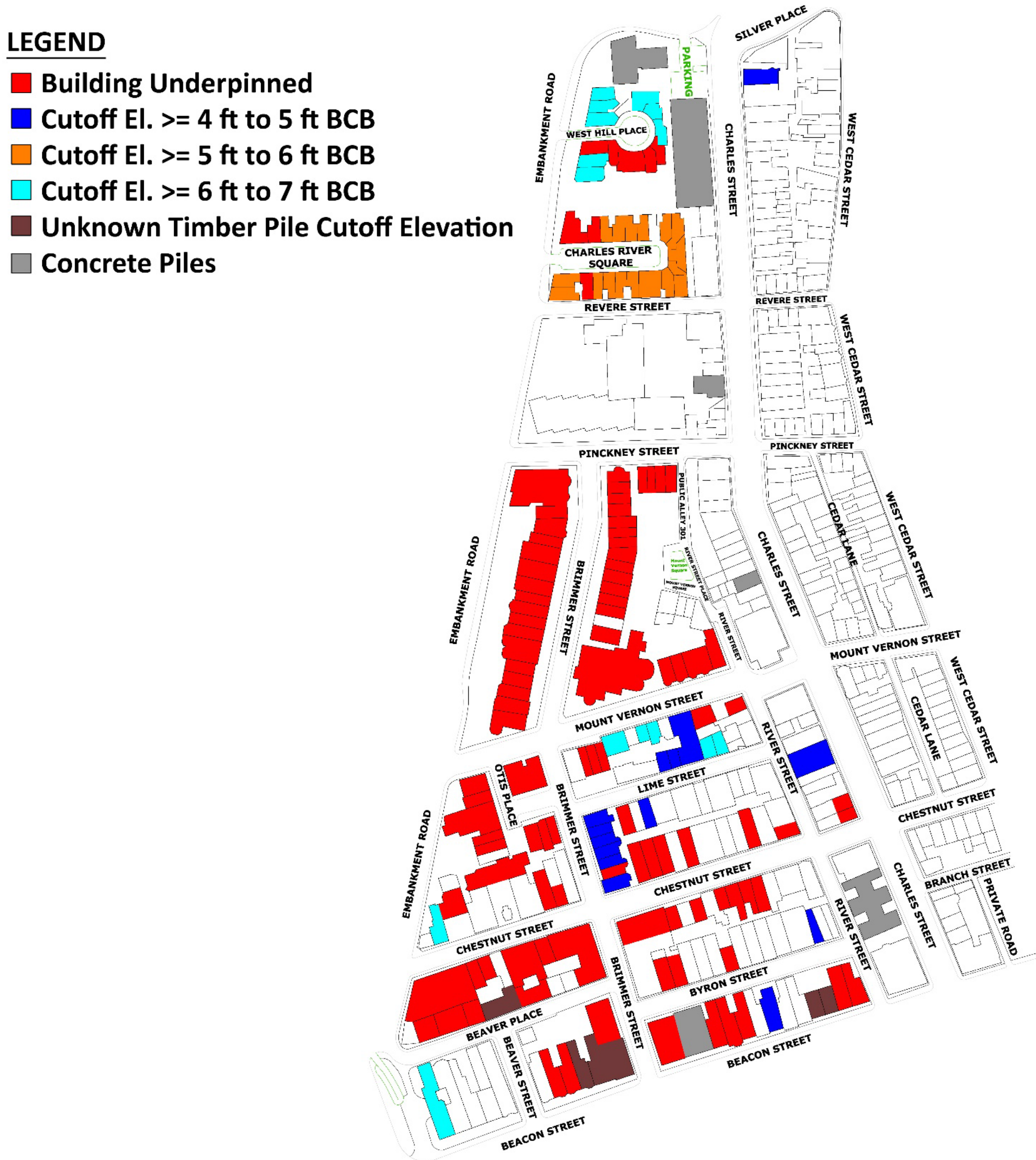


Figure 2. Timber Pile Cutoff Elevations and Underpinned Structures in Beacon Hill.

Source: Boston Groundwater Trust (2024)

3. Developing Boston and its Effects on Local and Regional Groundwater Levels

3.1 Developing Boston

The development of newly made land from the 1800s through the early 2000s had significant effects on the stabilized groundwater levels across Boston. To understand the effects of this land development, numerous local government entities and engineering firms have performed extensive studies of the groundwater levels around Boston, particularly in the Back Bay, Lower Beacon Hill, and the South End neighborhoods.

The timber pile cutoff elevation is consistent with Boston's early building code entitled The Building Law of the City of Boston, which stated: "the tops of all wooden piles shall be cut at an elevation not higher than grade 5.001, except that the commissioner may in his discretion permit a higher point of cut off, but not exceeding grade 9.00 in localities where the level of the ground water fluctuates with tidal variations" (City of Boston Building Department 1919).

BGwT observation well data indicates that currently stabilized groundwater levels across Boston fluctuate from below El. 0 ft BCB to greater than El. 10 ft BCB. Further, heavy infrastructure projects such as the Southwest Corridor project required temporary dewatering to significantly lower the groundwater level to El. -28 ft BCB for several years. The stabilized groundwater levels in the GCOD are generally lower than the untreated timber pile cutoff elevations. The lowered groundwater levels are most likely due to land development, groundwater leakage into sewer and stormwater pipes, the use of sub-slab dewatering systems to reduce groundwater levels within below-grade structures, temporary dewatering for below-grade construction and deep foundation installation, and the inability for stormwater to infiltrate into the soils because the majority of Boston is covered by impervious surfaces (e.g., streets, sidewalks, and buildings). Because the groundwater levels are generally below the untreated timber pile cutoff elevations, the top portions of the timber piles are now periodically or permanently exposed to air, leading to deterioration.

3.2 Effect of Lowered Groundwater Levels on Untreated Timber Piles

As the groundwater levels across Boston have decreased, temporarily or permanently, the timber piles were exposed (i.e., no longer submerged) to air (Fig. 3). Once the timber piles are exposed to air, they are susceptible to biological attack from fungal and bacterial growth that rot the timber piles. Further, the lowered groundwater levels create an environment that is favorable for insects, such as wood borers and termites, that will burrow and eat away at the wood, resulting in section loss along the exposed portion of the piles. Once significant deterioration occurs, building owners must undertake costly repairs to underpin the building, often utilizing the cut-and-post method to replace the deteriorated portion of the timber piles with concrete or concrete-encased steel posts or installing new piles.

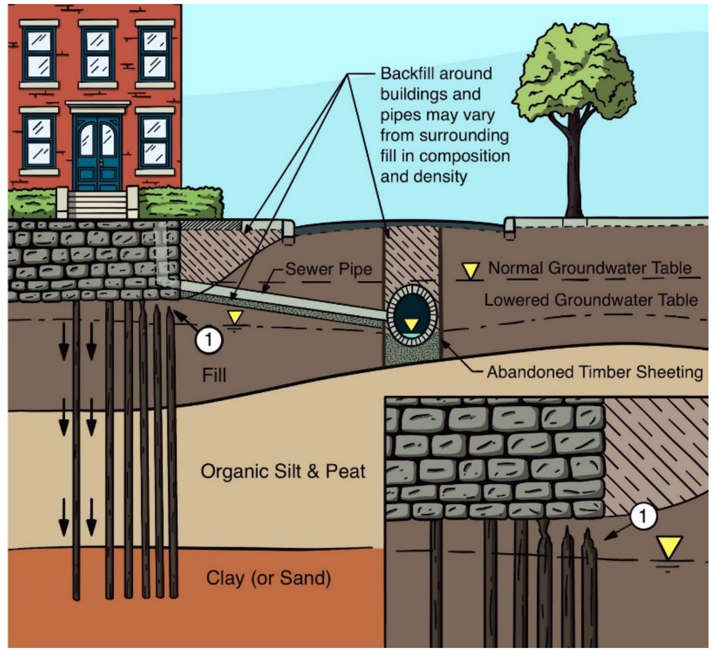


Figure 3. Timber Pile Deterioration. Figure modified from BSCES Civil Engineering Practice Journal, "Back Bay Boston, Part II: Groundwater Levels."

Source: Aldrich and Lambrechts (1986)

4. Establishment of Boston Groundwater Trust

In 1986, the Boston City Council established the BGwT with the mission of monitoring groundwater levels across Boston neighborhoods susceptible to untreated timber pile deterioration. The BGwT had a slow start, but in 1997, Boston Mayor Thomas Menino revived the BGwT and appointed new volunteer trustees to continue its mission. Initially, the new trustees developed a groundwater monitoring network using existing groundwater monitoring wells located on public property across Boston. In 2002, the BGwT's monitoring network expanded thanks to a $1.6 million Environmental Bond Bill, and now there are approximately 1,000 groundwater monitoring wells, including decommissioned wells, within the groundwater monitoring network. The data collected from the groundwater monitoring wells is readily available to the public via the BGwT website (Boston Groundwater Trust 2024).

In 2005, the City of Boston and the Commonwealth of Massachusetts governments signed a Memorandum of Understanding, which created a "Groundwater Working Group" to work together to understand the cause of the lower groundwater levels across Boston and repair the problems that were created due to the lowered groundwater levels. The Groundwater Working Group consists of the following:

- The City of Boston Environment Department.
- The Boston Groundwater Trust.
- The Boston Water & Sewer Commission (BWSC).
- The Massachusetts Bay Transportation Authority.
- Massachusetts Department of Transportation.
- The Massachusetts Water Resources Authority.
- Massachusetts Executive Office of Energy and Environmental Affairs.
- Massachusetts Department of Conservation & Recreation.

The United States Environmental Protection Agency provided funding for observation well installations and city, state, and private funding provided funding to achieve the Groundwater Working Group's objectives. Lastly, the City of Boston established the Article 32 – Groundwater Conservation Overlay District, which is discussed in detail in Section 5 (City of Boston 2005).

5. Article 32 - Groundwater Conservation Overlay District

On 15 February 2006, the City of Boston, under the auspices of the Boston Redevelopment Authority, adopted Article 32 of the Boston Zoning Code – Groundwater Conservation Overlay District. The purpose of Article 32 is to "(a) prevent the deterioration of and, where necessary, promote the restoration of, groundwater levels in the city of Boston; (b) protect and enhance the city's historic neighborhoods and structures, and otherwise conserve the value of its land and buildings; (c) reduce surface water runoff and water pollution; and (d) maintain public safety" (City of Boston 2006). Initially, the GCOD included the following neighborhoods: Back Bay, Lower Beacon Hill, a portion of the South End, Chinatown, the Leather District, the Prudential Center, and Bay Village. In 2007, the GCOD was expanded to include the Fort Point area, the North End waterfront area, and Bulfinch

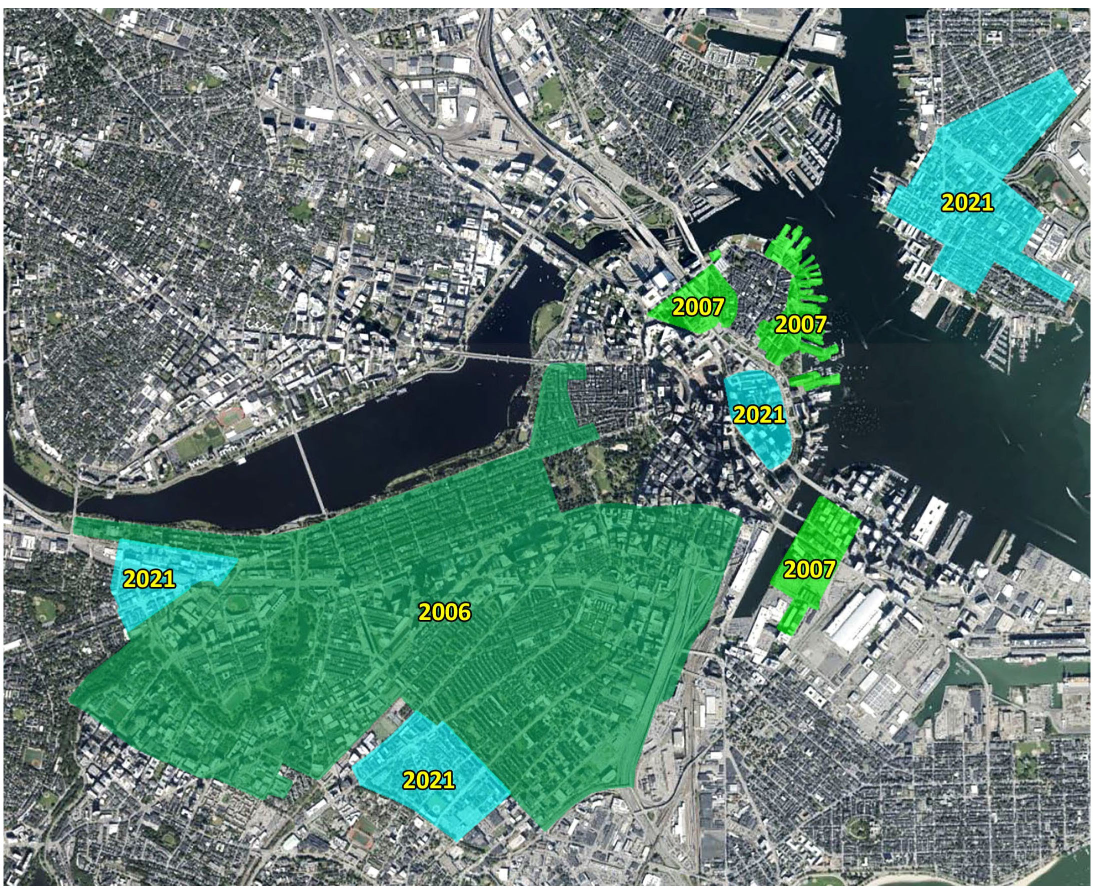


Figure 4. Evolution of GCOD.

Source: City of Boston (2021) and Nearmap (2024)

Triangle (City of Boston 2007). Most recently in 2021, the GCOD was expanded to include the portion of Lower Roxbury, Audubon Circle, Central Waterfront and a portion of Jeffries Point and Maverick Square areas of East Boston (Fig. 4) (City of Boston 2021).

Since 2006, the City of Boston has also updated the applicability of Article 32. Currently, any applicant performing work within the GCOD must comply with Article 32's requirements if their proposed work includes the following (City of Boston Planning Department 2024):

- "The erection or extension of any structure, where such new structure or extension will occupy more than fifty (50) square feet of lot area."
- "The erection or extension of any structure designed or used for human occupancy or access, mechanical equipment, or laundry or storage facilities, including garage space, if such construction involves the excavation below grade to a depth equal to or below eight (8) feet above Boston City Base (other than where such excavation is necessary for, and to the extent limited to, compliance with the requirements of this article)."
- "To Substantially Rehabilitate any structure." Article 32 defines substantial rehabilitation as "to cause alterations or repairs to be made to a structure or structures within any period of twelve (12) months, if such alterations or repairs cost more than fifty percent (50%) of the physical value of the structure or structures. Physical value shall be based on the assessed value, as recorded on the assessment rolls of the City as of January 1 preceding the date of the filing of an application for a building permit with the Inspectional Services Department."
- "Any paving or other surfacing of lot area."

To obtain a permit for a project in the GCOD, one must show that the proposed project complies with the following requirements:

- Install a recharge system capable of recharging a volume of rainwater equivalent to 1 in. times the area of the lot occupied by structures or otherwise impervious surfaces (City of Boston Planning Department 2024).
- Comply with BWSC's best management practices that the recharge system must be able to recharge the collected precipitation within a 72 hr period. This requirement is consistent with the Massachusetts Stormwater Handbook (Commonwealth of Massachusetts 2008). In addition, the bottom of the system must be at least two feet above the seasonal high groundwater level (BWSC 2013). This is not a requirement stated in Article 32, but must be followed to obtain approval from BWSC.
- Provide the certification of no harm letter prepared by a professional engineer licensed in Massachusetts stating that the proposed work "will result in no negative impact on groundwater levels within the lot in question or adjacent lots" (City of Boston Planning Department 2024).

The certification of no harm letter should discuss the proposed work, existing site conditions, and the proposed rainwater collection and groundwater recharge system. The letter must also address the following: are there any occupiable spaces below El. 8 ft BCB, and if there are elevators within the building, how many and what is the elevation of the bottom of the sump pits. Additionally, the engineer must certify that any portion of a new building or proposed renovation to an existing building that extends below El. 8 ft BCB will be fully waterproofed, and does not utilize a sub-slab drainage system and/or sump pumps to lower the groundwater levels beneath the building. Lastly, the engineer must explain how the proposed project will not lower the groundwater levels at the project site or adjacent properties.

6. Complying With Article 32

Installing a groundwater recharge system to comply with Article 32 is dependent on the size of the parcel, the footprint of the existing building(s) within the parcel, the condition of the below-grade spaces within the structures, the types of site features (e.g., landscaping, retaining walls, hardscape, etc.) within the parcel, and proximity to adjacent structures. Groundwater recharge systems are typically categorized as either subsurface recharge structures or recharge well systems. Recharge wells are more prevalent in an urban setting such as Boston's GCOD.

6.1 Subsurface Recharge Systems

Subsurface recharge structures are the more conventional system type used to collect and recharge stormwater and often include the following: infiltration pits, chamber systems, perforated pipes embedded within a permeable leaching bed, and galleys (i.e., perforated concrete rectangular vaults) (Donlon et al. 2022). Utilizing these structures in an urban setting such as Boston's GCOD is likely infeasible due to the space required to install these systems. There are certainly isolated cases where building owners may install new paving for parking and can utilize these structures. However, this is typically rare due to the high cost of real estate in urban settings. In addition, if the seasonal high groundwater level is close to the ground surface, the footprint of the system will need to be increased to maintain both the design recharge volume and the minimum 2 ft clear distance from the seasonal high groundwater level, further exacerbating real estate constraints. Additionally, the designer must consider the effect on adjacent structures due to the increased hydrostatic pressure as the water is recharged from the system into the subsurface soils. The increased hydrostatic pressure could increase the leakage rate through foundation walls and cause structural instability to foundation systems and foundation walls.

Alternatively, a groundwater recharge well system is frequently used when there is limited or no space to install subsurface recharge structures. A groundwater recharge well system generally consists of installing a short-term storage tank (Fig. 5) within the existing building to temporarily hold collected stormwater that is connected to a series of recharge wells (Fig. 6) adjacent to the building to discharge the stormwater from the storage tank. The groundwater recharge wells will generally consist of the following components:

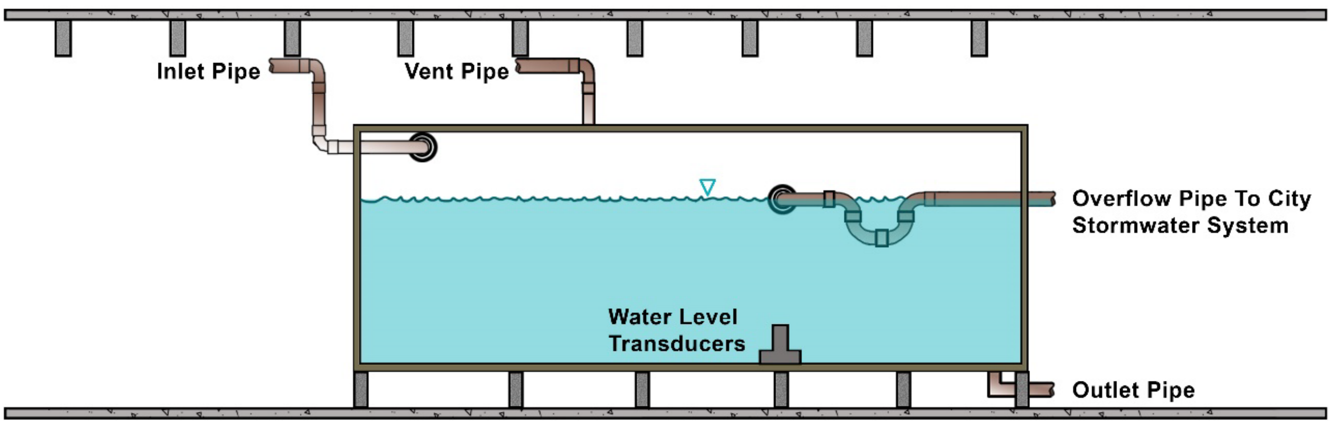


Figure 5. Short-Term Storage Tank for Groundwater Recharge System.

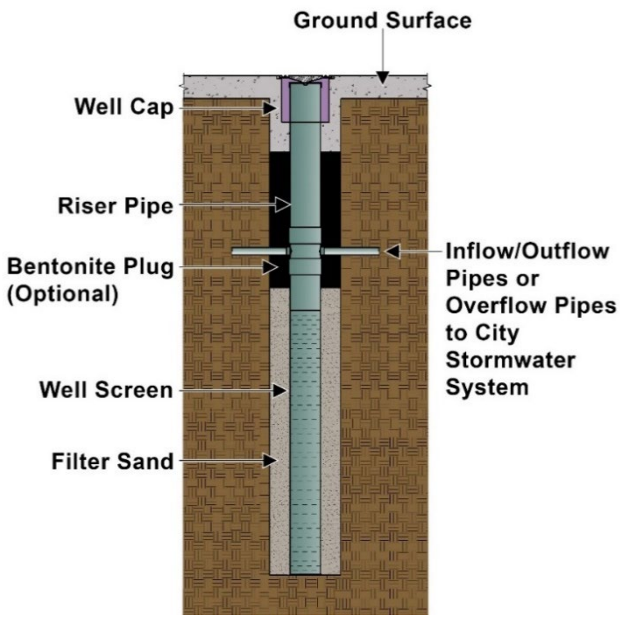


Figure 6. Groundwater Recharge Well.

- A well screen is at the bottom of the recharge well. The well screen is either slotted stainless steel or PVC. The size and spacing of the openings in the well screen depend on the gradation of the filter sand, which in turn depends on the gradation of the surrounding in-situ soils.
- A riser pipe is above the well screen and extends to a few inches below the well cap at the ground surface. The riser pipe is typically capped to prevent debris and surface water from flowing into the recharge well.
- Inflow/outflow pipes connect to the riser pipe. The inflow/outflow pipes tie the recharge well to the short-term storage tank, additional recharge wells, and an overflow to the city stormwater system.
- A permeable filter sand surrounds the well screen. The filter sand provides a barrier between the surrounding in-situ soils and the recharge well and reduces the risk of clogging of the well screen.
- A bentonite plug is frequently placed above the filter sand and below the well cap. The bentonite plug below the well cap precludes surface water from entering the recharge well. The use of a bentonite plug is optional.
- A well cap is at the top of the recharge well and flush with the ground surface. The well cap is typically held in place with concrete. The well cap allows for access for maintenance of the recharge well.

While groundwater recharge well systems are a commonly implemented solution to comply with Article 32, there are several design considerations that are unique to this solution, including the following:

- Integrating the short-term storage tank into the existing building to allow for adequate access to maintain the tank while minimizing disruption to the finished space.
- Strengthening structural elements and the foundation system, if necessary, to support the increased load from the short-term storage tank and its contents.
- Including backflow preventers between the recharge wells and the short-term storage tank can prevent the short-term storage tank from overtopping and flooding the finished space during extreme weather events. Additionally, the short-term storage tank should also connect to the city stormwater system to discharge collected stormwater into the city stormwater system that is greater than the volume equal to 1 in. of rainfall over the parcel's impervious area.
- Obtaining approvals to install the recharge wells within a public way (e.g., sidewalk or public alley), if necessary.

Significant coordination and constant communication between multiple disciplines, including the architect and the geotechnical, structural, civil, and mechanical/electrical/plumbing (MEP) engineers and the building owner is necessary to design a groundwater recharge well system.

7. Design Roles and Responsibilities for Groundwater Recharge Systems

Due to site constraints, it is often not possible to install subsurface recharge structures for most parcels located within the GCOD. Therefore, to meet Article 32 zoning requirements, a groundwater recharge well system must be used. Each of the following disciplines has an important role in the successful planning of a groundwater recharge system.

7.1 Geotechnical Engineer

The geotechnical engineer is responsible for performing the investigation to evaluate the existing subsurface and groundwater conditions at the site. As part of the subsurface investigation, the geotechnical engineer will perform field and laboratory tests to assist in designing the groundwater recharge wells. See Section 8 below for additional details regarding the different types of testing typically required.

Another critical factor is reliably determining the stabilized and seasonal high groundwater level at the site. As discussed above in Section 5, the bottom of the groundwater recharge wells must be at least 2 ft above the seasonal high groundwater level. If the seasonal high groundwater level is relatively high, the number of recharge wells will increase. The necessary analyses to size and space the groundwater recharge wells are discussed in Section 8.

7.2 Structural Engineer

The structural engineer is responsible for determining if the existing building structure has adequate capacity to support the short-term storage tank and its contents. Alternatively, if renovations are necessary (e.g., new floor or roof system, foundation, etc.) to increase the structural capacity, the structural engineer will perform the design and prepare the construction documents for the new structural elements. The structural engineer will need to understand the weight of the short-term storage tank and its contents to perform their analyses, which will require coordination with the MEP engineer, who often determines the size of the tank. Further, the structural engineer will coordinate with the architect to understand the tank's location and orientation to assist in layout out of the new structural system, if needed. The structural engineer is also responsible for evaluating the impact of the increased hydrostatic pressure, from the groundwater recharge system, on the foundation walls and below-grade slabs.

7.3 Civil Engineer

The civil engineer is responsible for determining the recharge volume that must be collected and recharged by the groundwater recharge well system. Since Article 32 only requires the recharge system to collect a volume equal to 1 in. of rainfall over the parcel's impervious area, the civil engineer will typically design and prepare the construction documents for the connection of the groundwater recharge well system to the local stormwater system to discharge any stormwater exceeding the required volume. Lastly, the civil engineer will typically assist with the permitting process for the groundwater recharge well system.

7.4 MEP Engineer

The MEP engineer will typically size the short-term storage tank using the recharge volume determined by the civil engineer. The MEP engineer will also determine the size and layout of the discharge lines, from the storage tank to the recharge wells, including evaluating clean-out locations, determining the pumping rate, and sizing the pumps to discharge the stormwater from the short-term storage tank to the recharge wells. The pump system could include primary and backup pumps and high-water alarms for the storage tank. If necessary, the MEP engineer will design the electric system upgrades for the pumps and install a backup power supply for the pump system to preclude tank overtopping during a power outage.

7.5 Architect

The project architect, if they are the prime consultant, coordinates the engineering disciplines designing the recharge system. The architect will also coordinate with abutters, which include the owners of adjacent underground utilities (e.g., steam, gas, water, communication), to inform the stakeholders of the internal recharge system and to assist with evaluating the potential impacts to the adjacent properties. Further, the architect will determine the location of the recharge system within the building and, if necessary, relocate non-structural elements (e.g., non-load-bearing walls) to provide adequate space to install the system. The architect can provide guidance on methods to protect the building, such as moisture-resistant finishes and/or waterproofing, should the short-term storage tank or discharge pipes from the storage tank to the recharge wells or the overflow pipe leak. Lastly, with assistance from a design professional experienced in waterproofing, the architect can also prepare waterproofing details for the spaces below the observed seasonal groundwater level.

8. Analyses to Design Groundwater Recharge Wells

8.1 General Approach

The objective of recharge well design is to select a layout of wells that will allow infiltration of the design recharge volume (equal to 1 in. of rainfall times the parcel's impervious area) within 72 hrs without negatively impacting structures within or adjacent to the subject parcel. Negative impacts include leakage into basements that are not fully waterproof, increased hydrostatic pressures on basement slabs and walls, and inundation of buried utility lines. Steam lines are particularly sensitive to changes in groundwater, as the pipe can experience thermal shock when exposed to the cooler groundwater, potentially leading to bursting of the pipe. The cooling effect can also cause the steam to produce excessive condensate, potentially leading to pressure spikes in the pipe.

The space available for recharge wells is often constrained for parcels in the GCOD. The BWSC requirement that the bottoms of recharge wells must be 2 ft above seasonal high groundwater means that in most cases, the wells must be located outside the building. Therefore, typical well locations are along sidewalks, alleyways, and patio spaces.

When water is placed in a well, the pressure of the water column forces the water out of the perforated or slotted well screen, into the filter pack material around the well screen, and into the surrounding soils. The infiltrating water causes the groundwater to rise locally around the well, decreasing with distance from the well, forming what is sometimes referred to as a groundwater mound or cone of influence. At a certain distance, called the radius of influence, the groundwater level is unaffected by the well. The groundwater rise due to closely spaced wells is additive, so the principle of superposition can be used to evaluate systems of multiple wells. The goal of groundwater recharge design is to provide the required rate of infiltration while not negatively impacting adjacent structures and utilities. The flowchart in Fig. 7 outlines the design process.

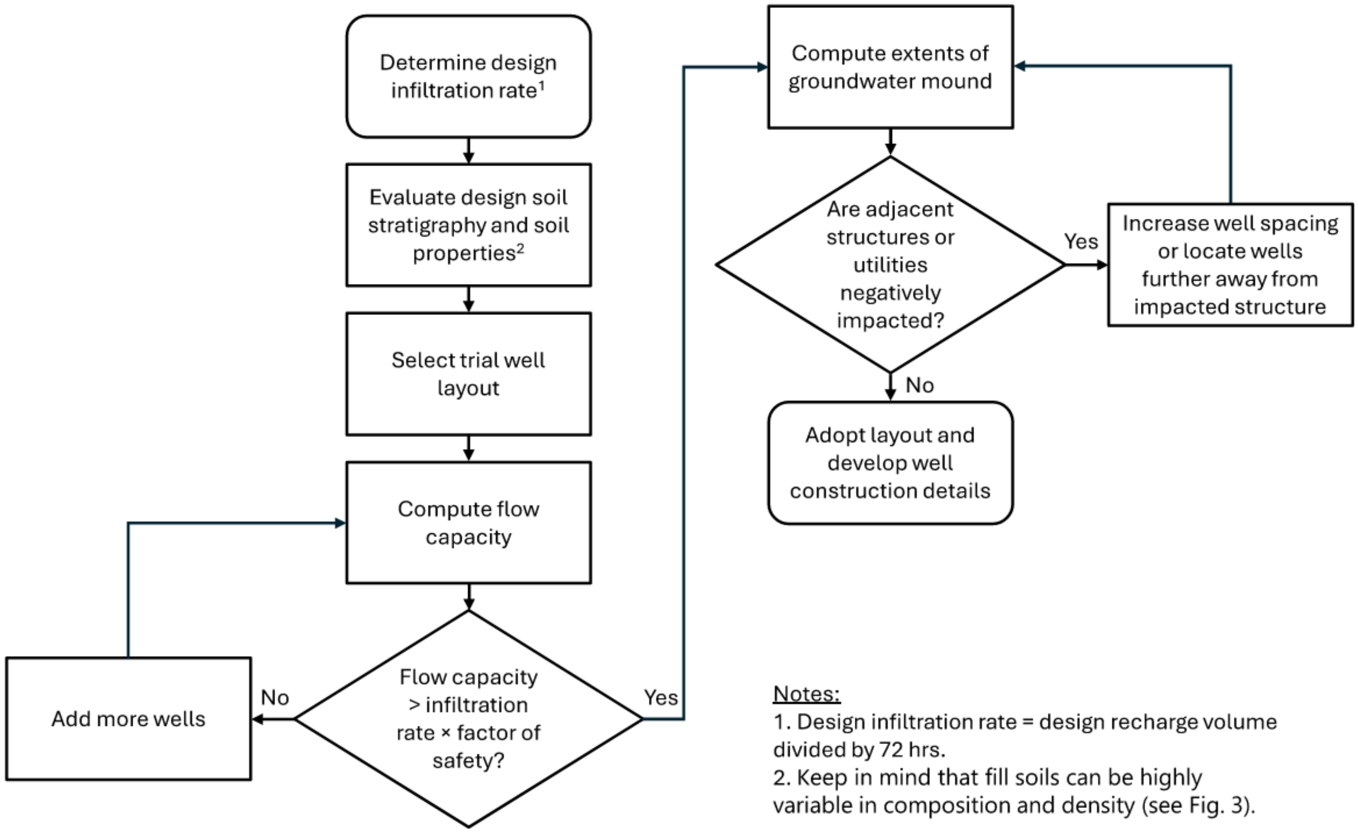


Figure 7. Recharge Well Design Process.

8.2 Soil Properties for Well Design

Hydraulic conductivity, also known as permeability, is a key physical property that describes how easily water can flow through soil. Generally, coarser-grained soils will have a higher hydraulic conductivity than finer-grained soils, as the hydraulic conductivity is dependent on the sizes of the pore spaces in the soil. Hydraulic conductivities can range over ten orders of magnitude from the finest clay to the coarsest gravel. Therefore, proper estimation of the hydraulic conductivities of the soils at a site is critical for the design of groundwater recharge wells.

Hydraulic conductivity can be estimated through correlations or by direct measurement. Correlations generally include some measure of grain size. Kasenow (2002) provides a summary of published correlations developed for several different soil types. The correlations noted above do not consider the electrochemical interaction between water and clay particles, which are naturally electrically charged. Therefore, other methods must be used to estimate the hydraulic conductivity of clayey soils.

Borehole permeability tests allow for in-situ measurement of hydraulic conductivity. These tests are performed in a cased drill hole, either by measuring the flow required to keep the borehole at a constant level (constant head test) or by rapidly adding or removing water from the borehole and measuring the water level over time as it returns to its original level (variable head test). Permeability tests can also be performed in an observation well or piezometers installed in completed boreholes. More rigorous aquifer tests involving pumping from a well and measuring the drawdown in an array of observation wells can yield useful information but are rarely performed for the design of recharge wells due to cost and time considerations.

Hydraulic conductivity can also be measured in the laboratory on soils collected from borings or test pits. Variable-head tests are typically performed on fine-grained soils, while constant-head tests are performed on coarse-grained soils. While relatively undisturbed samples of clayey soils can be collected using thin-walled tubes, such sampling is difficult to perform on coarse-grained soils.

In the absence of test data, ranges of typical hydraulic conductivities for various soil types can be found in textbooks and state and federal design guidance manuals (e.g., FHWA 2006, UFC 2022). Using such sources for the selection of design properties should be done with caution, perhaps with sensitivity analyses to help the designer understand the impacts of the variation of the properties selected for analysis.

8.3 Recharge Well Analysis Methods

8.3.1 Hantush Method

Hantush (1967) developed a method for estimating the rise in groundwater level in response to an infiltration basin above. The groundwater rise is highest immediately under the infiltration basin, and decreases with distance from the basin, forming what is commonly referred to as a "groundwater mound". The shape of the groundwater mound depends on the duration and intensity of infiltration and the hydraulic conductivity of the soil deposit.

The method relies on several simplifying assumptions: (1) the soil layer being infiltrated is isotropic, homogenous, unconfined (i.e., no impervious layer above), and sits on top of an impermeable base, (2) the rate of percolation from the infiltration basin is constant, (3) the infiltration basin is rectangular, and (4) that the mound expands due to horizontal water flow (i.e., the vertically infiltrating water flows horizontally once it hits the groundwater due to the presence of the impermeable base).

The Hantush method has been widely adopted in industry. The Massachusetts Stormwater Handbook (Commonwealth of Massachusetts 2008) recommends using the Hantush method for groundwater mounding analyses for infiltration basins. Although the Hantush method is intended for analysis of an infiltration basin, the method can be adopted for recharge wells. The U.S. Geological Survey has developed a publicly available Excel spreadsheet that implements the Hantush method. The development of the spreadsheet is documented in Carlson (2010).

The main limitation of the Hantush method is that it only considers a single infiltration source with no blockages to seepage near the groundwater mound. While the impacts of multiple wells can be estimated by adding the effects of multiple groundwater mounds, the impacts of basement walls or other buried structures, cannot be considered.

8.3.2 Analytical Solutions

Groundwater recharge wells in the GCOD almost always provide for water infiltration in the upper soil layers (i.e., the fill and outwash deposits above the Boston Blue Clay). The flow of water from a single well into a surrounding soil layer can be solved analytically. UFC (2004) provides an overview of these analytical solutions.

As with the Hantush method, the effects of multiple wells can be modelled by adding the effects of multiple groundwater mounds. Impervious boundaries like basement walls can be modelled (see USACE 1993).The addition of multiple wells and impervious boundaries adds to the complexity of the computations to the point where the use of computer software should be considered, as discussed below.

8.3.3 Computer Methods

Finite-element and finite-difference computer programs such as SEEP/W and MODFLOW solve the groundwater flow equation. In these software packages, the model geometry is discretized into smaller elements or volumes, which allows for the numerical solution of the governing equations. SEEP/W has both a two- and three-dimensional implementation; MODFLOW is solely three-dimensional. SEEP/W and its functional equivalents developed by others tend to be favored by geotechnical practitioners, while MODFLOW tends to be favored by hydrogeologists. The analysis of groundwater recharge wells is inherently a three-dimensional problem, but it can be simplified to two dimensions in certain, limited cases.

Three-dimensional models allow for considering complex basement geometries, variable soil conditions, barriers to groundwater flow, and adjacent properties in multiple directions. However, like all analytical models, the addition of a dimension adds complexity and, therefore, adds design time and expense. The decision to develop a three-dimensional model should include consideration of the complexities of the site and subsurface conditions, the overall size of the site (larger sites are typically more difficult to generalize), and the number of wells required (multiple wells will interact with each other if their radii of influence intersect).

8.3.4 Selection of Method

The method used to design recharge wells depends largely on the complexity of the site geometry. Properties with many buried utilities or adjacent basements and tunnels may require more detailed modeling. Understanding the strengths and weaknesses of each method is an important part of making this selection, as summarized in Table 1.

Table 1. Selection of Method to Design Recharge Wells

Method	Strengths	Weaknesses
Hantush Method	• Simple • Well-established use in Massachusetts for infiltration basins • Publicly available spreadsheets have been developed	• Applicability to wells is limited and designer must understand the assumptions made • Cannot evaluate blockages to seepage such as basement walls and tunnels
Analytical Methods	• Solutions are readily available in the literature • Can consider blockages to seepage	• Calculations for multiple, closely spaced wells and blockages can become unwieldy
Computer Methods	• User-friendly software • Can consider blockages to seepage • Can consider complex geometry and soil conditions	• Higher level of effort than other methods, particularly for complex conditions

9. Case Study

In 2021, a historic building in the Back Bay was undergoing extensive renovations to upgrade its facility. The facility is a lot-line building surrounded by either roadways or buildings and a small parking lot at the rear of the facility. The renovations were extensive enough that they were considered a substantial rehabilitation, so the owners needed to install a groundwater recharge system. Due to the lot-line construction and other site constraints, the work required the recharge system to be composed of a short-term storage tank (Fig. 5) constructed within the building to temporarily store the collected rainwater that is connected to a series of recharge wells (Fig. 6) installed adjacent to the facility beneath the sidewalk.

A subsurface investigation was performed to determine the subsurface soils and stratigraphy, and borehole permeability tests were performed in the fill layer to determine a design hydraulic conductivity. During the permeability testing, it was observed that the borehole permeabilities were atypically high for the Boston fill stratum. Estimates from correlations provided by Kasenow (2002) based on the grain size testing results were also considered to provide bounds for the design hydraulic conductivity.

A preliminary analysis using the analytical methods described in Section 8.3.2 indicated that multiple recharge wells would be needed to achieve the design infiltration rate. Due to the complexities of multiple wells, the proximity of the wells to the adjacent building, and the need to understand how the groundwater mounds from the recharge wells might interact with nearby underground utilities, a three-dimensional SEEP/W model was developed. The model indicated that three wells were required to achieve the design infiltration rate without impacting the adjacent structures and utilities.

After the recharge system was designed, design drawings and a Do No Harm Letter were submitted for the permit application to the authorities having jurisdiction (AHJ) for review and comment. The AHJ included the BWSC and Boston Inspectional Services Division (i.e., building department), and the owners of the adjacent underground utilities (e.g., National Grid, Eversource, etc.). During the permit review, the owner of a previously unidentified underground steam line requested confirmation that the groundwater from the recharge wells would not envelop the adjacent steam line pipe. As noted in Section 8.1, groundwater can potentially cause rupture of steam lines. The SEEP/W model indicated that the groundwater could envelop the steam line, so the spacing between the wells was increased until the groundwater mound was a reasonable distance (2 ft) below the bottom of the steam line (Fig. 8).

Once the project team resolved the comment for the underground steam line, the AHJ issued the permit to install the recharge system, which was installed shortly thereafter. The system has performed successfully since installation.

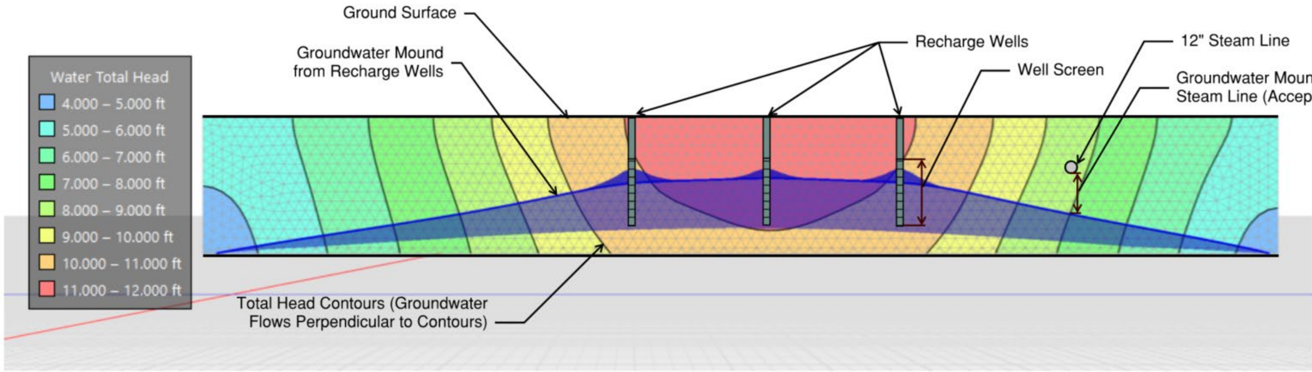


Figure 8. SEEP/W Results.

10. Closing Thoughts

Compliance with Article 32 and the design of a groundwater recharge system is an involved process, particularly for systems for existing buildings. Each groundwater recharge system is inherently unique to meet the constraints of installing a system within or adjacent to the building such that it will effectively recharge stormwater, in accordance with Article 32, while not negatively impacting adjacent structures or the building itself. The authors have found that by utilizing the above methods, a designer can successfully comply with Article 32 while meeting the needs of the building owner and other stakeholders.

The BGwT has observed positive impacts to the groundwater table due to the implementation of Article 32. In some areas of Boston, the BGwT has observed the groundwater table rise by approximately 1 ft. However, the impact on the groundwater table is contingent on the number of recharge systems within an area, the amount of precipitation, and Boston's continued effort to reduce the number of leaks within the city sewer and stormwater systems.

Acknowledgements

We thank Christian Simonelli of the BGwT, who provided us with thoughtful guidance and insight into the establishment and compliance with Article 32 and its positive effects on Boston's groundwater preservation initiative.

References

Aldrich H., and J. Lambrechts. 1986. "Back Bay Boston, Part II: Groundwater Levels." BSCES Civil Engineering Practice Journal Vol. 1 No. 2, pp. 1 – 64.

Boston Groundwater Trust. 2024. Accessed August 2024. https://www.bostongroundwater.org/overview.

Boston Water and Sewer Commission. 2013. "Stormwater Best Management Practices: Guidance Document."

Carlson, G.B. 2010. "Simulation of Groundwater Mounding Beneath Hypothetical Stormwater Infiltration Basins." U.S. Geological Survey Scientific Investigations Report 2010-5102.

City of Boston. 2005. "Memorandum of Understanding."

City of Boston. 2006. "Article 32: Groundwater Conservation Overlay District."

City of Boston. 2007. "Article 32: Groundwater Conservation Overlay District."

City of Boston. 2021. "Article 32: Groundwater Conservation Overlay District.".

City of Boston Building Department. 1919. "The Building Law of the City of Boston."

City of Boston Planning Department. 2024. "Article 32 – Groundwater Conservation Overlay District." Accessed July 2024. https://library.municode.com/ma/boston/codes/redevelopment_authority?nodeId=ART32GRCOOVDI.

Commonwealth of Massachusetts. 2008. "Volume 2 Chapter 2: Structural BMP Specifications for the Massachusetts Stormwater Handbook."

Donlon S.P., C.A. Cormier, B.P. Strohman. 2022. "Sub-Surface Recharge Systems Require Careful Planning." Development, pp. 20 – 24.

Federal Highway Administration (FHWA). 2006. "NHI Course No. 132012, Soils and Foundations Reference Manual", Vol. 1, FHWA Publication NHI-06-088.

Hantush, M.S. 1967. "Growth and Decay of Groundwater Mounds in Response to Uniform Percolation: Water Resources Research." v. 3, pp. 227 – 234.

Kasenow, M. 2002. "Determination of Hydraulic Conductivity from Grain Size Analysis." Water Resources Publications, LLC.

Nearmap. 2024. "Aerial Map of the City of Boston." Accessed June 2024. https://apps.nearmap.com/.

Seasholes N. 2003. “Gaining Ground: A History of Landmaking in Boston.” MIT Press.
Unified Facilities Criteria (UFC). 2004. “Dewatering and Groundwater Control”. UFC 3-220-05.
UFC. 2022. “Soil Mechanics (DM 7.1)”. UFC 3-220-10.
U.S. Army Corps of Engineers (USACE). 1993. “Seepage Analysis and Control for Dams,” Change 1. USACE Engineer Manual 1110-2-1901.
Zelada G., Konicki W., Westover P., and Vatovec, M. 2013. “Part 1: Understanding Biodegradation and Compressive Strength.” Structure Magazine, pp. 9 – 11.
Zelada G. A., Homem S. M. 2017. “Underpinning a Boston Landmark for the Ages: The First Mother Church of Christ, Scientist (TFCCS), the Original Mother Church (TOMC), Foundation Repairs. Geotechnical Frontiers, pp. 294 – 304.

Volume 32, Number 1

Instrumentation and Monitoring of a New FRP Composite Bridge using Sensing Textiles

Tzuyang Yu[1], Sanjana Vinayaka[1], Qixiang Tang[1], Rui Wu[2], Andres Biondi Vaccarriello[2], Xingwei Wang[2], Camila Garcia[3], Balaji Gopalan[3], Jackson Ivy[3], Thomas Hanna[3], Timothy Kenerson[4]

[1] Department of Civil and Environmental Engineering, University of Massachusetts Lowell, Lowell, MA 01854, USA
[2] Department of Electrical and Computer Engineering, University of Massachusetts Lowell, Lowell, MA 01854, USA
[3]Saint-Gobain Research North America, Northborough, MA 01532, USA
[4]AIT Composites, Brewer, ME 04412, USA

E-mail: tzuyang_yu@UML.EDU

Published December 15, 2024

Abstract

Fiber reinforced polymer (FRP) composite materials have been used in civil infrastructure systems as standard structural elements to mitigate the risk of steel corrosion in reinforced concrete and prestressed concrete structures. Recently, a new vehicluar bridge (Grist Mill Bridge, Hampden, Maine) using FRP composite materials as bridge girders is intrumented with sensing textiles to measure distributed temperture and strain data for long-term structural health monitoirng (SHM). In this paper, we report the design, preparation, laboratory testing, and field implementation of sensing textiles for instrumenting two girders of the new FRP composite bridge. In the design of sensing textiles for long-term SHM of bridges, distributed temperaure sensing and strain sensing using optical fibers were achieved by Brillouin Optical Time Domain Amplification (BOTDA). A layered structure in sensing textiles was proposed to protect optical fibers from environmental disturbances and to control the pattern of optical fibers during installation. A laboratory testbed (mockup bridge girder and installation cart) and an installation procedure were developed for efficient field installation of sensing textiles. From our laboratory and field test results, we demonstrated the field instrumentation of a distributed fiber optic sensor on a new FRP composite bridge through the pattern design of optical fiber cables, manufacturing of a laboratory testbed for trial installation, development of a field installation procedure, and field data collection. Through an academia-industry collaborative effort, such a field implementable technology can be further applied to existing civil infrastructures such as highway bridges, roadways, and tunnels.

Keywords: FRP Composite, Bridge Girders, Sensing Textiles, BOTDA

1. Introduction

Bridges are an essential compoment in transportation networks, as well as a valuable asset in civil infrastructure systems. Depending on the materials, structural system, environmental condition, and loading conditions (natural and manmade), bridges are vulnerable to different types of damages. They can age (materially) and deteriorate (structurally) at different rates. For example, concrete (reinforced concrete or RC and prestressed concrete or PC) bridges are vulnerable to the corrosion of steel members including reinforcing bars and prestressing strands, especially in aggressive environments where moisture, catalysts (usually chloride ions), temperature, oxygen, and acidity facilitate the electrochemical reactions (cathodic and anodic). Once corroded, steel members will start losing their cross sectional area for load bearing capacity. Consequently, corroded concrete bridges are prone to premature, brittle failures.

To mitigate the risk of steel corrosion, non-metallic/non-corrosive materials such as fiber reinforced polymer (FRP) materials have been used in civil infrastructure systems as standard structural elements. Glass FRP (GFRP) bars (ASTM 2022, ACI 2007, ACI 2022), GFRP rods (Bakis et al. 1998), and carbon FRP (CFRP) bars (ACI 2007, ACI 2022) were applied mostly for replacing steel rebars and for repairing in concrete bridges, while GFRP sheets/laminates (ACI 2017), CFRP sheets/laminates (ACI 2017, Yan et al. 2019) and CFRP strips (CSA 2022) were used for strengthening concrete beams, columns, piers, slabs, and walls. In such applications, FRP provides additional tensile strength, shear strength, and confinement (Ozbakkaloglu 2013) to strengthened members, but it is not considered as a major load bearing member.

In recent years, the use of FRP composites as a major load bearing member has been reported in the design of bridges. FRP composites have shown their promising advantages against tranditional structural materials (e.g., RC, PC, and steel) in bridge engineering, in view of their high strength-to-weight ratio, high endurance to fatigue, immunity to steel corrosion, enhanced durability against envrionmental attacks, flexible shapes in design, better quality controll in factory, accelerated construction, relatively-low maintenance, and lower life-cycle costs. Concrete-filled FRP tubes were used as bridge piers (Ozbakkaloglu 2013) without steel rebars. Pultrated FRP I-beams were used to connect concrete bridge decks in Spain (Mieres et al. 2007; Gutierrez et al. 2008). FRP composite bridge girders partially filled with foam and reinforced with transverse steel rebars were used in a bridge in Texas (Ziehl et al. 2009). Concrete-filled FRP tubes were also shaped as arches and used as bridge girders in Maine (Dagher et al. 2012; AASHTO 2012). FRP composite bridge girders used in bridge concrstruction were also reported in Poland (Siwowski et al. 2017). A new design of FRP composite bridge girders was recently implemented in a five-girder bridge in Hampden, Maine (Davids et al. 2022). Overall, most applications of FRP composites are in rebars for replacing steel, strips/sheets for repairing and strengthening, and laminates/wraps for providing confinement. Only limited applications of FRP composites have been reported in tub girders for bridge construction. In view of the novelty of FRP tub girders used in bridges, their long-term performance is of great interest to the civil engineering community.

There are three objectives in this bridge instrumentation; i) to collect distributed strain data using fiber optic sensors, ii) to better understand the long-term performance of FRP composite bridge girders, and iii) to examine the long-term durability of sensor installation. In this paper, we report the design, preparation, laboratory testing, and field implementation of sensing textiles for the instrumentation of a new FRP composite bridge in Hampden, ME. This research is a collaborative effort among the University of Massachusetts Lowell (UML), AIT Composites, Maine Department of Transportation (DOT), and the University of Maine (UMaine).

In the following sections, sensor design, development of intsallation plan, laboratory trial, field installation, sensor testing and calibration, and data interpretation will be described in detail.

2. Description of FRP Composite Girder Bridge

The bridge instrumented with sensing textiles is a 22.9-m (75-ft) vehicular bridge (Grist Mill Bridge) on the US Route 1A in Hampden, Maine, USA designed by AIT Composites and constructed by T Buck Construction, Inc for Maine DOT in 2020. The instrumented FRP composite girders were made by vaccum infusion using a female timber and polymer mold. The girders were made of a hybrid of E-glass and carbon FRP with Derakane 610c epoxy resin. There were five FRP composite bridge girders on the bridge. Figure 1 shows the location of the bridge. Figure 2 shows the layout of five FRP composite girders. Among the five FRP composite girders, Girders 1, 3, and 5 were selected for instrumentation.

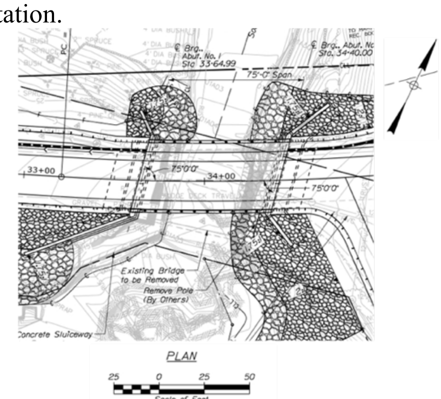


Figure 1. The Grist Mill Bridge, Hampden, Maine, USA. (Source: AIT Composites)

The FRP composite bridge girders have a width of 3'10" on the top and 1'5" (or 17") at the bottom. Their depth is 4'2". However, the inner width at the bottom is 18". Figure 3 shows the cross sectional dimensions of FRP composite girders. Further information regarding the design, manufacturing, and experiment assessment of FRP cmposite girders can be found in the literature (Davids et al. 2022; Davids et al. 2023).

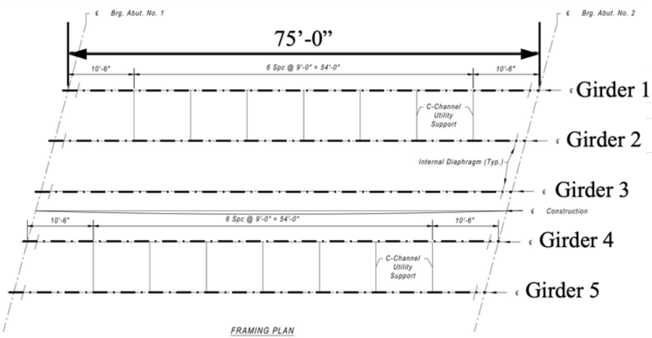


Figure 2. Layout of five FRP composite girders. (Source: AIT Composites)

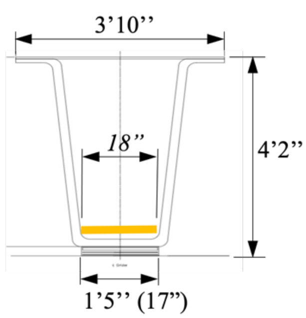


Figure 3. Cross section of FRP composite girders. (Source: AIT Composites)

3. Design and Manufacturing of Sensing Textiles

The sensing mechanism of sensing textiles is distributed temperature and mechanical strain sensing through Brillouin Optical Time Domain Amplification (BOTDA). The principle and application of using BOTDA for surface strain measurement can be found in our publication using pipe specimens and railway bridge as examples (Biondi et al. 2022; Biondi et al. 2023).

In the design of sensing textiles for bridge monitoring, the pattern of optical fibers needs to be oriented in the desired direction at selected locations. The reason in choosing a desired direction is for measuring certain strain component to be used in the structural health monitoring (SHM) algorithm of the structure. For these FRP composite bridge girders, our objective is to use distributed longitudinal strain measurements to calculate the stiffness of the girders for SHM purposes. The following sections describe the layered structure of installed sensing textiles for long-term SHM and the pattern design of optical fibers inside the sensing textile for strain measurement.

3.1 Layered Structure of Installed Sensing Textiles

To achieve long-term bridge monitoring in New England, the installed sensors must be durable in order to survive the severe local weather condition such as drastic seasonal temperature variation (e.g., from 95ºF in the summertime to -8ºF in the wintertime in Masachusetts). We proposed a layered structure for the installation of sensing textiles as shown in Figure 4.

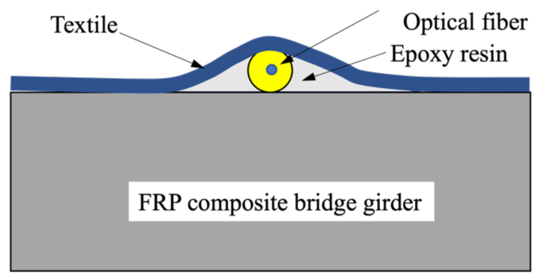


Figure 4. Layered structure of sensing textiles

In Figure 4, optical fibers are first stitched to the weaved textile at the designed pattern to form a sensing textile. When installing the sensing textile onto the surface of FRP composite bridge girders, the sensing textile is surmerged into an epoxy resin to make sure that the entire surface of the sensing textile can provide adhesion with the surface of FRP composite. To better protect optical fibers from an outdoor environment and to hold optical fibers at the installed location for a long time, optical fibers are placed between the textile and the surface of FRP composite to form a layered structure of installed sensing textiles. In this design, the triangular gaps adjacent to an optical fiber must be filled up with expoxy resin to avoid the formation of air pockets from happening. When installing sensing textiles, a paint roller is used to apply pressure on sensing textiles to remove or eliminate air pockets.

3.2 Pattern Design of Optical Fiber Cables

In the pattern design of optical fibers for sensing textiles, the major function of a structure is identified at first. The second factor to consider is the design of SHM algorithms. In the design of an SHM algorithm based on structural mechanics, health-related parameters are usually extracted or calculated from experimentally measurments such as displacement, velocity, acceleration, or strain. In our case, we used distributed longitudinal strain as the experimental measurement in our SHM algorithm. Two types of optical fibers were used for temperature and strain measurements; SMF-28e+ and 62.5/125 GIOF (Graded-Index Optical Fiber). One SMF-28e+ optical fiber cable was used for DTS (distributed temperature sensing). One multimode 62.5/125 GIOF optical fiber cable was used for distributed temperature and strain sensing based on BOTDA. Table 1 provides the technical specs of these two optical fiber cables.

Table 1. Specs of used optical fiber cables.

Fiber type	Temp. range (°C)	Mandrel radius (mm)	Outer diam. (μm)	Tensile stress (ksi)
SMF-28e+	-60 ~ 80	25	245	≥ 100
62.5/125 GIOF	-60 ~ 80	≥ 17	245	≥ 100

On the pattern design of optical fibers, a 74' (length) by 18' (width) textile was used to house two optical fiber cables configured along the longitudinal direction of the FRP composibe bridge girders. Eight strain gauges were also installed adjacent to the 62.5/125 GIOF optical fiber cable to calibrate distributed strain measurement. A U-shape pattern is used for both optical fiber cables, in which the first half (Section 1) and the second half (Section 2) sections of each cable can provide sufficient amount of data for our future analysis. In the event of optical fiber breakage during either girder transportation or bridge installation or long-term deterioration, the U-shape pattern would allow us to switch the launching end with the termination end in order to collect the maximum of data possible from installed sensing textiles. At the beginning and the end of the sensing textile, there were two 20-m long lauching and termination cables for signal conditioning purposes. Figure 5 illustrates the U-shape pattern of optical fiber cables designed in the sensing textiles to measure distributed longitudinal strains of Girders 3 and 5.

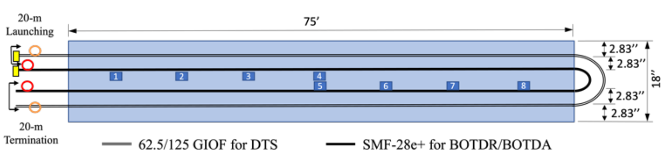


Figure 5. Pattern of optical fiber cables.

It should be noted that, in order to connect sensing textiles to the optical fiber sensing equipment at a distant location, additional length of optical fibers and strain gauge wires must be considered in the desitn.

3.3 Manufacturing of Sensing Textiles

Once the pattern design of optical fiber cables was completed, manufacturing of sensing textiles is carried out by an electronic crochet knitting machine (Comez Testronic 1600) located at Saint-Gobain Research North America (Northborough, MA). This knitting machine can produce a wide range of bouclé, plain and openwork knitted fabrics, and sensing textiles with embedded optical fiber cables. Figure 6 shows the machines located in the facility of Saint-Gobain Research North America.

Figure 6. Comez Testronic 1600 machine at Saint-Gobain Research North America.

During the manufacturing of sensing textiles, optical fiber cables were embedded by knitting optical fiber cables onto the substrate fabric with stitches at a given design pattern controlled by the electronic crochet knitting machine. After the optical fiber cables were embedded into the substrate fabric, eight small openings were manually made on the substrate fabric for future installation of strain gauges. Both strain gaues and their associated wires were temporarily fixed on the substrate fabric for the ease of transportation and installation. Figure 7 shows a portion of sensing textiles with embedded SMF-28e+ and 62.5/125 GIOF optical fiber cables. Figure 8 shows a fixed strain gauge with its wires temporarily fixed on sensing textile with blue tapes.

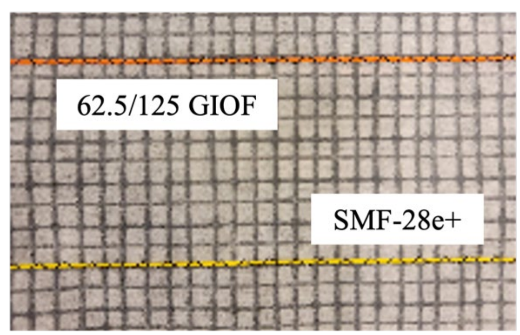


Figure 7. Embedded SMF-28e+ (orange) and 62.5/125 GIOF (yellow) optical fiber cables on the sensing textile.

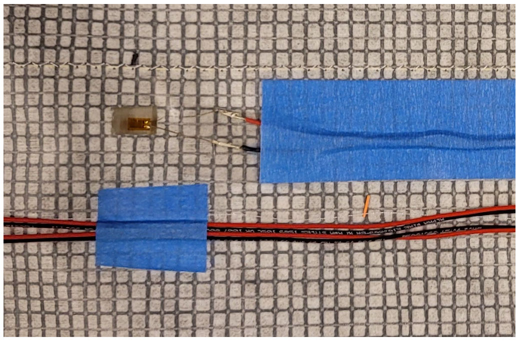


Figure 8. Fixed strain gauge and its wires on sensing textile.

Transporting a 74'-long sensing textile with a number of wire bundles attached requires proper packaging. We decided to fold sensing textiles around themselves into rolls for the ease of transport. Figure 9 shows a roll-up sensing textile with a bundle of extra length of optical fibers and a spool of extral wires for strain gauges. One roll was prepared for an FRP composite bridge girder.

Figure 9. Manufactured sensing textile in a roll.

4. Laboratory Testbed for Trial Installation

4.1 Selection and Deployment of Epoxy

In the installation of sensing textiles on FRP composite bridge girders, strong adhesives capable of resisting chemicals and water infiltration are needed since the installation of sensing textiles is designed to be permanent. A two-agent epoxy (105A epoxy resin and 206A slow epoxy hardener, West System) was selected from our previous laboratory experimentation on various types of adhesives with sensing textiles. However, preparation of this two-agent epoxy requires several minutes (depending on the volume) of mixing and 10 to 15 hours of curing time once deployed. In view of the surface area (108 ft^2 per girder, 216 ft^2 in total) to cover and the need to entirely submerge sensing textiles in epoxy, an amount of 0.546 gallon of epoxy was estimated. With a conservative percentage of loss (10~15%) during epoxy mixing and transportation, a total amount of 0.628 gallon of epoxy was obtained for this installation.

It is noteworthy to point out that, to avoid early curing and loss of viscocity of epoxy in an open, outdoor environment, we should mix two agents of epoxy at an proper amount to be consumed in 15~25 minutes. We might loss the design quality of epoxy if the mixed epoxy was left unused for too long (e.g., more than 30 minutes). Since we would not be able rapidly deploy epoxy to the entire surface area of FRP composite bridge girders, we would need to gradually mix a small portion of epoxy and deploy only that portion of epoxy. Epoxy was deployed by using paint brushes.

While depolying epoxy inside a confined space like FRP composite bridge girders, air ventilation and respiratory protection (OSHA 29 CFR 1910.134) must be provided. We used one portable industrial fan (supplied by AIT Composites) at the end of FRP tub girder to blow fresh air into the girder to improve the air circulation inside the girder. The installer also wore a respirator (3M 6503QL) with a cartridge (3M P100) for lung protection, a safety google for eye protection, and a pair of silicone gloves for skin protection as necessary personal protection equipment (PPE).

Furthermore, the confined space inside the FRP composite bridge girders also prohibited the installer from re-arranging or organizing sensing textiles inside the FRP composite bridge girders. It was expected that the installer can only deploy sensing textiles by unrolling the sensing textile rolls in one direction, considering the fact that the surface of FRP bottom flanges was covered by uncured epoxy.

4.2 Mockup Bridge Girder

Since this was our first instrumentation on FRP composite bridge girders in the field using sensing textiles, we built a laboratory testbed to detect and eliminate potential issues arising from field installation. This laboratory testbed was comprised of a mockup brige girder with actual cross sectional dimensions and a custom-built installation cart for installing sensing textiles. This testbed was necessary for us to develop a feasible, efficient installation procedure with the minimum manpower working inside the FRP composite bridge girders.

The FRP composite bridge girders to be instrumented have a trapezoidal cross section with a height of approximately 4', an upper base of 26" and a lower base of 18". The small cross sectional area prevented two people from working at the same location. It was even too small for a person greater than average size to easily maneuver inside the FRP composite bridge girder. Therefore, a one-person (installer) installation scheme was decided. To prepare the installer for navigating along the FRP composite bridge girder, a full-size mockup bridge girder was designed and built as shown in Figure 10.

(a) FRP composite bridge girder (b) Lab mockup girder

Figure 10. FRP composite bridge girder and lab mockup.

Two styrofoam panels (1” thickness) made of extruded polystyrene (Foamular NGX, Owens Corning) as the side walls and one polyisocyanurate panel (2” thickness, Super TUFF-R) as the bottom flange were used, as shown in Figure 10 (b). These panels were connected by styrofoam glue and reinforced by heavy-duty waterproof duct tape to maintain a stronger hold.

Once the mockup girder was completed, the installer used it to practice performing various tasks including deploying epoxy and installing sensing textile. To move from one location to another inside the FRP composite bridge girder, the installer would need a device to reduce his level of physical fatigue and to improve his mobility with logistic support to supply epoxy. Therefore, an installation cart was designed and built.

4.3 Installation Cart

To order to improve the mobility of the installer, a multi-functional installation cart was designed with the following main functions:

1) To reduce the physical fatigue of the installer during the installation process by providing a seating area – A two-layer cushion was installed at one end of the cart.
2) To serve as a receiving point for a bucket of epoxy transported by the rest of the team – One pulley was installed.
3) To mobilize the installer and physically connect the installer with the rest of the team to allow the rest of the team to pull the cart in one direction – Four pneumatic rigid casters with breaks, a pulley, and a polyester rope were installed.
4) To provide a temporary storage spage of tools for the installer – A storage area was preseved at the other end of the cart.

Figure 11 illustrates our design of the installation cart. In Figure 11, an epoxy container is connected to the close-loop polyester rope. It should be noted that the installation cart was operated by the rest of the team outside the FRP tub girder, rather than by the installer. Nonetheless, the installer can still move the cart in an emergency.

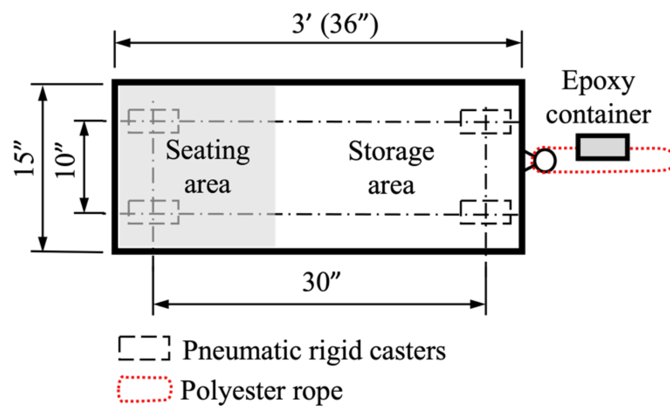


Figure 11. Design of installation cart.

Our design to move the installation cart and to transport epoxy (through an epoxy container) was by selectively pulling different numbers of the rope. When moving the installation cart, the close-loop rope is treated as one rope and pulled in one direction. Since the installation can only move in one direction (the other direction is uncured epoxy), we only need to use the rope as a cable constantly under tension. When transporting epoxy from ourside the tub girder to the installer inside the tub girder, the close-loop rope is treated as a ring cable and operated in two different directions; clockwise and counterclockwise. In the design shown in Figure 11, rolling the rope in the clockwise direction will transport the epoxy container from the installer to the rest of the team outside the tub girder. In other words, rolling the rope in the counterclockwise direction will bring the epoxy container from outside the tub girder to the installer. This way, we use one close-loop rope to provide two functions in the design of this installation cart.

Figure 12 shows the two-layer cushion on the cart. Figure 13 shows the custom-built installation cart.

Figure 12. Two-layer cushion on installation cart.

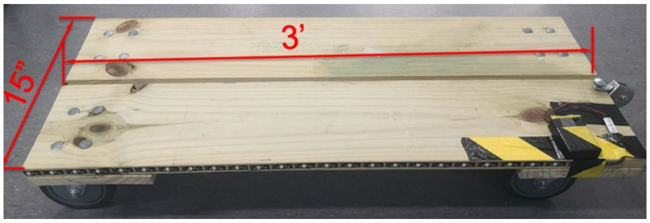


Figure 13. Installation cart.

Formation of an installation team is described in the following section.

4.4 Formation of the Installation Team

An installation team comprised of at least four members was designed for this instrumentation. Their responsibilities are described in the following:

- Installer: Responsible for i) deploying epoxy, ii) unrolling and installing sensing textile, iii) compacting the sensing textile to remove air pockets trapped between the sensing textile and the surface of FRP tub girder, and iv) communicating with the rest of the team for any needs (e.g., advancing the cart, requesting for epoxy supply). The installer is equipped with one unit of walkie-talkies for communication, a headlamp for better illumination, and one raspirator
- Cart operator: Responsible for i) pulling the installation cart toward the outside direction of the tub girder, ii) transporting additional expoy through moving the epoxy container, and iii) communicating with the installer. The carr operator is equipped with one unit of walkie-talkies.
- Epoxy mixer: Responsible for i) mixing the two agents of epoxy to make sure the epoxy is uniformly mixed, and ii) monitoring the idle time of epoxy to make sure it will be used within 10 minutes from mixing.
- Team captian: Responsible for i) documenting the starting time and ending time of each installation, ii) measuring the ambient temperature, iii) reminding other team members with any possible issues that may occur, and iv) communicating with other companies and state DOTs in case the installation has to stop.

4.5 Installation Procedure

We proposed a backward advancing scheme with the following installation steps for the instrumentation of FRP composite bridge girders.

1) Place the sensing textile roll, the installation cart, and a small portion of mixed epoxy on the cart with tools (e.g., paint brushes, walkie-talkie). The installer enters the FRP tub girder by siting on the cart and wearing required PPE. An industrial fan is turned on. Wireless communication using walkie-talkies is tested.
2) The epoxy mixer prepares a small portion of epoxy and transports to the installer through the epoxy container. Upon receiving the epoxy container, the installer starts deploying epoxy onto the surface of FRP tub girder.
3) After deploying epoxy, the installer unrolls the sensing textile roll and installs it over the surface area covered by uncured epoxy. The installer compresses the sensing textile to remove air pockets trapped underneath the sensing textile.
4) The installer informs the cart operator to advance the cart to the next position and the epoxy mixer to supply more epoxy.
5) Repeat Steps 2) to 4) until the installer completes installing the FRP tub girder.
6) Once one FRP tub girder is completed, the installation team moves to the next girder and repeat Steps 1) to 5).
7) After all FRP composite bridge girders are instrumented, the sensors are tested for their integrity and quality.

Figure 14 illustrates the installation procedure in which the installer moves backward in order to unroll sensing textiles in front of him.

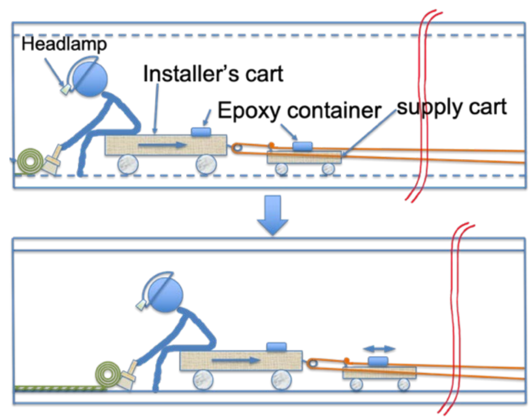


Figure 14. Backward advancing scheme.

5. Field Instrumentation

5.1 Installation of Sensing Textiles

Three FRP composite bridge girders were intrumented on October 6, 2020 in the parking lot of AIT Composites (Brewer, ME), where all FRP composite bridge girders were temporarily stored before construction. A power generator was provided by AIT Composites. Figure 15 shows the UML installation team and five FRP composite bridge girders. Figure 16 shows one installation cart and three sensing textile rolls.

Before we started installing sensing textiles, we noticed that the bottom surface of FRP composite bridge girders was covered in dust and not ready for epoxy deployment. After using a leaf blower to clean the composite surface, we used wet cleaning cloths to further remove any stains or mud from the composite surface. The leaf blower was used again to dry up the surface. Figure 17 (a) shows one UML student cleaning the surface using a leaf blower.

Figure 15. The UML team and five FRP composite bridge girders in Brewer, ME.

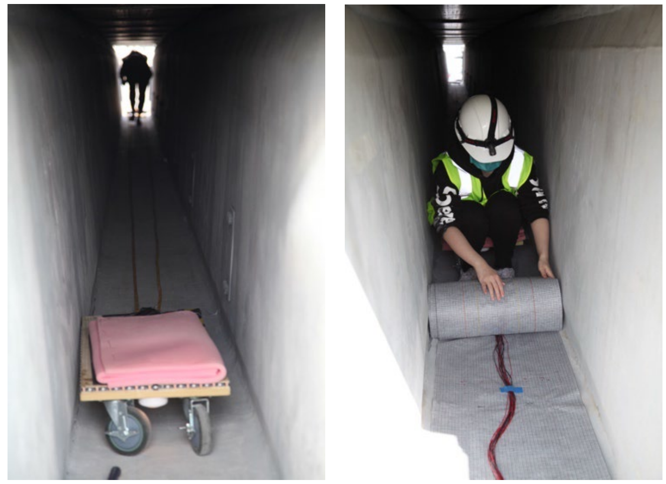
Figure 16. Installation cart and three sensing textile rolls.

(a) Surface cleaning. (b) After cleaning.

Figure 17. The UML team and five FRP composite bridge girders in Brewer, ME.

After the surface was cleaned, we started the installation procedure as shown in Figures 18 (Step 1) and 19 (Steps 2 to 4).

Figures 20 and 21 shows the instrumented FRP composite bridge girder (Steps 5 and 6). After installation, the baseline data of fiber optic sensors and strain gauges were collected on October 6, 2020, to make sure all installed sensors are intact, even though the epoxy was still uncured.



(a) Installation cart. (b) Unrolling sensing textile.

Figure 18. Installation procedure – Step 1).

(a) Deploying textile. (b) Mixing epoxy.

Figure 19. Installation procedure – Steps 2) ~ 4).

(a) Installed textile. (b) Epoxy container.

Figure 20. Installation procedure – Step 5).

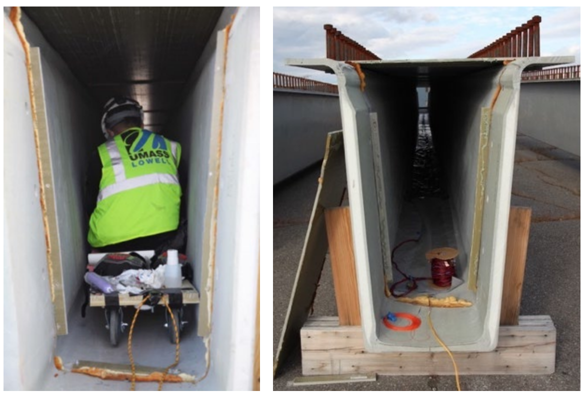


Figure 21. Instrumented procedure – Steps 5) and 6).

After 28 days of installtion, we returned to the FRP composite bridge girders in Brewer, ME on November 3, 2020, when we believe the epoxy was completed cured. The objective of this visit was to examine the quality of installation and to collect data collection was to test the integrity of installed sensing textiles. Figure 22 shows two instrumented FRP composite bridge girders at the parking lot at AIT Composites (Brewer, ME).

Figure 22. Instrumented FRP composite bridge girders

4.2 Sensor Testing and Calibration

On November 3, 2020, we used a laser source to test the integrity of optical fibers embedded in sensing textiles and found out that all signal strengths are strong. Figure 23 shows our signal strength test in the field using the equipment shown in Figure 24.

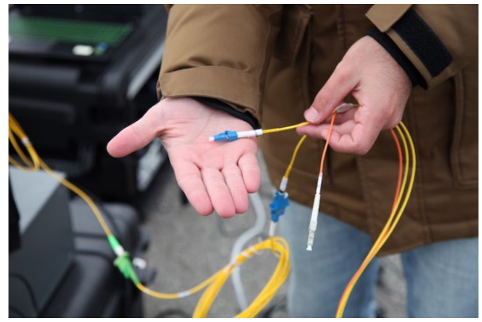


Figure 23. Signal strength test using a laser source.

Figure 24. Optical fiber sensing equipment.

After collecting the baseline data, we also re-arranged the additional length of optical fibers and wires by using heavy-duty duck tapes. Figure 25 shows Girders 3 and 5 after instrumentation. Figure 26 shows the constructed bridge.

Figure 25. Instrumented FRP composite girders 3 and 5.

Figure 26. Constructed Grist Mill Bridge.

Distribued longitudinal strain measurements collected on October 6 and November 3, 2020 are illustrated in Figures 27 and 28, respectively. In Figure 27, one spike of longitudinal strain in Section 1 of Girder 3 is found due to the accidental streching of opfical fiber cable during installation before the epoxy resin was fully cured. In Figure 28, another spike in Section 2 of Girder 1 is found during epoxy curing. After substracting the distributed strain data on October 6 from the one on November 3, we obtained the distrubuted strain difference on girders 1 and 3 to illustrate the effect of epoxy curing. Figure 29 will be used as the baseline in our data analysis for SHM of the bridge.

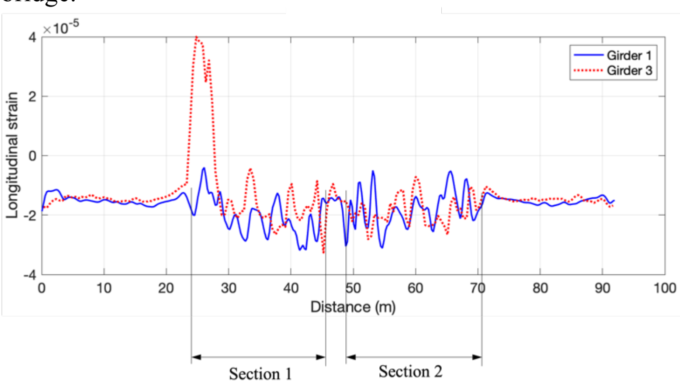


Figure 27. Instrumented FRP composite girders 1 and 3 on 10/06/20 with uncured epoxy.

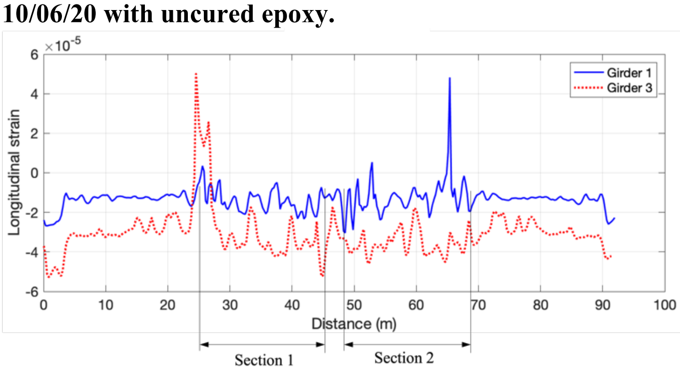


Figure 28. Instrumented FRP composite girders 1 and 3 on 11/03/20 with cured epoxy.

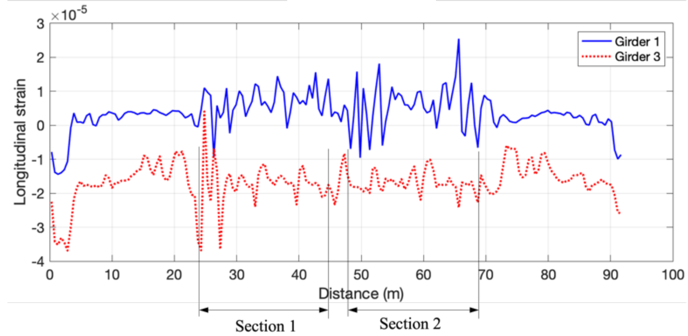


Figure 29. Distributed strain difference on girders 1 and 3 – The epoxy curing effect.

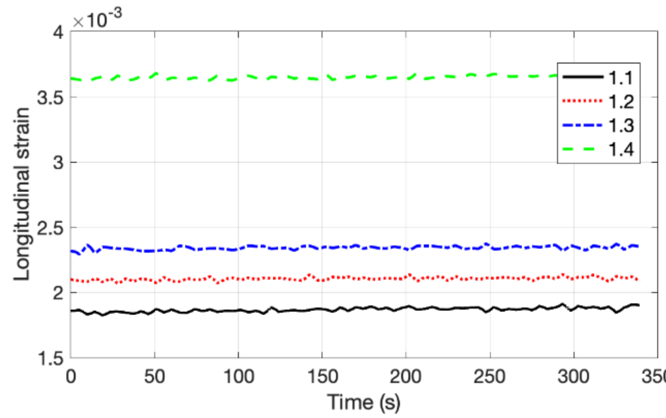


Figure 30. Strain gauge measurements on Girder 1 – 1.1 to 1.4 on October 6, 2020.

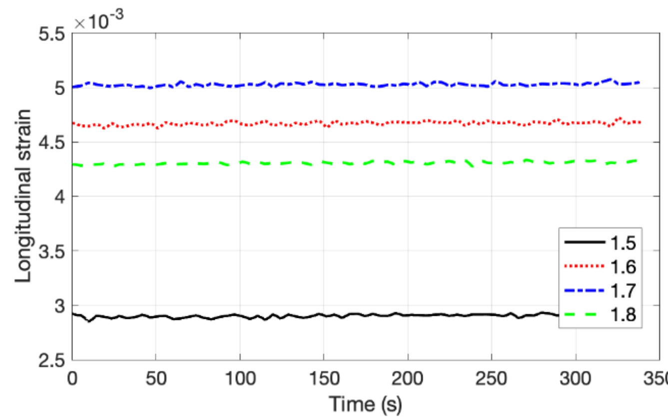


Figure 31. Strain gauge measurements on Girder 1 – 1.5 to 1.8 on October 6, 2020.

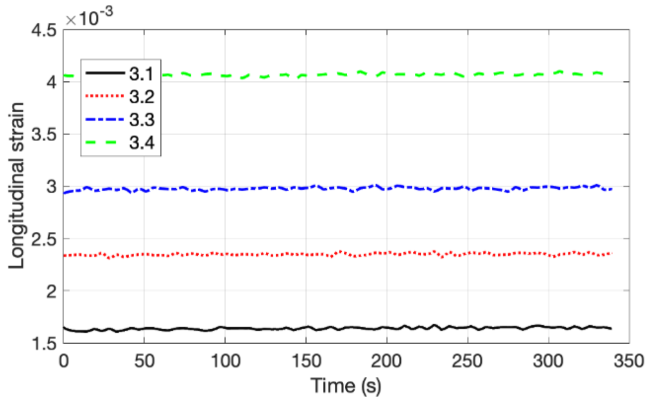


Figure 32. Strain gauge measurements on Girder 3 – 3.1 to 3.4 on October 6, 2020.

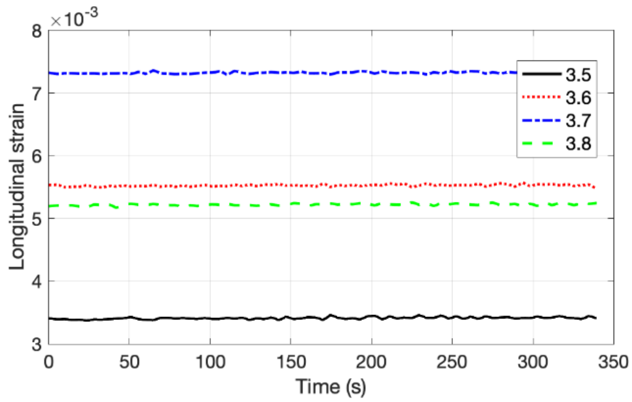


Figure 33. Strain gauge measurements on Girder 3 – 3.5 to 3.8 on October 6, 2020.

Figures 30 to 33 show the strain gauge time-history curves for 340 seconds from Girders 1 and 3, collected on October 6, 2020. From these longitudinal strain measurements, we can see the stability in the performance of sixteen installed strain gauges. The values of these strain curves will be used as the baseline values for future load tests on the bridge. The strain gauge curves collected on November 3, 2020, look similar to the ones in Figure 30 to 33.

6. Conclusion

In this paper, we reported our research activities on the instrumentation of a new FRP composite bridge through our laboratory and field efforts on the pattern design of optical fiber cables, manufacturing of a laboratory testbed (a mockup bridge girder and an installation cart) for trial installation, development of a field installation procedure, and field data collection. It is through this academia-industry-government collaborative project that we have demonstrated the practicality and feasibility of distributed sensing on bridges. Such a distributed sensing technology utilizing surface strains can be potentailly applied to other existing critical civil infrastructure systems like roadways and tunnels.

Acknowledgements

We appreciate the financial supports from Advanced Functional Fabrics of America (AFFOA) through Project "Sensing Textiles for Civil Infrastructure Moniroting" (2018~2019) and the U.S.DOT University Transportation Center (UTC) Transportation Infrastructure Durability Center (TIDC) through Project C.11 "Development of a System-level Distributed Sensing Technique for Long-term Monitoring of Concrete and Composite Bridges" (2019~2024). We would like to thank Dale Peabody from Maine DOT for initiating the idea of instrumenting Grist Mill Bridge (Hampden, ME) with sensing textiles and for providing necessary administrative assistance. We also want to thank Anthony Diba, Wendell Harriman, and Ken Sweeney from AIT Composites (Brewer, ME) for their help and logistic supports during our two visits to their parking lot on Oct. 6th and Nov. 3rd, 2020. Assistance provided by graduate students Jianing Wang and Harsh Gandhi in field experimentatoon is appreciated.

References

AASHTO (American Association of State Highway and Transportation Officials). (2012). LRFD Guide Specifications for Design of Concrete-Filled FRP Tubes for Flexural and Axial Members. Washington DC.

ACI (American Concrete Institute). (1989). Building code requirement for reinforced concrete. ACI 318-89. Farmington Hills, MI: ACI.

ACI. (2007). Report on Fiber-Reinforced Polymer (FRP) Reinforcement for Concrete Structures. ACI PRC-440-07. Farmington Hills, MI: ACI.

ACI. (2022). Building Code Requirements for Structural Concrete Reinforced with Glass Fiber-Reinforced Polymer (GFRP) Bars—Code and Commentary. ACI CODE 440.11-22. Farmington Hills, MI: ACI.

ACI. (2017). Guide for the Design and Construction of Externally Bonded FRP Systems for Strengthening Concrete Structures. ACI PRC-440.2-17. Farmington Hills, MI: ACI.

ASTM (American Society for Testing and Materials). (2022). Standard Specification for Solid Round Glass Fiber Reinforced Polymer Bars for Concrete Reinforcement, ASTM D7957/D7957-22, West Conshohocken, PA

Bakis, C.E., Al-Dulaijan, S.U., Nanni, A., Boothy, T.E., Al-Zahrani, M.M. (1998). Effect of Cyclic Loading on Bond Behavior of GFRP Rods Embedded in Concrete Beams, J. Compos. Tech. Res., 20 (1), 29-37.

Biondo, A.M., Guo, X. , Wu, R., Cao, L., Zhou, J., Tang, Q., Yu, T., Goplan, B., Hanna, T., Ivy, J., Wang, X. (2023). Smart textile embedded with distributed fiber optic sensors for railway bridge long term monitoring. Opt. Fiber Tech., 80, 103382. s

Biondo, A.M., Zhou, J., Guo, X., Wu, R., Tang, Q., Gandhi, H., Yu, T., Goplan, B., Hanna, T., Ivy, J., Wang, X. (2022). Pipeline structural health monitoring using distributed fiber optic sensing textile. Opt. Fiber Tech., 70, 102876.

Bremer, K., Weigand, F., Zheng, Y., Alwis, L.S., Helbig, R., Roth, B. (2017). Structural Health Monitoring Using Textile Reinforcement Structures with Integrated Optical Fiber Sensors. Sensors, 17 (345), 1-12.

CSA (Canadian Standards Association). (2022). Fibre reinforced polymer (FRP) reinforcement for concrete structures — Part 2: Specifications of CFRP strips. ISO 18319-2:2022. Toronto, Ontario, Canada: CSA.

Dagher, H.J., Bannon, D.J., Davids, W.G., Lopez-Anido, R.A., Nagy, E., Goslin, K. (2012). Bending behavior of concrete-filled tubular FRP arches for bridge structures, Const. Build. Mat., 37, 432–439.

Davids, W.G., Diba, A., Dagher, H.J., Guzzi, D., Schanck, A.P. (2022). Development, assessment and implementation of a novel FRP composite girder bridge. Const. Build. Mat., 340, 127818.

Davids, W.G., Guzzi, D., Schanck A.P. (2022). Development and Experimental Assessment of Friction-Type Shear Connectors for FRP Bridge Girders with Composite Concrete Decks. Materials, 15, 3014.

Hughes-Riley, T., Dias, T., Cork, C. (2018). A Historical Review of the Development of Electronic Textiles. Fibers, 6 (34), 1-15.

Gutierrez, E., Mieres, P.S., Calvo, J.M. (2008). Structural testing of a vehicular carbon fiber bridge: Quasi-static and short-term behavior, J. Bridge Eng., 13 (3), 271–281.

Karbhari, V.M., Seible, F., Burgueno, R., Davol, A., Wernli, M., Zhao, L. (2000). Structural characterization of fiber-reinforced composite short- and medium-span bridge systems, Appl. Comp. Mat., 7, 151–182.

Mieres, J., Calvo, I., Pineda, L., Botello, F., Gomez, M., Primi, S., Bonilla, J. (2007). First bridge constructed of carbon fibre reinforced polymers in Spain, Patras, Greece, 596–597.

Nawaz, W., M. Elchalakani, A. Karrech, S. Yehia, B. Yang, O. Youssf. (2022). Flexural behavior of all lightweight reinforced concrete beams externally strengthened with CFRP sheets. Constr. Build. Mater., 327, 126966-1-22.

OSHA (Occupational Safety and Health Administration). (2006). Respiratory protection – Personal Protective Equipment. Occupational Safety and Health Standards, 1910 Suboart I. 29 CFR 1910.134. US Department of Labor. Washington DC.

Ozbakkaloglu, T. (2012). Concrete-filled FRP tubes: Manufactire and testing of new forms for improved performance. J. Compos. Constr., 17 (2), 280-291.

Ozbakkaloglu, T. (2013). Compressive behavior of concrete-filled FRP tube columns: Assessment of critical column parameter. Eng. Struct., 51, 188-199.

Yan, Y., Lan, S., Jiang, Q. (2019). A Review on Concrete Structures Strengthened with CFRP Sheets Bonded with Organic and Inorganic Cementation Materials. Adv. Civil Eng. Mater., 8 (1), 1-8.

Seyam, A.M., Hamouda, T. (2013). Smart textiles: Evaluation of optical fibers as embedded sensors for structure health monitoring of fiber reinforced composites. J. Text. Inst., 104, 892–899.

Siwowski, T., Rajchel, M., Kaleta, D., Własak, L. (2017). The first Polish road bridge made of FRP composites, Struct. Eng. Int., 27 (2), 308–314.

Zhou, G., Sim, L.M. (2002). Damage detection and assessment in fiber-reinforced composite structures with embedded fiber optic sensors-review. Smart Mater. Struct., 11, 925–939.

Ziehl, P.H., Engelhardt, M.D., Fowler, T.J., Ulloa, F.V., Medlock, R.D., Schell, E. (2009). Design and field evaluation of hybrid FRP/reinforced concrete superstructure system, J. Bridge Eng., 14 (5), 309–318.

Volume 32, Number 1

Challenges and Innovations in Designing Underground Reservoirs for Urban Water Management

Kishore Bandela[1]

[1] Civil Engineer, Massachusetts Department of Transportation, 811 N. King Street, Northampton, MA 01060
E-mail: kishore.k.bandela@dot.state.ma.us

Published March 17, 2025

Abstract

The challenges of managing water are becoming more and more common in cities across the world. This is due to rapid urbanisation, population growth, and the consequences of climate change. The project looks at whether subsurface reservoirs might be a sustainable solution for addressing water shortages in metropolitan areas and controlling flooding. The research quantitatively assesses stakeholder views and technical designs, as well as environmental sustainability and economic feasibility. This reveals that subsurface reservoirs are useful for improving urban water management. 79.3% of respondents acknowledged that urban systems successfully address water shortages, while 80.2% said that these systems help avoid floods when there is more rain than usual. There are significant challenges to its application, including technical concerns like as durability problems and building costs. The research shows that it is essential to mix smart technology with valuable materials. It also involves stakeholders in order to improve the operations of subterranean reservoirs while adhering to improved sustainability requirements. In order to be as successful as possible, underground water storage facilities need to be designed specifically for varied environmental circumstances, and they need to interact that is more public in order to get acceptability. Urban planning authorities and water management engineers conduct important research to develop sustainable water management systems that are able to withstand challenges in urban areas.

Keywords: urban water management, underground reservoirs, water scarcity, flooding, sustainability, stakeholder engagement, smart technologies.

1. Introduction

1.1 Urban Waste Management System: An Overview

Contemporary cities have issues managing water supply and demand due to increasing urban populations and climate change. By 2050, 67% of the global population will reside in urban areas, exerting pressure on water infrastructure (Huang et al., 2024). Consequently, cities worldwide confront water scarcity, flooding, and water quality challenges threatening human health, economic stability, and environmental integrity (Israilova et al., 2023). Rapid urbanisation is intricate. Urbanisation transforms natural water recharge zones, such as wetlands and forests, into urban landscapes, exacerbating surface runoff and flooding (Wu et al., 2024). The expansion of impermeable surfaces diminishes aquifer recharge, exacerbating the water crisis. Climate change exacerbates droughts and extreme weather events due to shifting precipitation patterns (Aghakouchak et al., 2020). Subsurface reservoirs might address these challenges. Abdeldayem et al., (2020) assert that these subterranean storage structures for excess rainfall or treated water offer flood mitigation during inclement weather and water supply during droughts. Both Tokyo and Singapore have a few good urban water management stories to tell. The Metropolitan Area Outer Underground Discharge Channel in Tokyo has reduced flood harm and improved the water table stock (Gholami-Shabani and Nematpour, 2024). Optimisation of subsurface reservoirs in urban construction contributes to solving water problems and improves sustainable water utilisation.

Water management strategies prioritised in urban-centric nations are becoming inadequate for addressing the challenges arising from heightened urbanisation, population expansion, and climate change. Old structures represent systems that use open roof topped water storage facilities and piped surface water supply system that do not meet water demand making them prone to pollution and volatilisation (Smakhtin et al., 2020). New more created surfaces comprise originally of non-impervious areas that prevent the infiltration and soaking of natural water in rainy seasons and does not allow water recharging when a dry climate is being experienced (Noori & Singh, 2023). Therefore, the need to enhance more efficient and cost-effective technologies of water storage become imperative. Water availability has become unpredictable today, especially because of global warming which lengthens the durations of dry seasons and increases the frequency of flooding situations (Seneviratne et al. 2021). This has fostered the need for systems that offer water storage and with and impact towards the disasters and the allocative space. Groundwater sources are more sustainable and proven to be safe, easy to utilise and less costly for water storage in the cities. It reduces water evaporation, prevents floods and aids in water recharge so it does qualify to be called sustainable development. Contemporary urban ventilation systems present several challenges such as lack of focus on urban challenges, high costs of construction, complicated maintenance and little involvement by users in decision making about the facilities. This means that filling these gaps with, for example, the use of new ideas and approaches for water sustainability is crucial since the research is very important when it comes to urban areas.

This initiative is specifically based on water and flood practices, which are two problems associated with the increase of the population of the modern world and climate change, particularly in the development of urban areas. According to the guidelines provided by the authors in the study by Slekyanzi et al., (2024), more than half of the global population is threatened by water shocks making subsurface reservoirs a sustainable source for the expansion of urban cities. Therefore, given the emphasis on design interventions and stakeholder interpretations within this study, it is intended to provide policy-relevant information to policymakers and urban strategists. A study shows that it is plausible to capture more floodwater and store water during the dry season, with subterranean reservoirs applied consequently in Tokyo and Singapore (Dąbrowska et al., 2023). This study also shows there is a gap in understanding and assessment by the public and professionals on the sustainability of the supporting infrastructure needed in the creation of sustainable environments. It offers guidance for incorporating photogenic effective subsurface reservoirs into urban planning, sustainable environments, and long-term urban performance.

The study exclusively focuses on primary data obtained from professionals engaged in urban water management, including urban planners, engineers, and key stakeholders actively participating in the management of water in urban environments. It examines and assesses the utilisation and implementation of underground reservoirs concerning water scarcity and flooding challenges, including the function and design of subterranean reservoirs for these issues. The research focuses on the examination of urban water issues arising from urban expansion and climate change in designated urban locations (2021). Despite the advantages of innovative methodologies, the research fails to consider rural or industrial water systems. Moreover, it is restricted by the number of participants and the data they provide, thereby constraining cross-geographical generalisation.

Research Objectives:

• To identify key challenges faced in the design implementation of underground reservoirs in urban areas.

• To evaluate the efficiency of current underground reservoir designs in managing urban water resources during peak demand and flood scenarios.

• To assess the impact of innovative materials and technologies on the structural integrity and cost-effectiveness of underground reservoirs.

• To analyse public and stakeholder acceptance of underground reservoirs as a sustainable solution for urban water management.

Research Questions

• What are the key challenges faced in the design implementation of underground reservoirs in urban areas?

• How efficient are current underground reservoir designs in managing urban water resources during peak demand and flood scenarios?

• What is the impact of innovative materials and technologies on the structural integrity and cost-effectiveness of underground reservoirs?

• How do public and stakeholder perceptions influence the acceptance of underground reservoirs as a sustainable solution for urban water management?

1.2 Urban Water Management Challenges

Impacts of Urbanisation on Water Systems

Figure 1: Smaller cities and towns in many regions are recording faster growth in slum populations than major cities. (UNstats, 2023)

Urbanisation has significantly transformed water systems, increasing the demand for water resources and altering natural hydrological cycles. Nearly 70% of the global population is expected to reside in urban areas, intensifying pressure on existing water infrastructure (UNstats, 2023). Although the percentage of the urban population residing in slums decreased somewhat from 25.4 to 24.2 percent between 2014 and 2020, the absolute number of slum inhabitants persists in rising due to escalating urbanisation. In 2020, over 1.1 billion urban inhabitants resided in slums or comparable circumstances (UNstats, 2023). The population growth rate has exerted significant strain on urban water supplies, resulting in competition among human, industrial, and agricultural water demand.

Moreover, the impermeable surfaces in the metropolitan region have markedly diminished, encompassing woods and other wetlands, which are essential for natural water penetration and aquifer replenishment. Consequently, impermeable materials like concrete pavements and asphalt, exacerbating surface runoff have supplanted these surfaces during heavy rainfall events, as emphasised by Huang et al. in 2024. The diminished infiltration capability decreases water storage in aquifers, leading to both water scarcity and an increased danger of flooding in metropolitan areas.

Climate Change and Water Resource Stress

Regular and severe weather conditions present an additional challenge to the management of water resources in urban areas owing to climate change. The Intergovernmental Panel on Climate Change (IPCC) states that rising average temperatures, together with alterations in the frequency of rainy days, affect the characteristics and prevalence of droughts and floods globally (Allan et al., 2023). The consequences appear to be more significant in metropolitan areas due to substantial population demands and centralised water delivery systems.

Cities like Cape Town and Chennai have experienced significant water scarcity; during the 2018 water crisis in Cape Town, the city was on the brink of "Day Zero." Conversely, Jakarta and Bangkok persistently face flooding challenges due to inadequate drainage infrastructure and elevated sea levels (Edelman, 2023). The two extremes illustrate the necessity for robust strategies to manage water in urban areas due to the challenges of both shortage and unregulated floods.

Need for Sustainable Water Solutions

The elements presented illustrating the realities of the water-related situation in metropolitan settings emphasise the significance of sustainable policies to regulate demand and supply and their environmental impacts. Lit blocks are extensively utilised in contemporary society, and subterranean reservoirs have demonstrated efficacy in addressing the aforementioned issues. Subterranean storage systems surpass surface reservoirs due to reduced evaporation, efficient space utilisation in densely populated regions, and mitigation of excessive rainfall impacts during storms (Yang et al., 2022).

Implementing sustainable water management in urban design is essential to achieve long-lasting sustainable outcomes. In addition to traditional systems, business/partitioned subterranean reservoirs, when combined with smart sensors for monitoring and operations, provide a forward-thinking answer to the water challenges faced by modern communities. They also facilitate Aquifer Recharge, hence reducing reliance on the central Water Supply System. Integrated Water Resources Management (IWRM) aims to utilise water resources efficiently and sustainably (Mseli et al., 2024).

This section illustrates the necessity of planning and integrated aquatic solutions, especially subterranean reservoirs, for the resilience of urbanisation, acknowledging the connectivity and impact of dual shocks: urbanisation and climate change on water systems. It not only helps ease existing problems but also prevents issues from going into the domain of sustainability, which makes its area very important in the context of urban water management.

1.3 Underground Reservoirs: An Overview

Definition and Functionality

Underground reservoirs are human-made structures designed for subterranean water storage and serve as ecologically sustainable solutions for urban water issues. These reservoirs consist of substantial concrete or steel tanks or tunnels that retain and subsequently employ rainwater from precipitation, stormwater, or pre-treated water (McCarton et al., 2021). They are subterranean, enabling their placement in densely populated urban areas due to the spatial limitations associated with surface reservoirs.

In an effort to understand the work duties of subsurface reservoirs, they may be defined into a basic two forms. The delivery of portable water, management of is irrigation and water storage systems. They are notably efficient in moving surplus rainfall during a storm, thus augmented flood control in developed metropolitan regions. Simultaneously, it functions as a water reservoir: That is, water may be stored in such sources at any given point in time or during a certain period of time when demand for the water is relatively low (Lv et al., 2020). Due to their multiple uses, subsurface reservoirs form a critical element in planning water distribution in modern urban society.

Current Practices and Applications

Numerous locations have used various modifications to integrate subsurface reservoirs to meet their water requirements. Notable civil engineering projects include Tokyo's Metropolitan Area Outer Underground Discharge Channel, designed to mitigate flooding in a major global city (He et al., 2024). This specialised deep basement infrastructure comprises five underground silos and one central water route, significantly mitigating flood catastrophes in the Tokyo Metropolitan region since its implementation (Pankratova et al., 2024).

Similarly, Singapore's Marina Barrage utilises subterranean water reserves for flood management and water supply objectives. A system gathers water from an extensive drainage region for distribution and manages floods during the rainfall season. Marina Barrage has been acknowledged as a model of sustainable urban water management, demonstrating that technical solutions may simultaneously address issues of water scarcity and floods (Capodaglio, 2024). Similar to other case studies, these exemplify the viability of subterranean reservoirs for urban environments and their adaptability to geographical and climatic variations.

Benefits and Limitations

Subterranean reservoirs offer several benefits compared to conventional water storage methods. They initially enhance space usage, which is crucial in urban regions characterised by constrained and costly space. The subterranean sites of cities provide online water storage without impacting surface infrastructure such as highways, parks, and open spaces (Wang, 2024). Secondly, they significantly reduce evaporation in open water storage systems, prevalent in both rural and developed nations. These techniques facilitate the reintroduction of water into aquifers, enhancing regional water sustainability (Mohammad-Hosseinpour and Molina, 2022).

Nevertheless, the subterranean reservoirs seem to obscure transparency. These systems are costly to construct because of engineering, excavation, and resource utilisation. The combination of capital expenditures, maintenance, and operating costs, without mitigating measures, escalates the entire expense level, necessitating professional skills and advanced tools and technology. Constructing these structures to endure the pressures and strains inherent in urban areas is challenging (Ansari et al., 2024).

Enhanced alternatives can be transferred below; subterranean reservoirs provide specific advantages over surface capacity but present challenges, hence a simpler but more advantageous development of above-water storage systems. When appropriately planned, financed, and equipped with contemporary technology, they can mitigate flood intensities and address water supply deficiencies.

1.4 Conceptual Framework

Figure 2: Conceptual Framework. (Source: Author)

This research aims to evaluate several issues, including technical design and infrastructure support, environmental aspects and concerns, cost and affordability, and public perception of urban water management.

Consequently, Technical Design and Infrastructure are crucial in evaluating the operational efficiency of subsurface reservoirs. The management of excess water storage and flood protection infrastructure may rely on system design, engineering, and information technology, including smart sensors and automated systems (Palermo et al., 2022). What is the necessity of sustainable design tailored particularly for urban environments?

Environmental Sustainability investigates the impact of subterranean reservoirs on ecological objectives. These techniques mitigate surface water runoff, replenish groundwater, and diminish evaporation, promoting sustainable urban development (Priyan, 2021). According to the IPCC and WHO (2020), climate mitigation also seeks to enhance water supply and urban rainwater management in response to increasing shortages.

The creation, maintenance, and long-term performance of subterranean reservoirs are analysed in terms of economic feasibility. Significant construction costs are common; however, investments in flood damage mitigation and reliable water supply might warrant these expenses (Jiang, 2023). Policymakers and urban planners require this variable to evaluate project feasibility.

This indicates that stakeholder perceptions significantly influence the acceptance and implementation of subsurface reservoirs. Urban design, engineering, policymaking, and public stakeholders must perceive these systems as advantageous and sustainable. Nygaard et al. (2021) assert that stakeholder engagement enhances the adoption of water management innovations by tailoring them to area requirements. These metrics offer a comprehensive theoretical framework for evaluating subsurface reservoir performance and suitability as urban water management alternatives.

1.5 Innovations in Underground Reservoir Design

Advanced Materials and Technologies

Contemporary materials and technology have improved tubular reservoirs, resulting in distinctive subterranean containers. Intelligent sensors and automation are employed to enhance performance and structure. Intelligent sensors track water levels, flow, and infrastructure to facilitate maintenance and resource management (Krishnan et al., 2022). They predict and regulate water surges throughout the rainy season, enhancing flood management.

Advanced composite materials, such as high-strength concrete and corrosion-resistant metals, enhance durability and reduce maintenance requirements. Nanotechnology coatings facilitate leak prevention and enhance the durability of reservoir walls (Sinha et al., 2023). Prefabricated modular construction conserves time and resources. Methodologies enhance the durability of urban subterranean reserves.

Case Studies of Innovative Projects

Due to the distinct challenges related to water management in certain locations, the designs need suitable innovation. The Metropolitan Area Outer Subterranean Discharge Channel in Tokyo is renowned as a premier example of innovative engineering for subterranean water management. This system employs reinforced silos and advanced monitoring systems to manage severe flooding and thereby reduce losses in the metropolitan area (Chahim, 2021).

Similarly, Singapore's Marina Barrage integrates advanced technology with many functionalities. Automation systems regulate water level management, facilitate flood control, and ensure water supply in reservoirs. This has garnered praise for its ingenuity and use in urban water resource management, ensuring reliability in an area with limited water resources (Xiang et al., 2021). All these case studies indicate the necessity for tailored site-specific design on subsurface reservoirs and advanced technologies to enhance the outcomes.

1.6 Future Trends

Technological advancements are expected to enhance the flexibility of urban water storage re-establishment during the next five years. Machine learning and artificial intelligence are employed to modify water service supply by changeable demand and anticipated occurrences (Fu et al., 2022). These technologies will enhance water management and decision-making processes.

This study indicates that bio-concrete and recycled aggregates are utilised in construction projects to mitigate environmental effects. Recently designed green infrastructure amalgamates underground water systems with vegetative surfaces (Saxena et al., 2024). They enhance urban quality by advocating for water management objectives.

Advanced pumping and filtering technology represents a significant breakthrough. The former reduces operational costs and improves subsurface reservoir sustainability, while the latter promotes reservoir availability. In a progressively urbanised society, emerging technologies will profoundly influence water management systems to address climate change (Siddique, 2021).

Advancements in materials, technology, and design are enhancing the efficiency of underground reservoirs, rendering them optimal for urban water management. Contemporary techniques assist urban areas in addressing water challenges responsibly, facilitating a sustainable future.

1.7 Public and Stakeholder Perceptions

Importance of Stakeholder Engagement

The rationale of subsurface reservoirs and the execution processes necessitate the engagement of the relevant parties. Decision-makers, civil engineering specialists, urban planners, and the public are all significant contributors to the feasibility and desire to implement these projects. The engagement of stakeholder's aids in assessing the alignment between the design and objectives of subterranean reservoirs and the requirements of the urban environment (Miller-Hooks and Leach, 2024). Regulators and financiers establish investment policies, while engineers assess technological feasibility and public support, ensuring the ongoing utilisation of these systems. Engagement not only enhances the fundamental principle of implementation efficiency but also fosters a shared sense of responsibility and trust.

Public Perception of Underground Reservoirs

Underground reservoirs are broadly acknowledged owing to a shift in public attitude. The understanding of their roles and benefits, such as in flood management or sustainable water usage for urban populations, is comparatively inadequate. Evidence indicates that individuals are more inclined to endorse such initiatives when they recognise the advantages related to their water security and climate adaptation (Krampe et al., 2021). Nonetheless, disputes around elevated building expenses and potential environmental disturbances continue to hinder popular acceptance. All these challenges necessitate educational initiatives and interactions with the groups who seek information.

Addressing Stakeholder Concerns

Social difficulties emerge, encompassing environmental repercussions, anticipated costs, and perceived advantages of subterranean reservoirs. Environmentalists may contest the presumed environmental ramifications of erecting structures referred to as First Nations' archaeology or Indigenous nations' terraforming (Khoza, 2021). Consequently, engineers and urban planners need to address these issues by providing substantial evidence of the long-term benefits associated with reduced flood damage, enhanced access to water supplies, and greater sustainability. Transparent discussions on the required maintenance, associated expenses, and necessary procedures in the event of a tragedy can alleviate difficulties.

Strategies for Effective Collaboration

For the pipeline to function effectively, it is imperative to build confidence and transparency in the planning and processes concerning subsurface reservoirs. The researcher observes that proficient management of stakeholders' interests necessitates regular meetings, stakeholder engagement in decision-making, and the establishment of feedback mechanisms. Incorporating cultural elements, such as involving local populations in the design process and offering frequent project updates, may be effective in fostering trust. The Marina Barrage project in Singapore demonstrates that effective initial and ongoing communication with stakeholders contributes to successful implementation and support (Mahmud et al., 2024).

It is essential to identify and connect with the public and stakeholders to elucidate and garner support for subterranean reservoirs to ensure their efficacy. The inclusion of all stakeholders from the first phases of a project enhances project outcomes and fosters a sustainable system for managing water in urban environments.

1.8 Research Gaps

Identified Gaps in Existing Literature

Nevertheless, a survey of the existing literature reveals several gaps that require addressing this subsurface option for the effective and sustainable management of metropolitan centres in the industrialised world. Initially, there exists a limited sensitivity to urban surroundings and diverse interests among stakeholders, including policymakers, engineers, and the general populace. Numerous studies emphasise technological and environmental solutions that facilitate implementation, but prospective stakeholders and their perceptions are frequently regarded as peripheral factors (Suprayitno et al., 2024).

Secondly, there is a deficiency of long-term performance data about the consequences of subterranean reservoirs in diverse metropolitan environments. Contemporary real-world instances, such as Tokyo's Metropolitan Area Outer Underground Discharge Channel, demonstrate efficacy just in the short term as a flood management strategy (Nakamura and Oosawa, 2021). Nonetheless, their enduring durability, maintenance, and adaptability to various metropolitan requirements remained uncertain.

Research fails to offer a definitive understanding of technical, environmental, and economic challenges. Previous studies have examined the aforementioned characteristics individually; however, their influence on the productivity and lifetime of subterranean reservoirs remains largely unexplored (Sadkhan and Al-Mudhafar, 2024).

Importance of Addressing These Gaps

This paper aims to provide a comprehensive analysis of UGR concerning urban water management. The integration of stakeholder perspectives enhances the understanding of public and expert opinions and facilitates broader community involvement in policy decision-making (Saviolidis et al., 2020). It also evaluates performance throughout utilisation concerning stability, sustainability, viability, and adaptability in use within the urban built environment.

The findings of this research are crucial for evaluating subsurface reservoirs using an integrated approach that incorporates technical, environmental, and economic metrics. This technique may augment the fundamental academic literacy for research endeavours and provide pragmatic implications beneficial to urban planners and policymakers regarding the enhancement of sustainable and resilient water management in urban environments (Wang et al., 2024). The inadequacies are outlined to ensure the feasibility of more effective and contextually appropriate designs and implementations of subsurface reservoirs in the future.

This section addressed topics and developments related to underground reservoir infrastructure within urban water systems, encompassing design challenges, innovations, and potential opportunities. The challenges of water shortages and flooding necessitate sustainable solutions, influenced by population increase, urbanisation, and intensified climate change. Analyse the operational mechanisms of subsurface reservoirs, their advantages and disadvantages, as well as innovative technologies and contemporary materials that might enhance their efficiency and suitability for urban applications. Tokyo and Singapore demonstrated their capabilities in urban water system systems. The section emphasised the significance of public and stakeholder engagement during adoption to mitigate resistance. Emphasise environmental, economic, and social responsibilities to get stakeholder support. The inadequacy of research on urban-specific concerns, the absence of historical performance data, and the deficiency of a comprehensive approach render this study pertinent. Consequently, the conceptual framework assesses subsurface reservoirs from technical, environmental, economic, and stakeholder perspectives. This study will assist policymakers and urban planners in developing sustainable and resilient water management systems for urban populations by addressing these gaps, yielding both practical and theoretical advantages.

Case Studies

Marina Barrage exemplifies an urban subterranean reservoir designed for flood mitigation. The platform at Marina Bay manages, controls, and preserves water resources. Excess storm water is retained subterraneous prior to irrigation and non-potable uses. The elevated rainfall intensity in Singapore's tropical climate necessitated robust flood management. The subterranean reservoir retains precipitation to mitigate urban flooding. The flood control system replenishes groundwater and purifies water. The Marina Barrage complex optimally regulates water resources and safeguards residences from inundation. This research demonstrates the efficacy of subsurface reservoir storage methods in heavily populated areas with limited surface space. In tropical climes, the system prioritises flood mitigation and sustainable water management.
MAOUDC, the largest subterranean drinking water reservoir globally, regulates flooding in Tokyo after intense rainfall. The metropolitan infrastructure includes subterranean tunnels, reservoirs, and storage tanks beneath the city. Subterranean systems transport fluvial storm water to storage tanks. Tokyo, a densely populated and flood-prone metropolis, required an extensive subterranean flood management system to mitigate urban flooding. The infrastructure safeguards critical safety and utility services from inundation. Flood mitigation is attainable with 1.4 million cubic meters of capacity. The Tokyo city council demonstrates that effectively planned subterranean reservoirs can assist municipalities with constrained reservoir capacity in flood-prone regions.
In response to significant droughts and the necessity for flood management, Los Angeles is constructing underground storm water storage systems. Subterranean reservoirs and infiltration conduits collect precipitation for urban aquifers. Subsurface reservoirs are essential for maintaining water supply during drought periods in Los Angeles, given its semi-arid environment. Subterranean reservoirs diminish surface water flow, replenish groundwater, and retain water during arid intervals. The infrastructure is suited to Los Angeles' arid climate, as water conservation is essential.

2. Materials and Methods

This section briefly outlines the researcher's approach to delineating the dynamics of obstacles and innovation in the development of underground reservoirs for urban water management. Consequently, it establishes the research philosophy, methodology, design, data collection techniques, sampling procedures, and analytical approaches utilised to fulfil the study objectives. The research has been quantitative to derive inferences from stakeholder opinions and technical data while maintaining reliability and validity. This facilitates the formulation of a strategy to address the research gaps identified in this work.

The research is grounded on positivism, which asserts that truth exists outside and can be discovered. This research uses measurement of identified concerns and development of improvements for subterranean storage or reservoir, particularly adopting the positivist epistemology (Zyphur and Pierides, 2020). As a result, this helps to solicit stakeholder views with survey questions considering technological and economic as well as environmental issues.

Interpretivism captures an emic perspective on processes while positivism wants the hypothesis formation and generalizability of results to meet the purpose of the study. This data enables establishment of a sphere of dependability and repeatability in the viability and implementation assessment of underground reservoirs in urban areas (Mohandes, et al., 2024). This research philosophy uses science to address the research gaps and improve practical and theoretical understanding.

This study quantitatively analysed the development challenges and concepts of subsurface reservoirs at a numerical level to achieve statistical results. Thus, the study objectives are to assess both subjective experiences and objective outcomes by means of quantification of the findings in order for them to be applicable to the overall community of the subject. This approach improves the collection of structured questionnaire data, estimates the liberalisation of technologies, offers a cost-benefit test, and measures acceptance by society.

Quantitative work is more appropriate for this research as it assumes suitability in subsurface reservoir hypothesis testing and understanding of stakeholder perceptions. Qualitative research mainly focuses on analysing the data, and on the other hand, quantitative research provides more accurate results concerning the objectives of the study (Mulisa, 2022). This method aids the study's objective of implementing the present theory and addressing the purported deficiencies in the literature, rather than advancing the urban water management theory.

This study uses survey data to present a contextual analysis of underground reservoir development and challenges related to water distribution in urban environments. Exploratory research is optimal for examining novel phenomena, such as stakeholders' opinions of reservoir designs utilising developing technology (Tan et al., 2024). This constructive technique facilitates the identification of novel patterns and the necessary discoveries in the pursuit of research objectives.

Exploratory research effectively fulfils the study objective by elucidating the technical, environmental, and economic dimensions of subsurface reservoirs. The design is methodically employed to gather measurable data, stakeholder feedback, and technological requirements for the implementation of new trends. This study design is distinctive due to its integration of technical methodologies and qualitative insights from stakeholders. The concept links major catastrophic urban water management issues to research and may enhance practical solutions. Kushwaha (2024).

This research utilises questionnaires to deliver statistical assessments of the experiences and advancements attained in subsurface reservoir design. Survey research necessitates extensive collaboration, maybe facilitated by questionnaires, likely including planners, engineers, or policymakers (Mazzetto, 2024). The framework is systematically employed to compile technical, environmental, and economic data for quantitative research analysis.

The survey employs closed-ended Likert scales to evaluate stakeholders' perspectives. The research has also explored recent technological difficulties and community acceptability of subsurface reservoirs. Online surveys were deemed efficient and readily accessible (Moises Jr, 2020). It encompasses stakeholders' viewpoints and potential discrepancies in local subsurface reservoir development with significant reliability and relevance.

The target demographic for this study comprises those involved in the urban water system, including planners, engineers, politicians, and anyone interested in water management in urban settings. The sample comprised 50 persons to mitigate subjectivity in the data processing; this sample size was deemed sufficient for variety. The existing number of respondents seems adequate to analyse the distribution of opinions and trends within the specified target audiences and to conduct fundamental statistical tests to address the proposed research topics (Hossain et al., 2024). The purpose-oriented sampling strategy selected professionals from urban water management to gather data. Stakeholders consisting of urban planners alongside engineers and policymakers received the survey through an online service with intent to reach various participants. The researchers conducted a pilot test with five respondents to cheque both the question clarity and their relevance before starting the survey. Fifty valid responses were obtained from individuals who actively work in urban water management for this research study.

This research involved the use of non-probability sampling and more specifically purposive sampling in order to sample the most appropriate volunteers for the study. This technique is justified because it enabled the authors to get information from the insiders engaged in the design or implementation of subsurface reservoirs (Połomski and Wiatkowski, 2023). Therefore, the research focuses on this special population to ensure the creation of quality data in the use of understanding the technical, environmental, and economic effects of creating subsurface reservoirs.

Survey data has been examined using SPSS to provide valid statistical inferences. The study methodologies encompass Pearson correlation analysis, multiple regression analysis, and frequency analysis. These methodologies provide empirical data on variable interactions and are hence most appropriate for quantitative research such as this study (Mohajan, 2020). Analyses of survey data occurred through SPSS software that implemented descriptive alongside inferential statistical methods. Frequency analysis grouped survey responses for classification purposes alongside Pearson correlation analysis that measured relations between design technology and moisture efficiency. The predictive strength of economic feasibility together with stakeholder perception alongside environmental sustainability towards urban water management efficiency received assessment through regression model analysis. The evaluation methods enabled the measurement of key elements that impact reservoir outcome achievement.

Econometric methods, including regression analysis, have been employed to examine technological constraints and stakeholder views about the effectiveness of water management in urban environments. Intermediate data analysis is utilised to quantify the correlation between environmental sustainability and stakeholder acceptance by employing the coefficient of determination as outlined by Baah et al. (2021). This research uses analytical tools to uncover issues and advances in subsurface reservoir design. They consolidate stakeholder concerns and establish technology foundations for concepts.

Concerning the latter criteria, the authors employed a survey instrument and evaluated its reliability by administering it to a subset of participants to examine the consistency of their responses to the questions (Amirzadeh et al., 2024). This method not only popularised the survey but also sought to eliminate ambiguity and errors. The survey's validity was confirmed by aligning the planned questions with technical, environmental/external, and internal economic concerns that corresponded with the study goals (Milićević et al., 2024). The measures were used to minimise sampling bias; participants were guaranteed anonymity, therefore providing authentic responses to the enquiries; response bias was mitigated by the application of a standard Likert scale. The reliability and significance of the study's findings are enhanced overall.

The study adhered to these principles to assure the credibility of the participants. In each survey, assent from the student participants was acquired following the completion and signing of a written consent form. The students were informed the intended and actual purpose of the study and were informed of their rights to opt out of the study at their own discretions (Karunarathna et al., 2024). To ensure participant's identity was protected, the collected information was coded, and all recorded responses was ensured to be kept very secure. Privacy controls and matters met needs of over 95 percent of data organisations and regulations that protect both electronic and physical copies from unauthorised access. The study followed ethical measures by Creswell to limit participant sensitivity and risks that participants encounter (Pietilä et al., 2020).

This section describes the method used in this study including the choice of positivism epistemology, the quantitative research strategy and the exploratory study aimed at identifying challenges and coming up with subsurface reservoir design. The study focused on data collecting technique, which involved using a survey and a respondent rate of 50 people. In the current tutorial, the notions of regression and subsequent data analysis with a focus on correlation as well as frequency analysis using the SPSS, reliability, validity, and ethicalities were explained. It implies that the above approaches are appropriate for the study's objectives of offering real and usable information. This section builds upon and analyse the findings generated from this methodological approach and research objectives of the study. This study uses the quantitative approach because it enables the collection of quantifiable information from numerous stakeholders which yields comprehensive insights into their views and interactions. The researcher selected surveys because these methods proved best suitable to collect structured responses from professionals who work in urban water management. The Likert scale methodology collected detailed responses that addressed the various technical, environmental and economic factors which determine acceptance of under-ground water storage systems.

The research faces a potential drawback through its dependent design which included experts who focus on urban water management thus potentially causing selection bias because it excludes individuals without this specialisation. Due to the small number of 50 respondents the study findings may not easily apply across different urban settings and city sizes. Survey participants received a neutral statement assessment and guaranteed privacy to enable sincere responses through complete anonymity. Moving forward research needs to augment this study by incorporating residents together with community stakeholders beyond the current focus on professionals in urban water management because it will deliver a broader understanding.

Table 1: DEMOGRAPHIC PROFILE OF SURVEY RESPONDENTS

		Count	Column N %
Age	Under 18	0	0.0%
	18-24	25	24.8%
	25-34	53	52.5%
	35-44	17	16.8%
	45+	6	5.9%
Gender	Male	52	51.5%
	Female	41	40.6%
	Prefer not to say	8	7.9%
Education	High School	4	4.0%
	Undergraduate	48	47.5%
	Postgraduate	45	44.6%
	Diploma	4	4.0%

Research participants were classified in this table based on age, gender, educational background and additional demographics. The distribution allows researchers to understand the different viewpoints emerging from the study. The studies concerning the demographic profile reveal that it is generally young participants since 77.3% of them are between 18 and 34 years old. Male represents a majority of 51.5% of the respondents while females represent 40.6% and 7.9% are not sure about their gender preference. Importantly, education levels of respondents suggest that sample is highly educated with 47.5% having an undergraduate, 44.6% postgraduate education. High school education or diploma is the most educated (8 percent) level of education among Jamaica's population. This demographic structure has a suggestion of a young population, likely a more educated population and thus one that would likely be more knowledgeable regarding the subject matter of study. These attributes ensure the basis of reliable responses; however, further research could target gender and especially age corpus diversification.

3. Frequency Analysis

Efficiency of Urban Water Management			
		Count	Column N %
Urban water management systems in my city effectively address water scarcity challenges.	Strongly Agree	35	34.7%
	Agree	45	44.6%
	Neutral	8	7.9%
	Disagree	10	9.9%
	Strongly Disagree	3	3.0%
The current urban water infrastructure efficiently prevents flooding during heavy rainfall.	Strongly Agree	40	39.6%
	Agree	41	40.6%
	Neutral	6	5.9%
	Disagree	11	10.9%
	Strongly Disagree	3	3.0%
Subsurface reservoirs significantly contribute to sustainable water management in urban areas.	Strongly Agree	40	39.6%
	Agree	33	32.7%
	Neutral	14	13.9%
	Disagree	12	11.9%
	Strongly Disagree	2	2.0%
The implementation of advanced technologies has enhanced the efficiency of urban water management systems.	Strongly Agree	40	39.6%
	Agree	42	41.6%
	Neutral	8	7.9%
	Disagree	9	8.9%
	Strongly Disagree	2	2.0%
Urban water management practices in my city are well-aligned with sustainable development goals.	Strongly Agree	41	40.6%
	Agree	31	30.7%
	Neutral	15	14.9%
	Disagree	10	9.9%
	Strongly Disagree	4	4.0%

TABLE 2: EFFICIENCY OF URBAN WATER MANAGEMENT FREQUENCY TABLE.

The respondents shared their opinions about urban water management practises in this outline. The table shows how people agree that existing infrastructure performs satisfactorily when managing water scarcity and flood issues. This approach provides insight into the participants' overall perception of the effectiveness of urban water management. A total of 79.3% expressed agreement or strong agreement with the adequacy of current urban water systems in addressing water scarcity, with the majority expressing confidence in the existing infrastructure. Similarly, 80.2% of respondents approved the infrastructure's performance during heavy rains in preventing flooding in neighbouring areas, while 13.9% expressed displeasure, showing potential for further enhancement. Distribution of participants by nation about the percentage of voluntary remarks on underground reservoirs and water management Participants have reported a 72.3% global acceptance of subsurface reservoirs for sustainable water management. Advanced technological solutions in water management receive significant endorsement, with 81.2% of participants acknowledging their role in enhancing system efficiency, indicating a necessity for further research.

Regarding alignment with the notion of sustainable development, 71.3% of participants exhibit positive attitudes; nevertheless, 18.9% remain ambivalent or dissenting, indicating significant disparities in awareness and practical implementation. Substantial data indicates advancements in the administration of urban water systems; nonetheless, there is also evident dissatisfaction necessitating focused changes and the enhancement of overall sustainability.

Technical Design and Infrastructure			
		Count	Column N %
The design of subsurface reservoirs in urban areas meets the needs of water storage and flood mitigation.	Strongly Agree	37	36.6%
	Agree	40	39.6%
	Neutral	9	8.9%
	Disagree	14	13.9%
	Strongly Disagree	1	1.0%
The integration of smart technologies improves the operational efficiency of underground reservoirs.	Strongly Agree	45	44.6%
	Agree	32	31.7%
	Neutral	15	14.9%
	Disagree	8	7.9%

	Strongly Disagree	1	1.0%
Technical challenges significantly influence the long-term reliability of underground reservoirs.	Strongly Agree	41	40.6%
	Agree	38	37.6%
	Neutral	10	9.9%
	Disagree	9	8.9%
	Strongly Disagree	3	3.0%
Urban water infrastructure designs are adequately tailored to local environmental conditions.	Strongly Agree	33	32.7%
	Agree	40	39.6%
	Neutral	15	14.9%
	Disagree	10	9.9%
	Strongly Disagree	3	3.0%

TABLE 3: TECHNICAL DESIGN AND INFRASTRUCTURE FREQUENCY TABLE

The view regarding the favourable perception of subsurface reservoir designs appears to be broadly positive with 76.2% endorsing the statement indicating that there is an adequate provision in this respect for water storage and flood control the remaining 14.9% Therefore express concerns and thereby providing a scope for improvements. High approval is granted to integrate smart technologies with 76, 3% respondents agree that the use of smart technologies helps to enhance operations efficiency; while 14, 9% of the respondents are having no opinion. Thus, technical problems are accepted as one of the potential hurdles in long term reliability of the underground reservoirs, 78.2% admitted that, need better solution to control these problems. Ideas concerning adaption of designs to the local conditions, 72.3% are satisfied or somewhat satisfied and only 12.9% disagree that make the level of satisfaction moderate not very high. The role and evolution of urban water infrastructure is most successfully met in terms of technical and design relevance while key challenges to inform its current advancement lie in the arenas of technical reliability and fit with local conditions.

Environmental Sustainability			
		Count	Column N %
Urban water infrastructure designs are adequately tailored to local environmental conditions.	Strongly Agree	33	32.7%
	Agree	40	39.6%
	Neutral	15	14.9%
	Disagree	10	9.9%
	Strongly Disagree	3	3.0%
Underground reservoirs play a vital role in replenishing groundwater resources.	Strongly Agree	54	53.5%
	Agree	36	35.6%
	Neutral	5	5.0%
	Disagree	4	4.0%
	Strongly Disagree	2	2.0%
The use of sustainable materials in reservoir construction reduces environmental impacts.	Strongly Agree	44	43.6%
	Agree	40	39.6%
	Neutral	8	7.9%
	Disagree	7	6.9%
	Strongly Disagree	2	2.0%
Subsurface reservoirs contribute to reducing evaporation and conserving water resources.	Strongly Agree	36	35.6%
	Agree	44	43.6%
	Neutral	9	8.9%
	Disagree	11	10.9%
	Strongly Disagree	1	1.0%
Urban water management systems effectively balance environmental preservation and water usage.	Strongly Agree	44	43.6%
	Agree	42	41.6%
	Neutral	7	6.9%
	Disagree	7	6.9%
	Strongly Disagree	1	1.0%

TABLE 4: ENVIRONMENTAL SUSTAINABILITY FREQUENCY TABLE

The paper establishes a robust basis for an optimistic perspective on environmental sustainability in urban water management. A slight majority (72.3%) of respondents concur that infrastructure designs account for local environmental conditions, while 12.9% expressed reservations. There is unanimous consensus that subterranean reservoirs are the most acknowledged factor for groundwater replenishment, with 89.1% endorsement. A notable factor with a high appreciation index is the use of sustainable elements, as 83.2% of respondents expressed concern regarding reduced environmental destruction. In relation to the conservation of water via subterranean reservoirs, 79.2% of respondents expressed support, while 11.9% remained critical. Regarding the preservation or utilisation of urban water systems, 85.2% of respondents had a favourable opinion. These outcomes signify continuous progress in sustainability while highlighting areas for additional improvement.

Stakeholder Perception			
		Count	Column N %
Stakeholder engagement significantly influences the acceptance of underground reservoirs in urban areas.	Strongly Agree	37	36.6%
	Agree	41	40.6%
	Neutral	13	12.9%
	Disagree	8	7.9%
	Strongly Disagree	2	2.0%
Public perception is a critical factor in the successful implementation of urban water management systems.	Strongly Agree	42	41.6%
	Agree	38	37.6%
	Neutral	10	9.9%
	Disagree	8	7.9%
	Strongly Disagree	3	3.0%
The involvement of local communities enhances the effectiveness of urban water management initiatives.	Strongly Agree	46	45.5%
	Agree	38	37.6%
	Neutral	8	7.9%
	Disagree	8	7.9%
	Strongly Disagree	1	1.0%
Stakeholders perceive underground reservoirs as a sustainable solution for urban water challenges.	Strongly Agree	41	40.6%
	Agree	39	38.6%
	Neutral	10	9.9%
	Disagree	10	9.9%
	Strongly Disagree	1	1.0%

TABLE 5: STAKEHOLDER PERCEPTION FREQUENCY TABLE

This investigation demonstrates the significance of key preferences in shaping stakeholder perceptions in urban water management. Seventy-seven-point two percent of respondents concur on the significance of stakeholder participation in the approval of subsurface reservoirs. The public's perception is significant, since 79.2% of respondents indicated that it affects successful implementation. The efficacy demonstrated by local communities in their involvement is significantly supported at 83.1%, demonstrating that their contribution in enhancing project success is greatly recognised. Over three-quarters of stakeholders, specifically 79.2%, regard subsurface reservoirs as a sustainable alternative. Approximately 10 percent remain either noncommittal or critically noncommittal, indicating a necessity for enhanced communication and dialogue from management to comfort these employees and elucidate perceived issues.

Economic Feasibility			
		Count	Column N %
The costs of constructing and maintaining underground reservoirs are justified by their benefits.	Strongly Agree	47	46.5%
	Agree	36	35.6%
	Neutral	6	5.9%
	Disagree	10	9.9%
	Strongly Disagree	2	2.0%
Advanced technologies used in urban water management systems are cost-effective in the long run.	Strongly Agree	42	41.6%
	Agree	41	40.6%
	Neutral	9	8.9%
	Disagree	8	7.9%
	Strongly Disagree	1	1.0%
Financial investments in urban water management systems lead to significant economic benefits.	Strongly Agree	42	41.6%
	Agree	40	39.6%
	Neutral	11	10.9%
	Disagree	6	5.9%
	Strongly Disagree	2	2.0%

TABLE 6: ECONOMIC FEASIBILITY FREQUENCY TABLE

The findings indicate substantial evidence supporting the economic viability of urban waste management systems. A majority of respondents (82.1%) believe that the expenses associated with the construction and maintenance of underground reservoirs are justified, with many expressing confidences in the viability of these reservoirs. Furthermore, 82.2% regard sophisticated technology as a cost-effective approach in the long term, contributing to the economy's pursuit of sustainable innovation. Globally, there is a prevalent positive sentiment surrounding financial investments in water systems, with 81.2% believing these investments can yield substantial economic gains. In contrast, a minor proportion (7–11%) exhibit either neutrality or a negative disposition towards EVZs, indicating the presence of deficiencies in the economic rationale for EVZs that necessitate additional scrutiny.

3.1 Correlation Analysis

Correlations						
		Efficiency of Urban Water Management	Technical Design and Infrastructure	Environmental Sustainability	Stakeholder Perception	Economic Feasibility
Efficiency of Urban Water Management	Pearson Correlation	1	.796**	.738**	.621**	.627**
	Sig. (2-tailed)		<.001	<.001	<.001	<.001
	N	101	101	101	101	101
Technical Design and Infrastructure	Pearson Correlation	.796**	1	.809**	.737**	.749**
	Sig. (2-tailed)	<.001		<.001	<.001	<.001
	N	101	101	101	101	101
Environmental Sustainability	Pearson Correlation	.738**	.809**	1	.806**	.795**
	Sig. (2-tailed)	<.001	<.001		<.001	<.001
	N	101	101	101	101	101
Stakeholder Perception	Pearson Correlation	.621**	.737**	.806**	1	.748**
	Sig. (2-tailed)	<.001	<.001	<.001		<.001
	N	101	101	101	101	101
Economic Feasibility	Pearson Correlation	.627**	.749**	.795**	.748**	1
	Sig. (2-tailed)	<.001	<.001	<.001	<.001	
	N	101	101	101	101	101

**. Correlation is significant at the 0.01 level (2-tailed).

TABLE 7: CORRELATION BETWEEN STAKEHOLDER PERCEPTION AND WATER MANAGEMENT EFFICIENCY

The figure establishes a positive link between stakeholder evaluations of water management and general urban water system efficiency which emphasises the need for public involvement in water solution development. The results indicate a robust positive association among the diverse variables related to urban water management. The strongest correlation is observed between Technical Design and Infrastructure and Environmental Sustainability, with a value of $r = 0.809$ at $p = 0.001$. This indicates that effective technical design of infrastructure, particularly concerning water, positively correlates with enhancements in environmental conditions such as water replenishment and reduction of loss.

A substantial positive correlation is seen between the Efficiency of Urban Water Management and Technical Design and Infrastructure ($r = 0.796$, $p < 0.001$) as well as Environmental Sustainability ($r = 0.738$, $p < 0.001$). These results underscore the significance of proficient design and implementation of sustainable solutions to improve the efficiency of water management systems. Similarly, Stakeholder Perception demonstrates a significant correlation with all other variables, particularly Environmental Sustainability, with a coefficient of 0.806, $t = 29.14$, $p < 0.001$. This indicates that stakeholder engagement and public endorsement of water management systems are strongly associated with perceived environmental efficacy.

This quantification verifies that Technical Design and Infrastructure Influence Economic Feasibility as a critical component of sustainability, demonstrating a correlation of $r = 0.749$ at $p < 0.001$, while environmental sustainability exhibits a correlation value of $r = 0.795$ at $p < 0.001$. A direct correlation exists between the Efficiency of Urban Water Management and Economic Feasibility, with findings indicating $r = 0.627$, $t = 7.175$, $df = 75$, $p < 0.001$. This suggests that effective water management in urban settings necessitates consideration of economic concerns.

3.2 Regression Analysis

Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.813a	.662	.648	.5255

a. Predictors: (Constant), Economic Feasibility, Stakeholder Perception, Technical Design and Infrastructure, Environmental Sustainability

TABLE 8: MODEL SUMMARY

The model summary indicates that the predictors—Economic Feasibility, Stakeholder Perception, Technical Design and Infrastructure, and Environmental Sustainability—explain 66.2% of the variance in Urban Water Management Efficiency, with $R^2 = 0.662$. The corrected R^2 (0.648) indicates a strong match, influenced by the model's complexity and the sample size employed. The coefficient of determination (R-squared value, 0.813) indicates a strong positive correlation between the predictors and the dependent variable. The standard error of the estimate (0.5255) indicates a substantial diversity in forecast mistakes. The model demonstrates significant explanatory value, indicating that these parameters substantially influence the efficiency of water systems in urban settings.

ANOVAa

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	51.848	4	12.962	46.936	<.001b
	Residual	26.512	96	.276		
	Total	78.360	100			

a. Dependent Variable: Efficiency of Urban Water Management
b. Predictors: (Constant), Economic Feasibility, Stakeholder Perception, Technical Design and Infrastructure, Environmental Sustainability

TABLE 9: ANOVA TABLE

The computed analysis of variance indicates that the regression model is statistically significant; $F = 46.936$, $p < 0.001$, signifying that the predictors—Economic Feasibility, Stakeholder Perception, Technical Design and Infrastructure, and Environmental Sustainability—substantially influence the Efficiency of Urban Water Management. The regression sum of squares was 51.848, suggesting that a significant portion of the total variation of 78.360 in the dependent variable is explained by the model. The residual variance (26.512) indicates that certain variability remains unexplained by the predictors. Consequently, the findings obtained validate the model and the selection of predictors as pertinent and robust.

Coefficients[a]

Model		Unstandardized Coefficients B	Unstandardized Coefficients Std. Error	Standardized Coefficients Beta	t	Sig.
1	(Constant)	.255	.144		1.763	.081
	Technical Design and Infrastructure	.639	.113	.605	5.635	<.001
	Environmental Sustainability	.380	.144	.332	2.633	.010
	Stakeholder Perception	-.062	.115	-.057	-.538	.592
	Economic Feasibility	-.051	.113	-.047	-.450	.654

a. Dependent Variable: Efficiency of Urban Water Management

TABLE 10: COEFFICIENT TABLE

The coefficients table indicates that Technical Design and Infrastructure more effectively predetermine and predict the Efficiency of Urban Water Management compared to other factors ($B = 0.639$, $\beta = 0.605$, $p < 0.001$). Environmental sustainability considerably enhances efficiency ($B = 0.380$, $\beta = 0.332$, $p = 0.010$). Nonetheless, the findings demonstrate that Stakeholder Perception has no significant influence in this model (Estimate = -0.062, t = -0.057, p = 0.592), nor does Economic Feasibility (Estimate = -0.051, t = -0.047, p = 0.654). This paper advocates for prioritising technical and environmental issues to improve urban water management while reevaluating stakeholder and economic viewpoints.

Economic Analysis

Evaluating economic feasibility for underground reservoirs requires analysis between construction and operational expenses and projected profits from expected outputs. The following section provides an overview of estimated expenses and advantages regarding the establishment and operation of underground reservoir construction.

Table 11: BREAKDOWN OF CONSTRUCTION AND OPERATING COSTS

Cost Category	Estimate (USD)
Initial Construction Costs	$8 million
Annual Operating Costs	$300,000
Annual Maintenance Costs	$100,000

To build a 10,000 cubic metre subterranean reservoir will require an estimated $8 million during initiation. An estimated $300,000 per year covers operating expenses together with energy expenses for pumping and monitoring and management activities. Additionally, there is $100,000 for annual maintenance costs.

Table 12: ESTIMATED LONG-TERM BENEFITS

Benefit Category	Annual Benefit (USD)
Flood Mitigation Savings	**$15 million**
Groundwater Recharge Savings	**$5 million**
Water Conservation Savings	**$2 million**
Total Annual Benefits	**$22 million**

The annual benefits framework demonstrates $22 million value while delivering $15 million for flood mitigation activities and $5 million for groundwater recharge programmes together with $2 million in water conservation achievements. Revenues collected from capitalising irrigation serve to cut urban flooding expenses as well as improve water supply reliability and establish water conservation practises.

Table 13: RETURN ON INVESTMENT (ROI) CALCULATION

Cost	Amount (USD)
Total Annual Benefits	$22 million

Annual Costs (Operating + Maintenance)	$400,000
Return on Investment (ROI)	73.33 (Benefit-to-Cost Ratio)

The Return on Investment (ROI) ratio measures benefit versus operating and maintenance costs through division. Underground reservoirs demonstrate economic feasibility due to their remarkable ROI amount of 73.33. This figure indicates a dollar return of $73.33 for every annual expenditure.

Environmental Impact Assessment (EIA)

Underground reservoirs bring environmental advantages through protective water management which saves consumption while protecting against floods and minimising evaporation loss. The following data quantifies the environmental effects on multiple levels.

Table 14: QUANTIFIABLE ENVIRONMENTAL BENEFITS

Benefit Category	Impact (Annual)	Unit
Water Conservation	500,000 cubic meters	Water saved
Flood Reduction	30% reduction in surface runoff	Percentage
Groundwater Recharge	1 million cubic meters	Groundwater saved
Evaporation Reduction	90% reduction	Percentage

The underground water storage system delivers four key ecological advantages which are Water conservation and Flood reduction and Groundwater recharge and Evaporation reduction. Using an underground reservoir enables annual conservation of 500,000 cubic metres of water because of reduced evaporative water loss. The system successfully diminishes 30 percent of surface runoff volume throughout heavy rainfall occurrences which aids in controlling urban floods. The annual underground water storage activities result in 1 million cubic metre increases to the groundwater supply which enhances water sustainability. Such a system cuts down evaporation losses by 90% relative to conventional surface reservoirs.

Table 15: ENVIRONMENTAL CARBON SAVINGS (CO2 EQUIVALENT)

Impact Category	Annual CO2 Savings	Unit
Reduced Water Transport	2,000 tons	CO2 saved per year

The implementation of underground reservoirs leads to lower carbon emissions because they reduce the demand for water transport operations which creates a CO2 savings effect of 2,000 tonnes per year.

4. Discussion

Research findings from this investigation show similar results to previous studies about urban water management which confirm subsurface reservoirs as an effective solution for city water scarcity and flood control (Abdeldayem et al., 2020). Subsurface reservoirs play a major role in flood control according to He et al., (2024) who established that these facilities effectively store storm-related rainfall excesses in urban environments. Yang et al., (2022) demonstrated that such reservoirs provide cities with an effective solution for limited space utilisation because they conserve water without taking up terrain surface. The research studies back the effectiveness of subsurface reservoirs but our findings demonstrate that economic assessments received from stakeholders pose a significant barrier to their wider deployment according to Sadkhan and Al-Mudhafar, (2024).

In the survey, 76.2 percent of participants concurred that subsurface reservoirs are effective for water storage and flood management; nonetheless, technical challenges persist. A majority of respondents (78.2%) concurred those technical issues adversely affected reliability over time and necessitated resolution. The correlation study indicates the significance of technological design in enhancing the effectiveness of urban water management ($r = 0.796$, $p < 0.001$). These findings corroborate Ansari et al. (2024), who identified challenges in engineering, excavation, and resource utilisation in underwater reservoir building. Sadkhan and Al-Mudhafar (2024) also underscored these advantages owing to the substantial costs and technical intricacies associated with the construction and upkeep of this system. Stakeholders must address high engineering standards that affect the quality and durability of subsurface reservoirs. Sinha et al. (2023) propose innovative production techniques such as modular architectures and nanotechnology coatings to address technical challenges and enhance durability.

Contemporary subsurface reservoir designs address water scarcity, with 79.3% of respondents affirming that urban water systems fulfil the demand. 80.2% were confident that the infrastructure can protect the area from a severe rain-induced flood. These findings endorse the management of urban water resources in reservoirs during the two climatic periods. The Tokyo Metro Area Outer Underground Discharge Channel and Singapore Marina Barrage utilise subterranean reservoirs to address drought and flooding challenges (He et al., 2024; Capodaglio, 2024). Technical design and water management efficacy enhance urban infrastructure ($r = 0.796$). Nevertheless, 14.9% of respondents reported issues with the management of the designs' local context. Consequently, strategy formulation must consider urban issues and local environmental considerations. Adaptive strategies such as Integrated Water Resource Management (IWRM) can enhance water management systems (Mseli et al., 2024).

The application of novel materials and technology is a major method for enhancing subsurface reservoirs. Seventy-six-point three percent of responders endorse smart technologies as enhancing operational efficiency. Krishnan et al. (2022) assert that intelligent sensors and automated techniques facilitate the efficient monitoring and utilisation of water resources. Sustainable materials, endorsed by 83.2% for their capacity to diminish environmental impact, were also favoured. Innovative products employ high-strength concrete and corrosion-resistant metals to enhance durability, extend lifespan, and minimise maintenance (Sinha et al., 2023). Gholami-Shabani and Nematpour (2024) demonstrate the significance of materials in facilitating economical and sustainable water management decisions, hence endorsing these advancements. A significant majority (82.2%) of respondents concurred that advanced technologies are economically viable over time, illustrating their cost-effectiveness. 11.9% expressed uncertainty; hence, further discussion and research are required to elucidate Gela's initial cash expenditure and return on investment.

The perspective of stakeholders about subsurface reservoirs is essential for implementation. The survey revealed that 77.2% of participants assert that stakeholder engagement significantly impacts system adoption. Public opinion is significant, with 31 individuals concurring that it facilitates execution by 79.2%. The significant positive correlation between perceived environmental stewardship and actual environmental sustainability ($r = 0.806$) reinforces the notion that water management strategies should align with public perceptions of water. Nygaard et al. (2021) discovered that engaging stakeholders in design and decision-making enhances implementation and increases the likelihood that integrated solutions would meet local requirements. The results indicated that 83.1% of natives engaged, which was favourably received. Local engagement enhanced project results. This enhances the Marina Barrage project in Singapore, where effective stakeholder management was a critical success factor (Mahmud et al., 2024). Ten percent of respondents expressed an unfavourable opinion; therefore, educators should improve their instruction and student engagement. Stakeholder antagonism may be mitigated by discourse on the advantages, disadvantages, and ecological ramifications of subterranean reservoirs. The active engagement of stakeholders is crucial for the effective deployment of underground reservoirs in urban environments. Stakeholder engagement throughout all phases, from planning to design and implementation, results in infrastructure projects that effectively meet objectives, garner public support, and ensure long-term success, as noted by Miller-Hooks and Leach (2024). Early stakeholder engagement facilitates the identification of issues and addresses potential problems, fostering stakeholder ownership that results in the effective acceptance of novel water management systems.

The research has significant managerial implications for urban water resource management. Initially, resolve technical challenges and stabilise subsurface reservoirs. It employs advanced technologies and new materials to enhance company efficiency and sustainability. Secondly, reservoir design optimisation entails consideration of the local environment. Huang et al. (2024) assert that adaptive and site-specific solutions assist society in addressing climate change and urbanisation. Third, effective water management systems necessitate continuous stakeholder engagement and public awareness. Transparency and engagement with local communities' foster trust and societal relevance. Ultimately, the economic advantages of subterranean reservoirs and advancements in technology enhance their acceptability. Disseminating references, pilot projects, and case studies from other sustainable procurement enterprises can mitigate concerns regarding cost and financial viability. This paper advocates for a multidisciplinary strategy addressing the technical, environmental, and social aspects of urban water management. Contemporary designs and technologies surpass their predecessors; yet, addressing technical challenges, engaging stakeholders, and ensuring local adaptation remain essential to optimise efficiency while minimising impact on subterranean reservoirs. These findings enhance the understanding of sustainable urban water management and provide guidance for politicians and urban planners.

The implementation of underground reservoirs for urban water management necessitates substantial operational solutions. The primary challenge is the high cost associated with the construction and maintenance of underground water storage. Ansari et al. (2024) assert that the building of underground infrastructure necessitates substantial financial investment, particularly for economically disadvantaged areas. Our survey participants expressed concerns regarding the economic sustainability of subsurface water reservoir projects. Gholami-Shabani and Nematpour (2024) discovered that investors neglect the longevity of subterranean reservoirs owing to substantial installation expenses and intricate construction. Constructing subsurface reservoirs beneath metropolitan areas is challenging due to technical limitations. The results corroborate Sinha et al. (2023), who observed that enhanced materials, intelligent sensors, and automated monitoring systems fortify these systems. Survey respondents expressed concerns over the technical stability of underground reservoirs. These technological advancements enhance operations but necessitate continuous maintenance and updates that may burden urban budgets. The societal and public perception of subsurface reservoirs is essential to their success. Miller-Hooks and Leach (2024) assert that stakeholder engagement is essential for surmounting system opposition. Individuals favoured subterranean reservoirs following their awareness of the advantages related to groundwater conservation and evaporation regulation. Public animosity towards subsurface reservoirs, particularly when viewed as costly remedies for urban expansion, may stem from inadequate educational initiatives and outreach efforts. Transparent communication channels and stakeholder involvement are essential to surmount this obstacle.

Due to economic viability concerns, metropolitan governments ought to establish public-private partnerships (PPPs) with financial resources to support underground reservoir initiatives. Collaborations between private sector specialists and municipalities would save public budget expenditures without compromising system management. Cities may finance sustainable water management solutions using innovative green bond financial mechanisms. Sinha et al. (2023) assert that cities ought to employ modular construction techniques and prefabricated platforms to facilitate the cost-effective and efficient construction of underground reservoirs. Municipalities must implement comprehensive outreach initiatives to inform local inhabitants about the advantages of subterranean reservoirs, such as enhanced greenery and flood mitigation. Engaging local communities in the planning process from the outset would promote ownership and facilitate technology adoption.

5. Conclusion

The purpose of this paper was to assess the feasibility of subterranean reservoirs in improving efficiency in Urban Water Management, Technical issues, Environmental Effects, Attitudes towards the concept and Economic viability. The objectives of the study were to establish the barriers to implementation of reservoirs, to examine the effectiveness of the currently used reservoir designs, to investigate potential new technologies, and to analyse the acceptance from the public. The results of this paper are significant as they contribute to the understanding of substance use disorders (SUDs) in urban water management, particularly as cities confront emerging climate-related challenges. This underscores the necessity to tackle diverse technical, environmental, and social issues in both pragmatic and theoretical frameworks for urban water resource management.

The following are some of the challenges that the study revealed about the underground reservoir design and implementation; Technical problems that affect the lasting reliability of underground reservoirs. Quite a number of the respondents (78.2%) for the fact that these are some of the challenges, thereby signifying the need to implement enhanced engineering to enhance structural strength and functionality. These findings are supported by the study by Ansari et al., (2024) who underlined that constructing reservoirs in an urban environment is a challenging task. The current designs were well defended and 79.3% strongly agreed on usability of urban water system in dealing with water shortage and 80.2% strongly agreed with their contribution to prevention of floods. However, 14.9% answered the problem of local adaptation, which is crucial due to the necessity of a more fit solution. These attest to Capodaglio's (2024) findings where site adaptations improve on endurance and efficiency among architectural designs.

Smart technologies were strongly supported with 76.3% agreeing that it enhances operational efficiency and 83.2% in favour of using sustainable materials in future. These results indicate innovative possibilities in the management of urban water resources, similar to what Gholami-Shabani and Nematpour predicted in 2024. Peculiarities of stakeholders were also greatly elicited with 77.2% concurring with the views that the perceptions of stakeholders affect acceptance, and 83.1% deemed that anybody from the community can contribute to the improvement of the success of projects. This aligns with Nygaard et al. (2021) call for participation to ensure that the relevant organisational initiatives reflect the local needs and wants. These results respond to the research questions by showing technical, environmental, and social obstacles should and must be dealt to better manage urban water, as well as to support the generalizability of the study by comparing it to literature works.

This study's findings may benefit urban planners and politicians. It also emphasises the necessity for advancing next generation designed solutions, such as modular reservoir constructions and nanotechnology coatings, to enhance the stability of subsurface reservoirs in the future (Asamoah et al., 2024). Government officials should oversee the integration of advanced technology, such as smart sensors and automated control systems, inside the water management organisation to improve operational efficiency in resource management. Site-specific designs that adapt to environmental and climatic conditions are crucial for achieving efficiency. Consequently, community interaction must be incorporated from the design phase to ensure that individuals embrace innovative solutions aligned with societal needs (Bartoloni et al., 2022). The aforementioned solutions can significantly enhance urban water management, mitigate adverse consequences associated with urbanisation and climate change, and address the pertinent issues.

This study contributes to the existing body of knowledge by elucidating the interdependencies across technical, environmental, and social frameworks in urban water management. Empirical evidence demonstrates the correlation between the proposed design and system performance concerning environmentally sustainable technological design, hence advancing understanding of how materials and technology improve efficient water resource utilisation (Zhang et al., 2021). The findings further enrich the current paper by deepening the comprehension of stakeholder perspectives regarding project success and the integration of sustainability.

Future studies should thus investigate more advanced materials for the sustainable construction of reservoirs, including bio composites. Investigating the extensive impacts of smart technologies on operational productivity would provide enhanced utility. Furthermore, literature on effective community engagement strategies may enhance stakeholder participation, leading to improved acceptance and implementation of urban water projects (Sigalla et al., 2021). These strategies require further examination to refine water management systems.

The inquiry contains specific limitations that may influence the generalisation of the results. The approach, both the quantity of respondents and the geographical breadth of the study, limits the diversity of urban environments. Although the study presents advantages, augmenting the sample size and varying the demographic and geographic distribution of participants might enhance its applicability across many contexts (Fan et al., 2022). The data acquired was limited to participant impressions; while this information is valuable for comprehending stakeholder viewpoints, it may be influenced by prejudice. Perhaps, more confident supporting the perception-based metrics, quantitative assessment or longitudinal research could greatly add to the conclusions. The study primarily focused on underground reservoirs and their impact on the facility's water supply management, whereas alternative possibilities such as surface reservoirs or independently managed minor reservoirs were excluded from the investigation (Polomski and Wiatkowski, 2023). The level of generalisation and specifics outlined here implies that the outcomes of this study can be used confidently to extend theoretical constructs and advance research in urban water management systems; this process has also revealed numerous areas for future research that would underpin optimising the usefulness of these findings for a range of urban, environmental, and socio-economic settings.

According to the findings of this paper, further study and development of subterranean water sources should be pursued to address emerging issues in urban water supply and demand, as urbanisation progresses, and climatic conditions change. The study's conclusions highlight critical elements regarding the technological, environmental, and social dimensions of enhancing the efficiency, sustainability, and societal acceptance of these systems. The results facilitate the progression of sustainable urban water management due to their focus on experiential. The targeted proposals for economic transformation, such as investing in infrastructure like composite materials and intelligent systems, provide a clear pathway for urban planners and policymakers to improve water resource efficiency (Wang et al., 2024). Moreover, public engagement emphasises community involvement and the improvement of strategies aligned with the environmental context to boost project efficacy and subsequent sustainability. This paper describes problems and offers implementable solutions to support future more sustainable and resource-resilient urban water systems. By adopting such strategies, urban water management and supply can see considerable enhancement, Water shortages and flooding can be drastically brought on reduction while conditions in the environment may elevate in the 21st century (Tzanakakis et al., 2020). In the future successful innovation and collaboration results will help cities satisfy the necessary water management standards and build further development model for the generations to come.

Community involvement is crucial during the entire process of incorporating subsurface reservoirs into urban environments. Public consultation meetings facilitate participation by enabling individuals and stakeholders to express issues over proposed infrastructure. Public assemblies enable communities to assert their requirements, hence impacting project designs. Community workshops integrate reservoir placement with communal preferences for design features that enhance public accessibility. Communities must be educated about subsurface reservoir flood protection, water replenishment, and evaporation mitigation through continuous education and communication. Local environmental organisations and community leaders advocate for project sustainability.

Current study indicates that subsurface reservoir systems are both operationally viable and useful; therefore, further investigation is necessary to optimise them. Advanced materials such as self-healing concrete, high-strength polymers, and environmentally sustainable coatings will enhance the durability of subsurface reservoirs. These materials would enhance subsurface reservoir resistance, hence enhancing long-term sustainability and reducing operational expenses. Future research should investigate the integration of these materials into subsurface reservoirs to minimise maintenance expenses and enhance operational stability amid environmental fluctuations. Research on the longevity of underground reservoirs is essential to assess their performance amid urban and environmental transformations. Establish real-time monitoring systems and predictive maintenance models to assess reservoir storage capacity, structural integrity, and water quality. Data gathered through sensors and IoT technologies enhances management systems and extends the durability of infrastructure systems. These findings necessitate additional research on public perceptions of underground reservoirs. Policymakers will develop enhanced outreach strategies informed by community perspectives on subsurface water systems. Subsequent studies ought to assess community leadership in regional planning and conduct public awareness surveys to measure the efficacy of urban water management initiatives. As urban areas face increased climate stress, research should concentrate on adapting subterranean reservoirs to address extreme climatic challenges such as flooding and drought. Integrating flood risk assessment and drought mitigation in reservoir design will enhance the sustainability of watershed projects.

This study provides practical recommendations for the installation of subsurface water reservoirs in urban water management systems. Government-provided financial incentives, including as grants or low-interest loans, are essential to encourage the use of subterranean reservoirs. Legislatures ought to require urban development plans to incorporate designated areas for sustainable water storage within zoning regulations. The government ought to establish public-private partnerships to distribute expenses and mitigate financial risk.
Self-healing concrete and sustainable construction practices enhance durability; therefore, engineers must implement them. Reservoir designers must create climate-resilient infrastructure to withstand adverse weather conditions. Real-time monitoring systems utilising IoT sensors are essential for performance assessment and predictive maintenance. Subterranean reservoirs necessitate urban planning that emphasises regions susceptible to flooding and drought. Consultation meetings on green and urban infrastructure will enhance community alignment with public needs.

References

1. AghaKouchak, A., Chiang, F., Huning, L.S., Love, C.A., Mallakpour, I., Mazdiyasni, O., Moftakhari, H., Papalexiou, S.M., Ragno, E. and Sadegh, M., 2020. Climate extremes and compound hazards in a warming world. Annual Review of Earth and Planetary Sciences, 48(1), pp.519-548.

2. Allan, R.P., Arias, P.A., Berger, S., Canadell, J.G., Cassou, C., Chen, D., Cherchi, A., Connors, S.L., Coppola, E., Cruz, F.A.

and Diongue-Niang, A., 2023. Intergovernmental Panel on Climate Change (IPCC). Summary for Policymakers. In Climate change 2021: The physical science basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change (pp. 3-32). Cambridge University Press.

3. Amirzadeh, S., Rasouli, D. and Dargahi, H., 2024. Assessment of validity and reliability of the Feedback Quality Instrument. BMC Research Notes, 17(1), p.227.

4. Ansari, A., Thadagani, K.S., Seshagiri Rao, K., Shekhar, S. and Alluqmani, A.E., 2024. Assessing seismic vulnerability in metro systems through numerical modelling: enhancing the sustainability and resilience of urban underground utilities (3U). Innovative Infrastructure Solutions, 9(10), p.366.

5. Asamoah, G.A., Korsah, M., Jeyasundar, P.G.S.A., Ahmed, M., Lau, S.Y. and Danquah, M.K., 2024. Nanotechnology-Based Lithium-Ion Battery Energy Storage Systems. Sustainability, 16(21), p.9231.

6. Baah, C., Opoku-Agyeman, D., Acquah, I.S.K., Agyabeng-Mensah, Y., Afum, E., Faibil, D. and Abdoulaye, F.A.M., 2021. Examining the correlations between stakeholder pressures, green production practices, firm reputation, environmental and financial performance: Evidence from manufacturing SMEs. Sustainable Production and Consumption, 27, pp.100-114.

7. Bartoloni, S., Calò, E., Marinelli, L., Pascucci, F., Dezi, L., Carayannis, E., Revel, G.M. and Gregori, G.L., 2022. Towards designing society 5.0 solutions: The new Quintuple Helix-Design Thinking approach to technology. Technovation, 113, p.102413.

8. Capodaglio, A.G., 2024. Urban Water Supply Sustainability and Resilience under Climate Variability: Innovative Paradigms, Approaches and Technologies. ACS ES&T Water.

9. Chahim, D.M., 2021. Flood Control Politics: Engineering, Urban Growth, and Disaster in Mexico City. Stanford University.

10. Dąbrowska, J., Orellana, A.E.M., Kilian, W., Moryl, A., Cielecka, N., Michałowska, K., Policht-Latawiec, A., Michalski, A., Bednarek, A. and Włóka, A., 2023. Between flood and drought: How cities are facing water surplus and scarcity. Journal of Environmental Management, 345, p.118557.

11. ECA, U., ECE, U., ECLAC, U., ESCAP, U., ESCWA, U. and World Health Organization (WHO, 2020. Water and climate change. Unesco.

12. Edelman, D.J., 2023. Management of the Urban Environment in Three Southeast Asian Coastal Metros: Bangkok, Manila and Jakarta. Advances in Applied Sociology, 13(10), pp.765-839.

13. Fan, X., Jiang, X. and Deng, N., 2022. Immersive technology: A meta-analysis of augmented/virtual reality applications and their impact on tourism experience. Tourism Management, 91, p.104534.

14. Fu, G., Jin, Y., Sun, S., Yuan, Z. and Butler, D., 2022. The role of deep learning in urban water management: A critical review. Water Research, 223, p.118973.

15. Gholami-Shabani, M. and Nematpour, K., 2024. Reuse of Wastewater as Non-Conventional Water: A Way to Reduce Water Scarcity Crisis.

16. He, R., Tiong, R.L., Yuan, Y. and Zhang, L., 2024. Enhancing resilience of urban underground space under floods: Current status and future directions. Tunnelling and Underground Space Technology, 147, p.105674.

17. Hossain, A., Al Mamun, M.A., Hossain, K., Rahman, H.B.H., Al-Jawahry, H.M. and Melon, M.M.H., 2024. AI-Driven Optimization and Management of Decentralized Renewable Energy Grids. Nanotechnology Perceptions, pp.76-97.

18. Huang, S., Wang, S., Gan, Y., Wang, C., Horton, D.E., Li, C., Zhang, X., Niyogi, D., Xia, J. and Chen, N., 2024. Widespread global exacerbation of extreme drought induced by urbanization. Nature Cities, 1(9), pp.597-609.

19. Huang, Y., Sun, H., Liu, Y., Zhao, K., Liu, T. and Liu, D., 2024. Application of pervious concrete pavement in the “breathe in-breathe out” design for sponge cities in China. Environmental Science and Pollution Research, pp.1-20.

20. Israilova, E., Voronina, A. and Shatila, K., 2023. Impact of water scarcity on socio-economic development. In E3S Web of Conferences (Vol. 458, p. 08027). EDP Sciences.

21. Jiang, Y., 2023. Financing water investment for global sustainable development: Challenges, innovation, and governance strategies. Sustainable Development, 31(2), pp.600-611.

22. Karunarathna, I., Gunasena, P., Hapuarachchi, T. and Gunathilake, S., 2024. The crucial role of data collection in research: Techniques, challenges, and best practices. Uva Clinical Research, pp.1-24.

23. Khoza, S., 2021. Department of Environmental Affairs investigating the potential use of public-private partnerships to fund green building initiatives: the case of the Department Of Environmental Affairs (Doctoral dissertation, Stellenbosch: Stellenbosch University).

24. Krampe, F., Smith, E.S. and Hamidi, M.D., 2021. Security implications of climate development in conflict-affected states: implications of local-level effects of rural hydropower development on farmers in Herat. Political Geography, 90, p.102454.

25. Krishnan, S.R., Nallakaruppan, M.K., Chengoden, R., Koppu, S., Iyapparaja, M., Sadhasivam, J. and Sethuraman, S., 2022. Smart water resource management using Artificial Intelligence—A review. Sustainability, 14(20), p.13384.

26. Kushwaha, V., 2024. Innovative Frameworks for Urban Water Security: Bridging Gaps in Planning, Management, and Governance (Doctoral dissertation, Northeastern University).

27. Lv, H., Yang, L., Zhou, J., Zhang, X., Wu, W., Li, Y. and

Jiang, D., 2020. Water resource synergy management in response to climate change in China: From the perspective of urban metabolism. Resources, conservation and recycling, 163, p.105095.

28. M. Abdeldayem, O., Eldaghar, O., K. Mostafa, M., M. Habashy, M., Hassan, A.A., Mahmoud, H., M. Morsy, K., Abdelrady, A. and Peters, R.W., 2020. Mitigation plan and water harvesting of flashflood in arid rural communities using modelling approach: A case study in Afouna village, Egypt. Water, 12(9), p.2565.

29. Mahmud, A.B., Rosli, H.B. and Hassan, N.B., 2024. Assessing the Impact of Regulatory Frameworks on the Success of Green Building Projects in Singapore. Frontiers in Management Science, 3(2), pp.58-66.

30. Mazzetto, S., 2024. A Review of Urban Digital Twins Integration, Challenges, and Future Directions in Smart City Development. Sustainability, 16(19), p.8337.

31. McCarton, L., O'Hogain, S., Reid, A., McCarton, L., O'Hogain, S. and Reid, A., 2021. The Worth of Water Technology Portfolio. The Worth of Water: Designing Climate Resilient Rainwater Harvesting Systems, pp.37-81.

32. Milićević, M., Ilijić, L. and Vujičić, N., 2024. Cross-cultural adaptation and content validity of the Measuring the Quality of Prison Life survey in Serbia. SAGE Open, 14(4), p.21582440241301422.

33. Miller-Hooks, E. and Leach, J., 2024. US-UK Workshop on Transformation in Urban Underground Infrastructure.

34. Mohajan, H.K., 2020. Quantitative research: A successful investigation in natural and social sciences. Journal of Economic Development, Environment and People, 9(4), pp.50-79.

35. Mohammad-Hosseinpour, A. and Molina, J.L., 2022. Improving the sustainability of urban water management through innovative groundwater recharge systems (GRS). Sustainability, 14(10), p.5990.

36. Mohandas, S.R., Kaddoura, K., Singh, A.K., Elsayed, M.Y., Banihashemi, S., Antwi-Afari, M.F., Olawumi, T.O. and Zayed, T., 2024. Application of a hybrid fuzzy-based algorithm to investigate the environmental impact of sewer overflow. Smart and Sustainable Built Environment.

37. Moises Jr, C., 2020. Online data collection as an adaptation in conducting quantitative and qualitative research during the COVID-19 pandemic. European Journal of Education Studies, 7(11).

38. Mseli, Z.H., Sankaranna, G. and Mwegoha, W.J., 2024. Toward Sustainable Groundwater Management: A Comprehensive Framework for Resource Protection and Utilization. Environmental Quality Management, 34(1), p.e22308.

39. Mulisa, F., 2022. When Does a Researcher Choose a Quantitative, Qualitative, or Mixed Research Approach? Interchange, 53(1), pp.113-131.

40. Nakamura, H. and Oosawa, M., 2021, March. Effects of the underground discharge channel/reservoir for small urban rivers in the Tokyo area. In IOP Conference Series: Earth and Environmental Science (Vol. 703, No. 1, p. 012029). IOP Publishing.

41. Noori, A.R. and Singh, S.K., 2023. Rainfall Assessment and Water Harvesting Potential in an Urban area for Artificial groundwater recharge with land use and land cover approach. Water Resources Management, 37(13), pp.5215-5234.

42. Nygaard, K., Graversgaard, M., Dalgaard, T., Jacobsen, B.H. and Schaper, S., 2021. The role of stakeholder engagement in developing new technologies and innovation for nitrogen reduction in waters: A longitudinal study. Water, 13(22), p.3313.

43. Palermo, S.A., Maiolo, M., Brusco, A.C., Turco, M., Pirouz, B., Greco, E., Spezzano, G. and Piro, P., 2022. Smart technologies for water resource management: An overview. Sensors, 22(16), p.6225.

44. Pandey, C.L., 2021. Managing urban water security: challenges and prospects in Nepal. Environment, Development and Sustainability, 23(1), pp.241-257.

45. Pankratova, N., Haiko, H., & Savchenko, I. (2024). Modeling the underground infrastructure of urban environments. In The urban book series. https://doi.org/10.1007/978-3-031-47522-1.

46. Pietilä, A.M., Nurmi, S.M., Halkoaho, A. and Kyngäs, H., 2020. Qualitative research: Ethical considerations. The application of content analysis in nursing science research, pp.49-69.

47. Połomski, M. and Wiatkowski, M., 2023. Impounding Reservoirs, Benefits and Risks: A Review of Environmental and Technical Aspects of Construction and Operation. Sustainability, 15(22), p.16020.

48. Połomski, M. and Wiatkowski, M., 2023. Impounding Reservoirs, Benefits and Risks: A Review of Environmental and Technical Aspects of Construction and Operation. Sustainability, 15(22), p.16020.

49. Priyan, K., 2021. Issues and challenges of groundwater and surface water management in semi-arid regions. Groundwater resources development and planning in the semi-arid region, pp.1-17.

50. Ritter, C., Koralesky, K.E., Saraceni, J., Roche, S., Vaarst, M. and Kelton, D., 2023. Qualitative research in dairy science: A narrative review. Journal of Dairy Science.

51. Sadkhan, R.A. and Al-Mudhafar, W.J., 2024. Key aspects of underground hydrogen storage in depleted hydrocarbon reservoirs and saline aquifers: A fundamental review and understanding. Energy Geoscience, p.100339.

52. Saviolidis, N.M., Olafsdottir, G., Nicolau, M., Samoggia, A., Huber, E., Brimont, L., Gorton, M., von Berlepsch, D., Sigurdardottir, H., Del Prete, M. and Fedato, C., 2020. Stakeholder perceptions of policy tools in support of sustainable food consumption in Europe: policy implications. Sustainability, 12(17), p.7161.

53. Saxena, A., Prakash Gupta, J., Tiwary, J.K., Kumar, A., Sharma, S., Pandey, G., Biswas, S. and Raghav Chaturvedi, K., 2024. Innovative Pathways in Carbon Capture: Advancements and Strategic Approaches for Effective Carbon Capture, Utilization, and Storage. Sustainability, 16(22), p.10132.

54. Seneviratne, S.I., Zhang, X., Adnan, M., Badi, W., Dereczynski, C., Luca, A.D., Ghosh, S., Iskandar, I., Kossin, J., Lewis, S. and Otto, F., 2021. Weather and climate extreme events in a changing climate.

55. Siddique, I., 2021. Sustainable Water Management in Urban Areas: Integrating Innovative Technologies and Practices to Address Water Scarcity and Pollution. The Pharmaceutical and Chemical Journal, 8(1), pp.172-178.

56. Sigalla, O.Z., Tumbo, M. and Joseph, J., 2021. Multi-stakeholder platform in water resources management: A critical analysis of stakeholders' participation for sustainable water resources. Sustainability, 13(16), p.9260.

57. Sinha, S., Kumar, R., Anand, J., Gupta, R., Gupta, A., Pant, K., Dohare, S., Tiwari, P., Kesari, K.K., Krishnan, S. and Gupta, P.K., 2023. Nanotechnology-based solutions for anti-biofouling applications: An overview. ACS Applied Nano Materials, 6(14), pp.12828-12848.

58. Smakhtin, V., Perera, D., Qadir, M., Aureli, A., Carvalho-Resende, T., Dhot, N., Findikakis, A., Villholth, K.G., Gurdak, J.J., Zandaryaa, S. and Hulsmann, S., 2020. Water availability, infrastructure and ecosystems. IWMI.

59. Ssekyanzi, G., Ahmad, M.J. and Choi, K.S., 2024. Sustainable Solutions for Mitigating Water Scarcity in Developing Countries: A Comprehensive Review of Innovative Rainwater Storage Systems. Water, 16(17), p.2394.

60. Suprayitno, D., Iskandar, S., Dahurandi, K., Hendarto, T. and Rumambi, F.J., 2024. Public Policy in The Era Of Climate Change: Adapting Strategies For Sustainable Futures. Migration Letters, 21(S6), pp.945-958.

61. Tan, L., Cui, Q., Chen, L. and Wang, L., 2024. An Exploratory Study on Spatial Governance Toward Urban-Rural Integration: Theoretical Analysis with Case Demonstration. Land, 13(12), p.2035.

62. Tzanakakis, V.A., Paranychianakis, N.V. and Angelakis, A.N., 2020. Water supply and water scarcity. Water, 12(9), p.2347.

63. unstats.un.org, 2023. Smaller cities and towns in many regions are recording faster growth in slum populations than major cities. https://unstats.un.org/sdgs/report/2023/goal-11/#:~:text=The%20world's%20population%20reached%208,70%20per%20cent%20by%202050.

64. Wang, D., Xu, P.Y., An, B.W. and Guo, Q.P., 2024. Urban green infrastructure: Bridging biodiversity conservation and sustainable urban development through adaptive management approach. Frontiers in Ecology and Evolution, 12, p.1440477.

65. Wang, L., 2024. Challenges to Green Infrastructure in Cities with High Water Tables: Appropriate Solutions and Suitable Locations in Richmond, BC.

66. Wang, R., Jia, Z., Ji, C., Wang, H., Yao, J. and Yang, Y., 2024. Advancing Urban Sustainability Through Public-Private Collaboration to Create Environmentally Conscious Infrastructure. ESTIDAMAA, 2024, pp.43-52.

67. Warner, J.F. and Meissner, R., 2021. Cape Town's "Day Zero" water crisis: A manufactured media event? International Journal of Disaster Risk Reduction, 64, p.102481.

68. Wu, S., Zhou, X., Reyns, J., Yamazaki, D., Yin, J. and Li, X., 2024. Climate change and urban sprawl: Unveiling the escalating flood risks in river deltas with a deep dive into the GBM river delta. Science of The Total Environment, 947, p.174703.

69. Xiang, X., Li, Q., Khan, S. and Khalaf, O.I., 2021. Urban water resource management for sustainable environment planning using artificial intelligence techniques. Environmental Impact Assessment Review, 86, p.106515.

70. Yang, B., Yao, H. and Wang, F., 2022. A review of ventilation and environmental control of underground spaces. Energies, 15(2), p.409.

71. Zhang, Y., Mao, Y., Jiao, L., Shuai, C. and Zhang, H., 2021. Eco-efficiency, eco-technology innovation and eco-well-being performance to improve global sustainable development. Environmental Impact Assessment Review, 89, p.106580.

72. Zyphur, M.J. and Pierides, D.C., 2020. Making quantitative research work: From positivist dogma to actual social scientific inquiry. Journal of Business Ethics, 167, pp.49-62