

iWISE: A Framework For Implementation of Intelligent Water Systems

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ABSTRACT

Aging infrastructure, along with the escalating occurrence and severity of extreme weather events linked to climate change, and the growing demands of an increasing population, have placed significant strains on wastewater and stormwater systems. Consequently, there has been a rise in instances of Combined and Sanitary Sewer Overflows (CSOs and SSOs), among other related problems. These challenges have intensified the impact of sewershed issues on both society and the environment. Fortunately, recent advancements in technology, such as sophisticated sensor technologies, more powerful processors, and advanced mathematical modeling techniques, have opened up new possibilities for developing intelligent water systems in the United States that are capable of making well-informed, data driven decisions. While the technological capabilities of these tools are advancing, their application in the water sector is limited and often siloed. Water utilities face a variety of challenges related to digitalization of sewershed management and require a more structured approach for their digital transformation. This research aims to present a comprehensive framework called iWISE (Intelligent Water Infrastructure Systems Engineering) that will serve as a blueprint to facilitate the implementation of Intelligent Sewersheds for water utilities across the country. The proposed framework will focus on enhancing our understanding of various aspects, including system of systems thinking, data management, modeling techniques, decision-making processes, and service delivery, in order to adopt a more intelligent and efficient approach to managing sewersheds. This framework was piloted with small, medium

and large scale utilities to capture feedback on the proposed building blocks from a real-world perspective and the findings from these interviews reveal that most utilities are in the preliminary stages of intelligent water systems implementation, and is more common among large utilities as compared to their small and medium counterparts.

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GENERAL AUDIENCE ABSTRACT

Water infrastructure in the United States is facing several challenges like the deterioration of infrastructure with time, increasing extreme weather events like flooding due to climate change, and growing population demands. These issues are putting a lot of pressure on wastewater and stormwater systems, leading to more instances of Combined and Sanitary Sewer Overflows (CSOs and SSOs) and other related problems that have significant negative impacts on both the society and the natural environment. Fortunately, recent advancements in technology like remote sensing, internet of things, increased computing power and advanced data analysis tools like artificial intelligence and machine learning, have provided opportunities for water utilities to improve their sewershed management practices. This research introduces a comprehensive framework called iWISE (Intelligent Water Infrastructure Systems Engineering) to help implement the new technologies and practices available for water utilities nationwide to improve the efficiency and reliability of sewershed management. The framework focuses on improving our understanding of different aspects like how a sewershed and its components are defined, collecting and managing data parameters, modeling techniques, decision-making, and service delivery. The framework was piloted with small, medium, and large scale utilities to get real-world feedback. The findings showed that most utilities are in the early stages of adopting intelligent water systems, and larger utilities are more likely to use these technologies compared to smaller ones.

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Chapter 1

Introduction

Wastewater infrastructure is an integral aspect of society that helps maintain the necessary sanitation standards required for healthy living. These wastewater systems face significant challenges such as aging infrastructure and stresses to infrastructure caused by extreme natural events, among others. These challenges lead to an increase in incidents of combined and sanitary sewer overflows (CSOs and SSOs), which lead to further sanitary challenges like pollution of surface water and groundwater. The manner in which we manage and operate our wastewater systems needs to be improved in order to effectively address these rising challenges.

There are various definitions of Intelligent Water Systems in open source literature that are based on terms such as "Smart Water", "Internet of Water", "Digital Twin" and "Integrated Water". These definitions are somewhat limited as they focus on the retrofitting of IT tools like smart metering, smart pumps, smart valves and remote sensors, among others [23]. An intelligent water system is one that is designed to not only gather meaningful and actionable data, but also enable the use of this data to make well informed, data driven decisions and provide reliable outputs.

The water sector is undergoing a digital transformation that is being driven by the advent of new sensor technologies, improved computing power and advanced modeling tools like machine learning and artificial intelligence. Wastewater utilities are recognizing the benefits of leveraging these smart technologies to support intelligent data driven decisions. Vari-

ous studies investigate the practical applications of smart technologies in utility operations. However, these applications are typically applied to specific operations that are often in silos. Wastewater systems consist of various components that all function as individual systems but also possess emergent properties that are a result of how they interact with each other, highlighting the importance of their interdependent nature. The silo-ed approach to wastewater governance can lead to unforeseen vulnerabilities, highlighting the need for a structured approach to the implementation of intelligent water practices in today's water utilities.

iWISE, the framework proposed in this work, provides a guide for wastewater utilities to understand how to define their sewershed system and its components, understand the key concepts of data collection, data analysis and data governance, develop a data driven decision support system and developing a strategic plan for implementation of a sustainable and reliable wastewater management system. The framework is built on seven building blocks: Physical Systems, Digital Systems, Planning and Implementation, Data Governance, Database Management, Data Analytics, and Decision Support System.

Based on this framework, we also conducted pilot interviews and surveys with water utilities of different scales to understand their current intelligent water practices. Our goal through the interviews and surveys was not only to capture their current intelligent water practices, but also help improve their maturity level in terms of intelligent water systems.

1.1 Background

The scope of intelligent water systems and there applications in wastewater management is vast. Although there are many studies that investigate the application and benefits of various technologies like remote sensing, AI and Internet of Things, there is a lack of application of the available technologies in a holistic way, both in literature and in practice. Intelligent

water systems require a step by step blueprint to help them implement these available technologies in a reliable way. The iWISE framework was developed as part of a project funded by The Water Research Foundation and the entirety of the framework consists of building blocks that cover technical, foundational and organizational aspects of wastewater utility management. My individual contribution to the project cover the technical building blocks, which are presented in this study.

1.1.1 Water System-of-Systems Approach

There is a need for cultural shift in the wastewater sector for more coordination and less siloed water management and governance. The transition, often referred to as One Water, Integrated Water, Our Water, or Total Water, is supported by numerous experts and driven by the necessity to enhance water governance and management, decrease vulnerabilities of utilities, and gain a better grasp of interdependencies within water systems. Allowing isolated approaches to persist in the decentralized governance of water systems could lead to escalating threats to both local and global water security if vulnerabilities remain unattended [32]. Implementing Intelligent Water Systems necessitates a System-of-Systems (SoS) strategy, where governance combines intricate, interrelated water management challenges across the natural, built, and social aspects of water. In a System-of-Systems, various components function as separate systems capable of independent operation. However, they must also interact seamlessly with one another to achieve overarching SoS-level functionalities. Consequently, the SoS transcends the mere sum of its individual constituents, exhibiting emergent properties arising from interactions between its component systems and the dynamic environments in which they operate. Using a System-of-Systems approach ensures that the complexity and uncertain nature of individual systems and their interrelationships are considered [19]. This approach can be used in conjunction with scientific principles to

develop and test hypotheses within individual subsystems and, using the knowledge of global interactions between the subsystems, arrive at better solutions to complex issues.

1.1.2 Complex Social-Ecological-Technological Systems (SETS)

The concept of the 'Anthropocene' encapsulates the current global situation where human society has an increasingly dominant influence on the Earth's functioning. The challenges faced during this era are intricate, socio-environmental, and systemic, with complex causes, interactions, and consequences. As a self-governing society dealing with these interdependent challenges, it becomes progressively harder to foresee the unintended outcomes of decisions and to align goals effectively across various systems. While scientific research brings societal benefits, knowledge tends to be isolated within narrow specializations.

To incorporate a Systems-of-Systems (SETS) perspective into adaptive management, it is essential to conceptualize the interrelated human and natural systems and assess the underlying interdependencies among social drivers, institutions, and accrued benefits. Water Systems-of-Systems (SoSs) can be classified into natural, built, and social sub-systems. A future focused on improving the understanding and management of risks and vulnerabilities in a Water SoS will be better equipped to handle the complex linkages within Water SETS, uncover unknowns and unexpected events (e.g., black swan events), and effectively manage risks to IWS water security from various emerging stresses and pressures.

1.2 Goals and Objectives

The goal of this study is to provide a blueprint to utilities for the implementation of intelligent water systems and to encourage them to leverage the use of advanced technologies and big

data to help them address complex challenges such as stormwater management, CSOs and SSOs, asset management, extreme natural events, eutrophication and algae blooms, and aging infrastructure, among others.

1.2.1 Research Questions

The piloting interviews and surveys conducted with participating utilities help us answer the following research questions.

- **RQ1: Are utilities currently implementing intelligent water practices, and to what degree?**

This question will help us understand the current maturity level of utilities in terms of understanding of IWS and IWS implementation.

- **RQ2: How do utilities of different scales compare to each other in terms of IWS implementation?**

During the piloting stage, we interviewed utilities that vary by the size of population that they serve. Through this question, we aim to understand what are the individual challenges that each type of utility faces and what are their current intelligent water practices.

- **RQ3: What aspects of IWS implementation present as major challenges to utilities?**

Through this question we aim to understand what major challenges utilities face when taking up intelligent water projects. This question also helps us understand which building blocks are more important to utilities and which ones can be improved on.

1.2.2 Methodology

The iWISE framework was developed in the following stages, as shown in Figure 1.1.

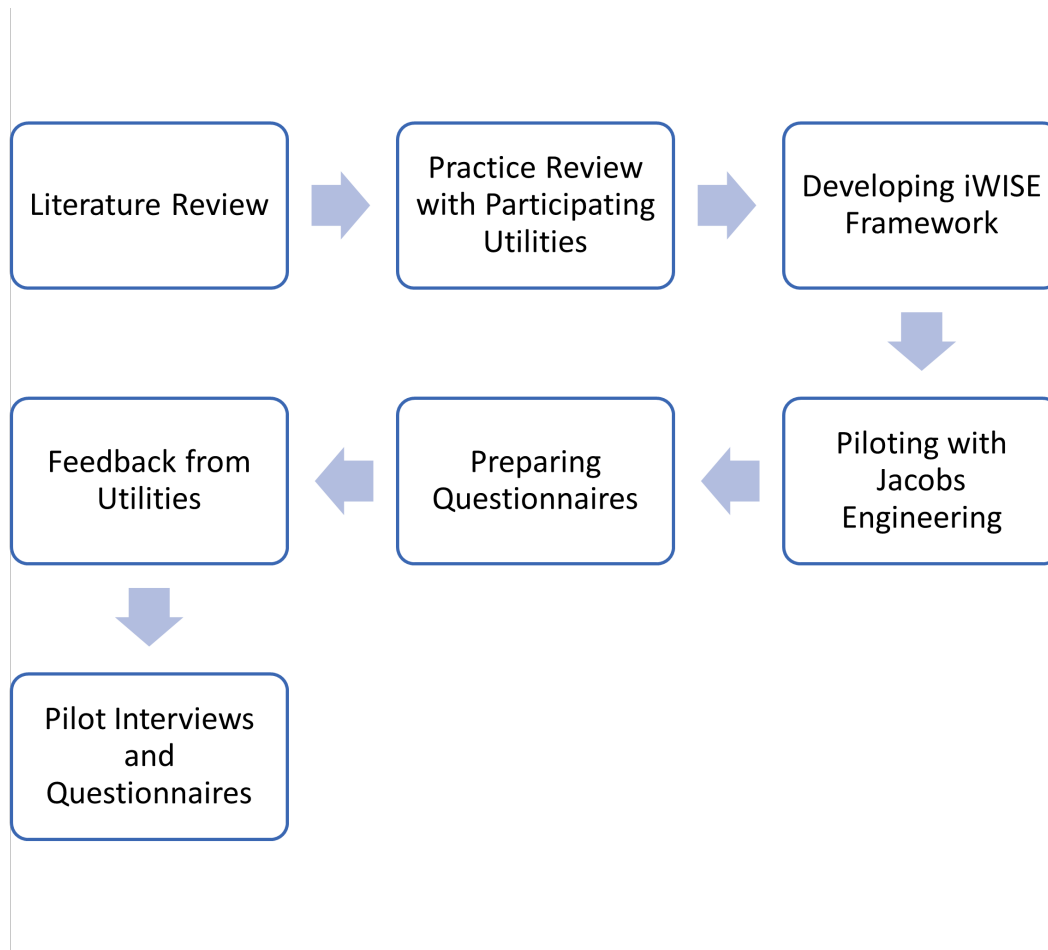


Figure 1.1: Research Methodology

1. **Literature Review:** We first conducted a comprehensive literature review of more than 200 articles published by water organizations, journals and conference proceedings. The literature review captured the work done by researchers in the domain of intelligent water practices in wastewater utility management for all the building blocks specified as part of this framework, that is, the type of analysis conducted by utilities, what type of data parameters are collected, their database management practices, their

decision support systems and cybersecurity protocols.

2. **Practice Review with Participating Utilities:** To understand the real world intelligent water practices, we interviewed utilities to capture their level of intelligent water system implementation.
3. **Developing iWISE framework:** Through the literature and practice review, we were able to understand the current practices, challenges and benefits identified by real world utilities and developed the building blocks of the iWISE framework that address the various technical aspects of wastewater utilities and the intelligent water practices associated with them.
4. **Piloting with Jacobs Engineering:** We piloted the framework with Jacobs Engineering during a two-day working meeting to ensure the framework's efficacy. Through these meetings we obtained feedback on each of the building blocks from the perspective of water domain experts.
5. **Preparing Questionnaires:** Once the framework was developed, we prepared questionnaires based on the building blocks of iWISE. These questionnaires were sent to wastewater utilities across the United States to capture their current practices in IWS.
6. **Feedback from Utilities:** We conducted working meetings with HRSD and Houston water utilities to obtain feedback on the questionnaires from a utility's perspective and incorporated their suggestions. An option 'other' was added to each question to provide a space for the utilities to provide their own feedback if the options provided were not sufficient for them to answer and to capture any practices that are not mentioned in the iWISE framework.
7. **Pilot Interviews and Questionnaires:** Finally, the questionnaires were sent to utilities across the United States to obtain their feedback and analyse the responses

to evaluate the current practices in IWS. We also conducted pilot interviews with small, medium and large scale utilities to capture their perspective on intelligent water practices and understand the individual challenges that they face.

Chapter 2

Literature and Practice Review

This chapter presents crucial discussions concerning the implementation of Intelligent Water Systems (IWS) concepts at the sewershed scale. These discussions are based on an extensive examination of published literature. The literature review serves multiple purposes: first, it offers an overview of the current state of the IWS field, highlighting recent advancements and trends in research and practice. Second, it identifies potential gaps in our understanding of the subject, signaling areas that require further research to address specific challenges or unanswered questions related to IWS. Third, the review helps to shape a national IWS framework by shedding light on the most significant issues and challenges in the field and the approaches utilized in the past to tackle them. This background information provides context and insights that can prove valuable when initiating a new research project or addressing specific problems related to IWS.

2.1 Literature Review

2.1.1 System of Systems Thinking

Wastewater utilities encounter a multitude of intricate social, environmental, and economic challenges. Implementing Intelligent Water Systems (IWS) demands a systems-of-systems approach because IWS often involves integrating multiple systems and technologies, which

can be complex and difficult to manage. In an IWS, various interconnected systems and technologies, such as wastewater treatment plants, collection and conveyance networks, sensors, and control systems, may be interdependent and interact with other systems like energy or transportation systems. This complexity can make it challenging to comprehend and predict the overall system's behavior and to identify and address potential challenges.

Systems of systems thinking provides a framework to comprehend and manage such complex systems comprising multiple interacting sub-systems. It entails considering the interactions and interdependencies between different systems and their components, enabling the identification and mitigation of potential risks or vulnerabilities in the overall system. Adopting a System-of-Systems approach ensures that the intricate and uncertain nature of individual systems and their interrelationships are duly considered [19]. This approach, in conjunction with scientific principles, facilitates the development and testing of hypotheses within individual subsystems and allows for better solutions to complex problems by leveraging insights into the global interactions between these subsystems.

Using watersheds as an example, the natural boundary is determined by the highest elevation points surrounding a lake or river segment. These boundaries can extend beyond local, state, and even national borders. Watersheds, in essence, have no political boundaries. This characteristic poses complexity in water management since many watersheds encompass multiple state, county, and local governments [13].

The variation in water quality regulations, stormwater ordinances, and political boundaries introduces complex governance and institutional challenges for watershed managers. An example is the Delaware River Basin, where the Brandywine Creek, a small tributary of the Delaware River, is regulated as a cold-water trout stream in Delaware and as a warm-water stream in Pennsylvania. McPhearson et al. [20] proposes that the hybridity of infrastructure, where built environments interact with landscape-scale biophysical structures and processes,

offers opportunities to address the intricate challenges surrounding water management and build resilience.

2.1.2 Interdependencies

The effectiveness of a total systems approach for water systems at the sewershed scale depends on how we position the three systems: natural, built, and social, in relation to each other and sewershed-related issues. The components of these subsystems interact in various ways, influencing each other's conditions. Rinaldi et al. [28] refers to this two-way relationship between components as "interdependencies." The natural system provides resources and may subject the built and social environments to stress and hazards due to natural events and climate change. In turn, the built and social environments exert stress on the natural subsystem, driven by wastewater service demands and urbanization pressures.

The built and social infrastructure is designed to withstand the stress from the natural system while facilitating connectivity, mobility, resource delivery, waste disposal, and other societal activities. A system-based approach for sewershed systems enables the recognition of challenges, risks, linkages, planning, strategies, models, and tools to better manage and resist stresses while supporting wastewater infrastructures and their interactions with others.

Each of these sub-systems has interactions and interdependencies that can be measured and quantified to enhance reliability and resilience while reducing vulnerabilities. This study aims to present a more detailed and intricate structure of these interactions across the three sub-systems. Understanding this feedback-based dynamic system can enhance the entire system's adaptive capacity and contribute to effective sewershed management plans.

2.1.3 Data Collection

Data collection plays a crucial role in comprehending the diverse components, creating meaningful models, and enabling evidence-based decision-making in sewersheds. To gather comprehensive data that can be analyzed to extract valuable insights, it is necessary to understand the types of data being generated, integration technologies, processing requirements, and sharing protocols. In this section, we will explain the types of data collected and the technological background needed to build functional data models, drawing from insights gained from existing literature and practices. These data models serve as central repositories from which data can be queried for multiscale modeling and to support decision-making at strategic, tactical, and operational levels.

Data is sourced from various channels, including real-time information from sensors. Consequently, handling the high volume, velocity, scalability, and fault tolerance in data processing, storage, and visualization poses several challenges, necessitating innovative techniques to manage data and make it available for analysis and modeling.

A list of metrics was developed which capture the various parameters required to develop models for sewershed components. These are important to identify the elements of the system which can provide the necessary data. The data is categorized based on the sub-systems and components identified in the system. The attributes for each of the sub-systems are shown in Figure 2.1.

Gaining insight into the essential characteristics of the sewershed facilitated the identification of data sources from various sewershed components. It is crucial to comprehend the origin of these attributes to assess data reliability, data collection methods, and integration protocols within the database. The data sources may include utility instrumentation data, such as CCTV, infrared, optical, or microwave data, utility operational data, such as inventory

Natural	Built	Socio-Economic
<p>Water: Availability, Demand, Beneficial use water quality</p> <p>Land: Land Cover (Vegetation, Impervious Surface, GI) & Topography, Landfill, Agricultural and GI Runoff</p> <p>Climate: Rainfall Intensity and Duration (Seasonal, 10 year), Temporal Variations (Seasonal), Wind Speed, Humidity</p>	<p>Wastewater and Stormwater Infrastructure: Asset Lifecycle Deterioration, CSOs/SSOs & Wet Weather Flows, Influent Characteristics, Asset Risk and Lifecycle Economics</p> <p>Households: Grey and Black Water Characteristics</p> <p>Commercial/Industrial: Effluent Characteristics based on Industry Types</p>	<p>Community: Median Household Incomes, Population Growth, Customer Engagement</p> <p>Economic: Renewal, CIP & O&M Budget (Yearly), Bonds/ Taxes and Revenue Sources</p> <p>Policy: MS4, CWA, GASB-34 Specifications, Historical Liability Costs</p>

Figure 2.1: Attributes for Natural, Built and Social Subsystems

records, time series data for pumps and CSOs/SSOs, GIS, SCADA data, and external data from organizations like USGS, EPA, NOAA, among others.

2.1.4 Data QA/QC

Data QA/QC encompasses quality assurance (QA) and quality control (QC) processes applied to data within an organization. The main objective is to guarantee the accuracy, reliability, and consistency of the data used and collected by the organization while identifying and rectifying any errors or issues that may arise.

Data QA involves continuous activities and practices to ensure data quality. This includes establishing protocols and procedures for data collection, management, and analysis, implementing robust data management systems, and providing staff with training in data management best practices.

On the other hand, data QC focuses on specific activities and checks performed on the data to ensure its quality and detect any issues. This may involve manual or automated inspection of data for errors or inconsistencies, employing statistical or computational methods for data

validation, and incorporating controls to prevent errors from occurring.

Overall, data QA/QC is a crucial aspect of data management within an organization, as it guarantees data accuracy and reliability, enabling effective decision-making and other purposes.

2.1.5 Data Analysis and Modeling Techniques

Mathematical models are widely employed by wastewater utilities to comprehend and analyze the intricate processes in wastewater treatment and management. These models come in diverse forms and serve various purposes, such as designing and optimizing treatment systems, forecasting future performance, and identifying possible issues and solutions.

There are different types of mathematical models that are commonly used by wastewater utilities, including:

1. **Physical Models:** These models are based on the fundamental laws of physics and are used to describe the physical processes involved in wastewater treatment, such as the flow of fluids, the transport of pollutants, and the interactions between different chemical species. Physical models can be used to predict the performance of treatment systems under different operating conditions and to identify potential problems and solutions.
2. **Statistical Models:** These models use statistical methods to describe the relationships between different variables in the wastewater treatment process. Statistical models can be used to identify patterns and trends in data and to make predictions about future performance based on historical data.
3. **Empirical Models:** These models are based on experimental data and are used

to describe the relationships between different variables in the wastewater treatment process. Empirical models can be used to predict the performance of treatment systems under different operating conditions and to identify potential problems and solutions.

4. **Simulation Models:** These models use computer algorithms to simulate the operation of wastewater treatment systems and predict their performance under different scenarios. Simulation models can be used to optimize the design and operation of treatment systems and to identify potential problems and solutions.

In order to recommend optimal modeling practices for water utilities and create a robust decision support system, it is essential to comprehend the state-of-the-art modeling techniques relevant to enhancing intelligence in the water sector. The majority of the models analyzed in this study can be broadly categorized as either deterministic or probabilistic models. Predictive models primarily fall into the probabilistic category, as they make forecasts based on the best available data, and the accuracy of the model relies on the reliability of the data. The modeling techniques applied in the focus areas of failure prediction, performance prediction, and risk assessment are mainly classified as stochastic ([16], [2], [29]). Figure 2.2 depicts the various modeling techniques applied to the natural, built and social subsystem components of a sewershed system.

Several studies have explored water quality and contaminant transport modeling and prediction. Modern computing techniques, such as machine learning and the Transient Storage Zone Model, have been employed to forecast the location of spills and identify the contaminant source [17]. Artificial intelligence (AI) has also been utilized to predict the water quality index [1]. Additionally, groundwater models have been developed using contemporary computing techniques like artificial neural networks (ANN), finite element analysis, and fuzzy logic to assess pollutant sources [4], water quality [15], and associated risks [38].

Sewershed-Scale System			
Natural Sub-System	Built Sub-System		Social Sub-System
<p>Water</p> <p>Contamination of surface water, groundwater by discharge and runoff water inflow & infiltration</p>	<p>Household/ Commercial/ Industrial</p>	<p>Wastewater Infrastructure</p>	<p>Stormwater Infrastructure</p>
	<p>ASSET INVENTORY</p> <p>Asset ID, Geospatial location and other identification data of all managed assets including but not limited to manholes, gravity pipes, network structures (lift station, siphon, junction box, etc.)</p>		
	<p>ASSET PERFORMANCE</p> <p>Asset current and historical condition and functional adequacy data used to support renewal decisions</p>		
	<p>ASSET RENEWAL</p> <p>Historical information of renewal activities (including forensic data) to identify trends and patterns to support renewal decisions</p>		
	<p>ASSET RISK</p> <p>Consequence of Failure parameters (including TBL impacts) for risk-based renewal prioritization (*Likelihood of Failure parameters are covered in Asset Performance)</p>		
	<p>ASSET FINANCE</p> <p>Costs involved in every stage (design, construction, installation, O&M, renewal & disposal) of the lifecycle of an asset to support comparative analysis of replacement alternatives</p>		
<p>Land</p> <p>Contamination of surface and groundwater due to runoff from landfills and agricultural activities</p>			<p>Community</p> <p>Modeling of system demand and social conditions of the residential, commercial and industrial population of a sewershed</p>
<p>Climate</p> <p>Frequency and duration of extreme events in the sewershed</p>			<p>Policy/ Governance/ Regulations</p> <p>Analysis of management practices, organizational structure and regulatory impacts on water utility management</p>
			<p>Finance & Economic</p> <p>Life cycle assessment modeling and analysis of sources of funding (community willingness to pay, private and government funding)</p>

Figure 2.2: Existing Modeling Techniques and Methodologies

In the realm of runoff modeling, various techniques have been developed over time. Devia et al. [8] provide a comprehensive review of these techniques, highlighting their benefits and challenges for specific use cases based on catchment type and environmental conditions. The models discussed include ANN, KINEROS, MIKE-SHE, and TOPMODEL, among others, which are classified as physically based, empirical, and conceptual models.

Within the land subsystem, several main components include soil erosion, vegetation, landfills, and agricultural activities, each with corresponding modeling approaches in the focus areas mentioned earlier. Studies by Li et al. [18] and Biglarijoo et al. [6] utilize genetic algorithms and neural networks to treat leachate in landfills. Mathematical and statistical modeling techniques have been employed by Yanidar et al. [36] to assess leachate's impact on the surrounding environment. In the agricultural sector, models such as ANN [31] and mathematical modeling [12] have been developed to evaluate the impact of agricultural runoff on water quality.

The impact of climate events like floods and heavy rainfall on water quality has been studied

using geographic information system (GIS) and physical modeling techniques by Ellis et al. [9] and Olds et al. [24]. Socio-economic impacts and government guidelines during such events have also been addressed in studies compiled by Prouty et al. [27] and Hughes et al. [10].

In the built subsystem of a sewershed, key components include the built infrastructure for water and wastewater utilities, households, commercial and industrial sectors, and green infrastructure. The main focus areas for all components in this subsystem, similar to the natural subsystem, include condition assessment, risk prediction, failure analysis, and renewal techniques. Significant research has been conducted on the condition assessment, risk analysis, performance prediction, and other aspects of infrastructure components like gravity pipes, force mains, and lateral pipes used in households, commercial/industrial entities, and water and wastewater utilities.

Uncertainty in data, complexity, and low accuracy are common challenges faced across various fields of data analysis. Yan and Vairavamoorthy [34] propose a method that uses fuzzy logic to predict the performance of gravity pipes and force mains, especially when dealing with uncertain data. Khan et al. [14] introduce a probabilistic neural network method for condition assessment by predicting the importance and impact of specific characteristics of sewer pipes on their structural performance. These are just a few examples of studies utilizing artificial intelligence, machine learning, and mathematical and statistical models for conceptual modeling of pipes and other built systems.

Similar to pipes, different models have been developed using various methods for other essential water and wastewater infrastructure components, such as catch basins, pump stations, and manholes. Various methods for modeling inlets have been established by Senior et al. [30]. Corrosion, a common threat to water infrastructure components, is addressed in the study by Božena et al. [7], which combines Finite Element Analysis (FEA) with ANNs to

provide comprehensive solutions. Fuzzy logic and genetic algorithms have been employed for analysis of pumping stations. Lifecycle assessments are essential tools for evaluating the environmental impacts of water treatment systems, and studies by Zaman [37] and Jocanovic et al. [11] have provided comprehensive insights into lifecycle assessment and lifecycle cost of wastewater pumping units.

Regarding households, septic tanks are commonly used in sewersheds for treating household sewage and waste. Pang et al. [26] present a numerical modeling method for the quantitative assessment of the impact of groundwater contamination from waste disposal in these septic tanks. Storage tanks, on the other hand, are used solely for the storage of wastewater or combined sewer/stormwater. Yang et al. [35] conducted a study assessing the impact of volatile organic compound emissions from wastewater collected from a pesticide plant.

Modern computing technologies have also been applied to cost modeling of treatment plants, helping assess cost structures and provide solutions for cost savings. Torregrossa et al. [33] utilizes machine learning to develop a high-performing cost model for wastewater treatment plants based on energy consumption and water quality parameters. Molinos-Senante et al. [21] employ statistical modeling to generate a sewage sludge and waste management cost function, contributing to a better understanding of the cost structure and cost savings potential from reducing sludge generation.

Advancements in technology related to green infrastructure have led to the development of modeling techniques for efficiency and performance assessment. Baryła et al. [3] present a comprehensive geospatial analysis and deterministic modeling technique for water-retention efficiency modeling of green roofs. Palla et al. [25] evaluate stormwater control managed by green roofs using hydrological modeling.

The research revealed a gap in the literature concerning the influence of socio-economic

factors on sewershed characteristics and management. Existing studies primarily concentrate on the effects of societal activities and civic structure [22]. However, there is a lack of focus on government policies and the impact of regulations on sewershed development.

2.1.6 Decision Support Systems

Data visualization involves the design and aesthetic aspects of computer interfaces, aiming to present complex abstract data in a clear and understandable manner, facilitating users in analyzing information using visual tools. This field combines technical backgrounds like information retrieval, data mining, computer graphics, and human-computer interaction.

An effective approach to develop decision support system tools is through the use of visualization techniques. Water utilities are utilizing visualization tools like Tableau and PowerBI to support their business decisions and offer interactive visual representations, making it easier to communicate problems to stakeholders both within and outside the organizations. Some utilities have explored Geo-BIM for their visualization needs. User-friendliness is a key feature of such tools since they are accessed and viewed by various users, including the general public who may lack technical skills to navigate complex visualization tools. In the water sector, specific visualization tools have been developed for their application. For example, GWVis is a tool created by Best and Lewis [5] to visually present ground-water data and educate the public on ground-water issues.

2.2 Practice Review

2.2.1 Houston Water

The City of Houston, situated in southeast Texas, is the largest utility in the state and is renowned as one of the top ten utilities in the entire United States. It provides services to a substantial customer base of 2.8 million. The Water and Wastewater systems are managed by the Public Works & Engineering Department, which is further divided into multiple divisions.

The strategy for implementing intelligent water concepts in Houston's wastewater operations revolves around adopting innovative solutions to address key challenges and achieve set objectives, including intelligent operations, effective solutions, sustainability, resiliency, community engagement, and a stronger organization.

Houston Water currently define their service area by the location of their wastewater treatment plants. They have a holistic data collection process and collect data for all three subsystems including rainfall data, asset performance, asset inventory, asset condition, asset financial data, asset maintenance, infrastructure R&R and demographic data for planned growth. These parameters can come from a variety of sources and need to be managed in a common platform to support advanced analytics.

The City of Houston established a data pipeline to enable data collection, QA/QC and analysis. This data pipeline has been developed for both automated data preparation and manual data preparation.

Houston Water have developed a series of models for supporting wastewater management operations, including:

1. Methodology to rate SSO risk level and optimize preventative cleaning
2. Optimized sensor-placement
3. Integrated operations data in real-time
4. Predictive analytics: alerts to detect SSOs
5. Preventative Risk based Maintenance program: Integrating real time work order information
6. Force Main & Gravity Risk
7. Pipe Defects identification using AI

The City of Houston devised an asset management risk approach to enhance the value and longevity of force mains. A force main renewal program was established to assess the risks involved in the renewal process, which involved steps like identifying individual assets, identifying factors affecting the renewal process, assigning relative importance of these factors, establishing scoring metrics and prioritization of assets based on the risk score.

Houston Water have a well established decision support system which integrates datasets, allows the development of multiple apps and is scalable. The platform includes links to visualization pages that offer valuable information for wastewater operations management. This information encompasses aspects like consent decrees, various operational databases, external data, inventory details, and condition assessments of different assets such as WWTPs, lift stations, force mains, and more. The platform also provides access to interactive applications that enable visualizations on GIS, along with training materials for managers and operators, covering different software used by the City of Houston.

2.2.2 NYC Department of Environmental Protection

The New York City Department of Environmental Protection (DEP) is responsible for safeguarding public health and the environment by providing clean drinking water, treating wastewater, and addressing pollution issues related to air, noise, and hazardous materials. To fulfill its mission, DEP manages and oversees a network of 7,500 miles of sewers, which transport approximately 1.3 billion gallons of wastewater daily to 14 wastewater resource recovery facilities located within the city.

The NYC Department of Environmental Protection's Bureau of Water Supply (BWS) actively participates in the regional Delaware River Basin Commission as a utility and as a Party to the 1954 Supreme Court Decree. DEP defines data governance as an organizational strategy for establishing policies and managing data within the organization. Data governance frameworks are either adopted or designed by organizations to ensure data quality, usability, and to mitigate risks throughout the data lifecycle. Currently, data within the BWS is governed separately in each work unit or directorate, often in collaboration with either the Bureau of Business Information Technology or at the Agency level. Implementing a Bureau-level governance program aims to enhance existing positive practices within directorates while reinforcing areas that require improvement.

The rapid advancements in technology within the Bureau have led to the proliferation of fragmented data silos and, in some cases, redundant data across different functional areas. Implementing an efficient data governance framework is essential to establish higher standards in data creation, usage, and management. While some industries adopt intricate data governance frameworks driven by regulations, BWS has designed a simpler model that offers sufficient governance to enhance data access, utility, and integrity. Although establishing and maintaining a data governance program will require effort, it will ultimately act as a

catalyst, rather than an impediment, as BWS transitions towards cloud-based solutions.

2.2.3 Hampton Roads Sanitations District (HRSD), Southeast Virginia

HRSD provides wastewater services to 20 cities and counties in Southeast Virginia, serving a total population of 1.8 million residents. The organization operates 9 major treatment plants, primarily utilizing pressurized systems. HRSD follows a separated sewer system approach and does not have any Combined Sewer Overflows (CSOs) in the region. Additionally, they manage over 100 pump stations and more than 1000 manifold sewage pump stations owned by different localities within their service area. These facilities have a combined capacity of over 225 million gallons per day. HRSD's service area is a political subdivision of the Commonwealth of Virginia serving the cities of Chesapeake, Hampton, Newport News, Norfolk, Poquoson, Portsmouth, Suffolk, Virginia Beach, Williamsburg and the Counties of Gloucester, Isle of Wight, James City, King and Queen, King William, Mathews, Middlesex, Surry and York (excluding the town of Clarendon).

HRSD has been actively working on developing a smart water system, which presents significant opportunities due to its pressurized nature. Unlike gravity sewers, HRSD's system is not dependent on elevation, allowing for greater flexibility in utilizing their various treatment plants with different capabilities and capacities. This strategic approach enables them to achieve cost savings and reduce capital and operational expenses effectively. The primary goals are to optimize the existing capacity and leverage the investment in hydraulic modeling, which was a requirement of their consent decree. Moreover, HRSD aims to assess risks from a more time and location-centric perspective. They also plan to address the issue of infrastructure designed for extreme storm conditions, which may not be efficiently sized

for smart water implementation, necessitating adjustments to ensure compatibility with the system's objectives.

HRSD has undertaken several projects as part of its sustainable water initiative, encompassing diverse aspects such as safeguarding groundwater resources from saltwater intrusion, addressing water quality concerns through Chesapeake Bay restoration measures, managing challenges posed by sea-level rise and land subsidence, and mitigating the impact of Wet Weather SSOs. One significant initiative is the Sustainable Water Initiative For Tomorrow (SWIFT) program, where HRSD treats wastewater to achieve drinking water quality, aligns it with the geochemistry of the aquifer, and subsequently injects it into the aquifer for recharge. This approach aims to reduce saltwater intrusion from the Chesapeake Bay, counteract land subsidence, and potentially replenish groundwater levels. The program's objective is to establish six advanced plants with a total capacity of 100 MGD to facilitate aquifer recharge.

SWIFT, being an innovative climate action initiative, prompted HRSD to adopt advanced technologies. They integrated building information modeling (BIM) designs with geographic information system (GIS) maps, workflows, and analysis. The combination of BIM and GIS data enabled the creation of a comprehensive digital twin model for the district, enriched with various features.

HRSD takes measures to safeguard water quality by regularly testing private and commercial irrigation wells in proximity to the aquifer recharge sites. Using sensors, they monitor water quality changes and integrate the sensor data on a GIS map for easy monitoring.

The digital twin has significantly improved operational intelligence, offering 3D data for newly constructed facilities and planning to extend the same for older facilities. Currently, they collect and visualize real-time sensor data, with plans to automate systems based on

sensor inputs in the future.

To ensure water quality, HRSD conducts regular testing of private and commercial irrigation wells near the aquifer recharge sites, using sensors to detect any changes in water quality. The sensor data is synchronized on a GIS map for easy monitoring.

Similarly, HRSD employs a sensor-driven approach to monitor pressure and pump performance across their extensive network of 651 miles of pipes and 131 pump stations. The GIS interface allows staff to examine assets at various locations, and the data is used to create an operational PI dashboard with a map, sensor readings, and graphs to track variables like salinity.

During storms, HRSD focuses on minimizing wastewater overflows and monitoring infrastructure. Given the increasing intensity of storms and the effects of subsidence and sea level rise, there is a greater need to safeguard wastewater drainage systems from spills. For this purpose, the district relies on its GIS and digital twin technology once again.

2.3 Framework Validation and Verification

The iWISE framework was developed based on extensive literature and practice review. The framework was then piloted with various utilities and water organizations to obtain feedback in order to verify and validate the proposed building blocks.

2.3.1 Framework Verification

The first step in the verification process was a series of two-hour workshops conducted with Hampton Roads Sanitary District (HRSD) and Houston Water. Through these piloting sessions, feedback was obtained on each building block, the overall structure of the framework,

the number of building blocks as well as the content addressed and practices proposed as part of each building block.

We also conducted a two-day brainstorming session with Jacobs Consulting, a leading consulting firm in the water sector. The building blocks were discussed individually and based on the feedback received, revisions were made to the content and the overall structure of the building blocks.

We also received input from the Intelligent Water Infrastructure Network (iWIN) Committee, which comprises of technical domain experts from Oak Ridge National Lab (ORNL), Jacobs, Arcadis, DC Water, City of Houston, MWRD Chicago, Clean Water Services and Virginia Tech.

Water sector experts from different organizations were consulted to confirm the accuracy and relevance of the iWISE building blocks for utilities. Their input verified that these building blocks can effectively guide utilities in their digital transformation. Once the building blocks and the overall framework were reviewed and validated through domain experiments, we created questionnaires to further assess and confirm the framework's effectiveness, which will be discussed in the next section.

2.3.2 Framework Validation

A questionnaire was designed to investigate the current adoption of intelligent water practices and the readiness to implement the proposed iWISE building blocks in both large, medium, and small utilities. The questions were formulated based on the iWISE framework. Before finalizing the questionnaire, we conducted a dry run with two large utilities, HRSD and Houston Water, through a workshop-style meeting. Their valuable input and suggestions were incorporated to improve the questionnaire's clarity and suitability for wa-

ter sector experts. The feedback and approval from these large utilities confirmed that the questionnaire effectively captures intelligent water practices in water utilities.

The questionnaire was distributed to over 100 utilities in the United States, Canada, and the UK. Additionally, we conducted pilot interviews with some of these utilities through video meetings to understand their current use of intelligent water practices and their future plans. The responses from the questionnaires revealed that some utilities are already implementing intelligent water practices at various stages, spanning small, medium, and large utilities. Interestingly, these utilities generally align with the steps proposed in the iWISE framework.

While not all utilities currently follow all the practices described in iWISE, many expressed their willingness to explore these practices in the future. They acknowledged that a framework like iWISE would greatly assist them in achieving a comprehensive and sustainable digital transformation and intelligent sewershed management.

Chapter 3

iWISE: The Framework

The framework in its entirety consists of three layers - the foundational layer, the technical layer and the organizational layer. Each layer consists of building blocks and each building block is based on three pillars. For the purpose of this study, the technical layer and its building blocks are discussed. The framework is represented in Figure 3.1.

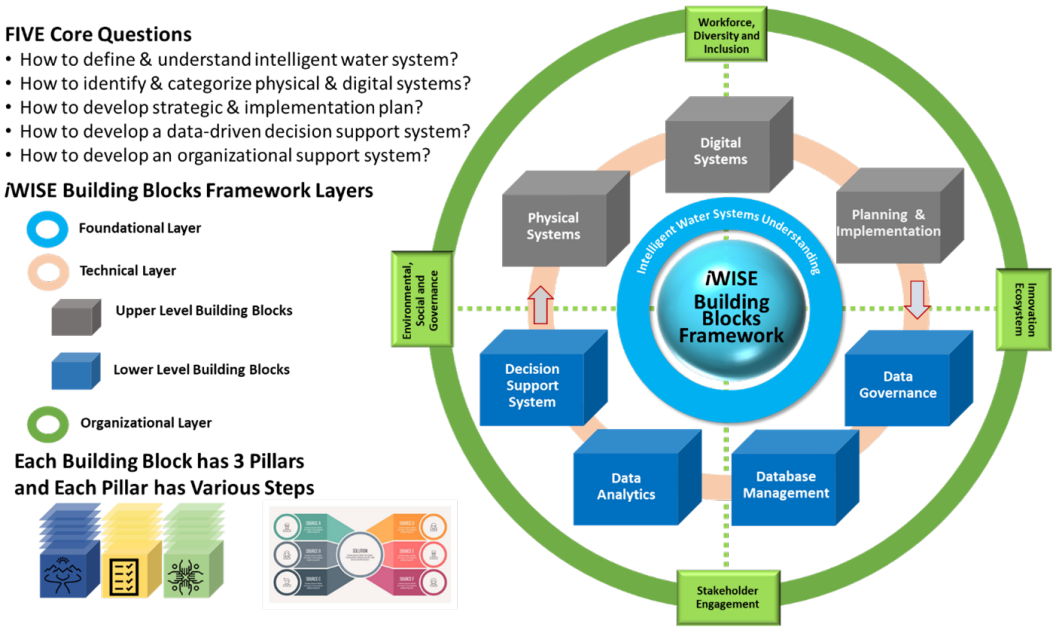


Figure 3.1: Building Blocks of iWISE

The seven technical building blocks refer to the technological tools and practices that improve efficiency and enable better decision-making in sewershed management. The technical layer is divided into the Upper Level and Lower Level building blocks. The Upper Level building blocks provide valuable insights into both the physical and digital systems, enabling the

reader to gain a deeper understanding of these systems. Moreover, they aid in the development of sustainable strategic and implementation plans for the systematic implementation of intelligent water systems. The Lower Level building blocks elucidate various concepts that assist utilities in implementing a system-of-systems approach to manage sewershed effectively. It covers topics such as data governance, database development, data analytics, and decision support systems. For the purpose of this work, the Physical Systems, Planning and Implementation, Data Governance, Data Analytics and Decision Support System building blocks will be discussed in accordance with my individual contribution to the overall project of the iWISE Framework development funded by The Water Research Foundation.

3.1 Physical Systems

The Physical Systems building blocks encompass fundamental principles, such as the System-of-Systems Approach, that enable a comprehensive understanding of individual sub-systems within a sewershed. This approach preserves the unique properties of each sub-system while considering their combined behavior when viewed holistically.

Appreciating the System-of-Systems thinking is crucial for gaining a holistic understanding of how a sewershed functions. This understanding requires a grasp of the sewershed system boundary, its sub-systems, their associated components, and the interactions between these sub-systems and components. The building block outlines three key pillars (as illustrated in Figure 3.2) and offers essential recommendations based on the System-of-Systems approach. These recommendations aid wastewater utilities in defining the sewershed boundary as a foundation for implementing the proposed framework. It also helps in identifying and categorizing various sub-systems and their components, as well as understanding the interactions between these components. By implementing this building block, wastewater utilities can es-

establish a solid groundwork to support data collection, modeling, and other technical aspects of Intelligent Water Systems at the sewershed scale.

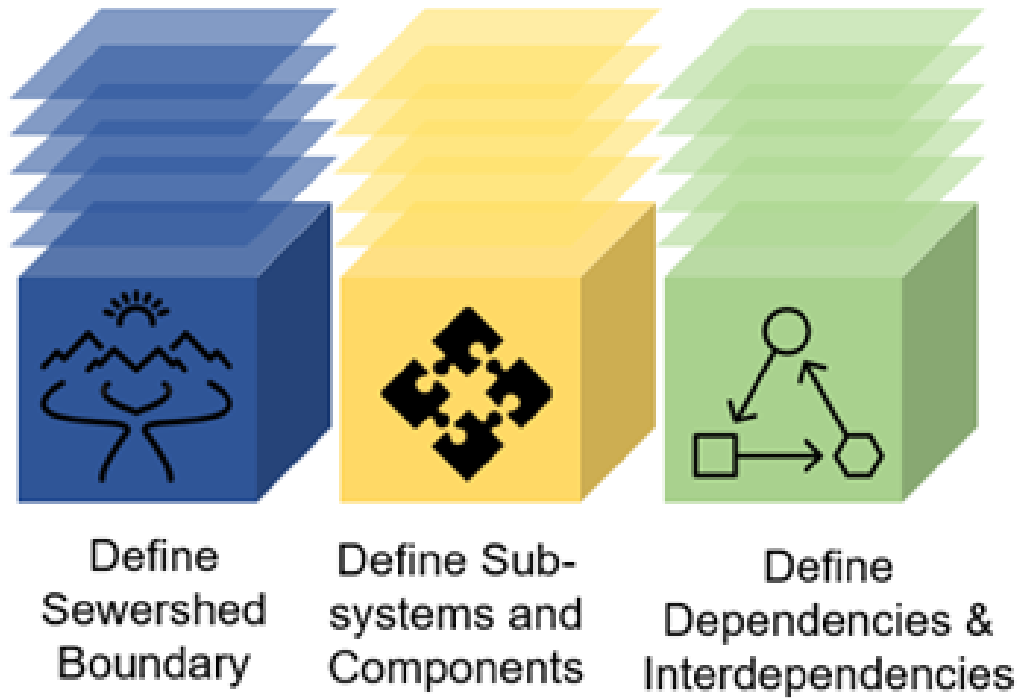


Figure 3.2: Pillars of Physical Systems Building Block

Pillar 1: Define Sewershed Boundary

The sewershed is a part of a larger watershed boundary within a defined basin, but its boundary is not visible. Wastewater utilities currently determine their sewershed boundaries based on the locations of the built infrastructure they manage. The area within this boundary, which includes the customers served by the utility, is known as the service area. This service area overlaps with both the social and built sub-systems, as well as the geographically larger natural watershed system. The natural watershed system governs the movement of contaminants, runoff, groundwater, and surface water across the land and through water bodies.

It is essential to consider the interactions within this natural sub-system as they can have

an impact on the operations of sewersheds within the same watershed. Moreover, these sub-systems can consist of multiple components, each comprising individual elements. For instance, the water component may include groundwater, the land component may involve landfills, and the climate component may encompass extreme weather events, all within the natural sub-system. Figure 3.3 illustrates how a sewershed system interacts with the natural, built, and social sub-systems. There can be multiple sewersheds within watersheds in each river basin. These basins are shown in the figure on the left.

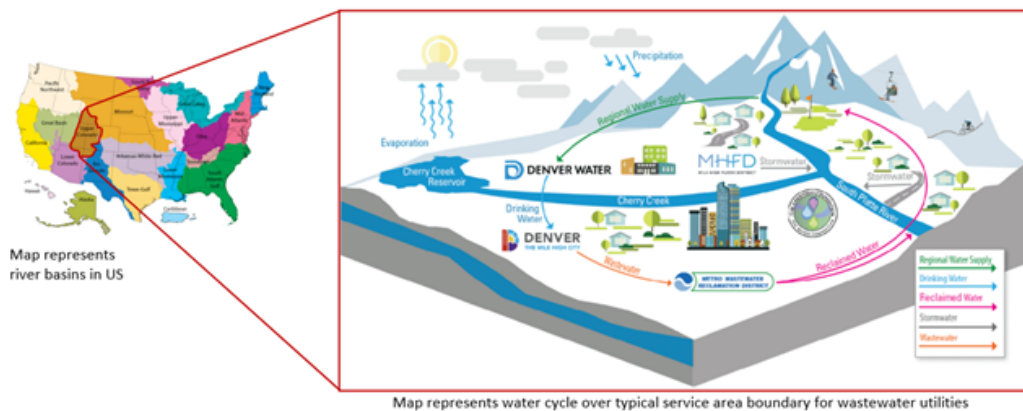


Figure 3.3: Utility service area boundary (right), a subset of natural catchment areas (left)

Pillar 2: Define Sub-systems and Components

The components of a sewershed system can be classified into three sub-systems: natural, built, and social. Each of these sub-systems consists of multiple components and elements. The natural sub-system encompasses all the naturally occurring resources and elements that influence sewershed characteristics, such as water, land, and climate.

The built sub-system includes human-made components developed for wastewater collection, stormwater capture, and treatment infrastructure. Key components within this sub-system are household, commercial, and industrial wastewater infrastructure, as well as stormwater infrastructure.

The social sub-system encompasses factors that affect societal aspects and have an economic impact on a sewershed. This sub-system can be further categorized into community, policy, financial, and economic components.

Figure 3.4 shows a conceptual depiction of a typical sewershed and its subsystems.

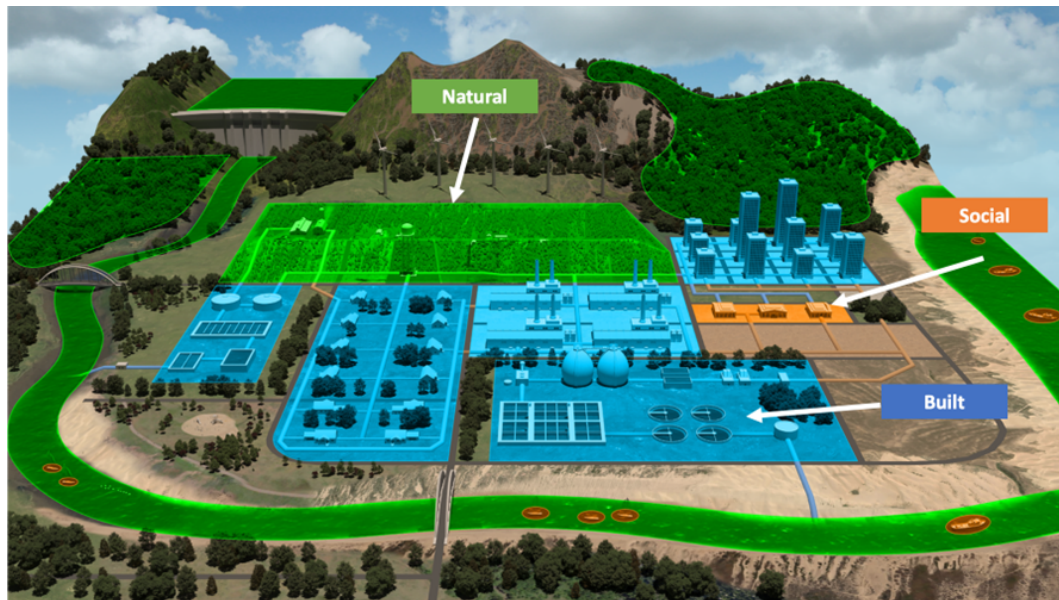


Figure 3.4: Conceptual Depiction of a Sewershed and its Subsystems

These three subsystems can be further categorized as their components. to identify parameters for understanding influencing factors, characteristics, functions, data collection. These different components of sewershed sub-systems are shown in Figure 3.5.

Pillar 3: Define Dependencies and Interdependencies

The sub-systems, components, and elements within a sewershed are interconnected and not isolated from one another. They collaborate within the sewershed system and exhibit various interactions or interdependencies. Understanding these interactions is essential to identify linkages, establish cause-effect relationships, and abstract critical features of the sewershed for modeling and analysis.

Sewershed-Scale System		
Natural Sub-System	Built Sub-System	Social Sub-System
<p>Water: Surface Water (Rivers/ Lakes/ Oceans/ Streams), Groundwater, Runoff Water</p> <p>Land: Land cover, Landfills, Agricultural Activities</p> <p>Climate: Rainfall, Temperature, Extreme Events</p>	<p>Households/ Commercial/ Industrial: Residential and Industrial Waste, Green Roofs, Lateral Pipes, Septic Tanks</p> <p>Wastewater Infrastructure: Gravity and Force Main Pipelines, Valves, Pumps, Manholes, Wastewater Treatment Plant and Resource Recovery Facility</p> <p>Stormwater Infrastructure: Pipelines, Bioswales, Permeable Pavements, Impervious Surfaces, Green Roofs, Rain Gardens</p>	<p>Community: Residential, Commercial and Industrial Customers, Population, Equity and Affordability, Morals, Beliefs and Values</p> <p>Finance and Economic: Revenue, Budgeting,</p> <p>Laws and Policies: Organizational Structure; Governance and Policy; Rules, Codes and Regulations</p>

Figure 3.5: Subsystems of a Sewershed And Their Components

An interdependency between two aspects in the sewershed system is a bi-directional relationship where each aspect relies on the other in multiple ways. In the context of a sewershed subsystem, interdependencies between components or sub-systems are mutual and multi-directional. Each sub-system has interacting components that influence the other sub-system components.

The various interactions shown between components can be categorized into four principal types of interdependencies: physical, cyber, geographical, and logical.

Physical interdependencies are defined as the dependency of one aspect of a system on the material output of the other. In a sewershed boundary, this can be explained with the example of dependencies between the built and natural subsystems where excess runoff leads to CSOs and SSOs, and failure of built assets leads to contamination of water resources.

Cyber interdependencies are defined as the state of a component in the system depending on information transmitted through the information and communication technology (ICT) layer of the system. For water utilities, this would include the sensor network, meters, IoT devices, and other data communication devices.

Geographical interdependencies are defined as the state change of a component is affected by the geographical state of another component.

Logical interdependencies are defined as when two components in the system depend on each other in a way that is not physical, cyber, or geographical. For example, the interaction between lifecycle analysis done on built assets that supports decision-making in the social sub-system that impacts both natural and built components in a sewershed is said to be a logical interdependency.

Figure 3.6 shows the different types of interdependencies between the subsystems within a sewershed.

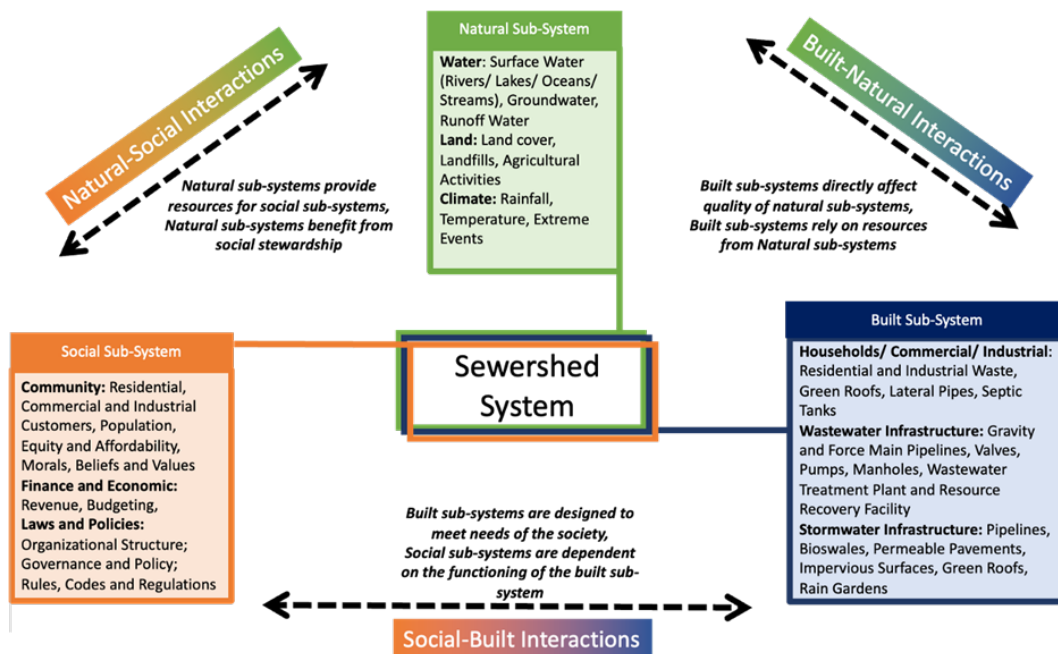


Figure 3.6: Interdependencies between different subsystems within a sewershed

3.2 Planning and Implementation

The Planning and Implementation building block examines approaches to create strategic and implementation plans, which should be implemented before applying the lower level building blocks to ensure proper execution.

Implementing iWISE at a sewershed scale is a substantial and long-term commitment, demanding diverse support throughout the entire project lifecycle to ensure sustainability. Developing strategic planning and implementation plans is crucial for the successful establishment of intelligent water systems in the water and wastewater sector for the following reasons:

- **Goal setting and alignment:** Strategic planning enables water and wastewater utilities to establish their long-term goals and objectives. By incorporating intelligent water systems into their strategic plans, utilities can ensure that their vision aligns with the anticipated benefits and outcomes of these systems. This alignment ensures that the development of intelligent water systems is guided by a well-defined strategic direction, enabling utilities to allocate resources efficiently, prioritize tasks, and make informed decisions during the implementation process.
- **Needs assessment and prioritization:** Strategic planning encompasses conducting a thorough needs assessment to gain insights into the existing challenges, gaps, and opportunities in water and wastewater management. This assessment assists in identifying specific areas where intelligent water systems can make the most significant difference. By prioritizing the implementation of intelligent technologies and solutions based on the identified needs, utilities can optimize resource allocation, maximize benefits, and effectively address critical issues in water management.

- **Resources allocation and budgeting:** Strategic planning enables utilities to allocate resources, encompassing financial, technological, and human resources, effectively for the successful development and implementation of intelligent water systems. By going through the planning process, utilities can identify the essential investments, budgets, and funding mechanisms necessary to support the development, procurement, and maintenance of these systems. This strategic resource allocation ensures sufficient financial backing and empowers utilities to meet the infrastructure, staffing, and technology needs for the successful implementation of intelligent water systems.
- **Stakeholder Engagement and Collaboration:** Strategic planning establishes a structure for involving stakeholders and promoting collaboration. Engaging stakeholders, including customers, community organizations, regulatory bodies, and technology providers, in the strategic planning process allows utilities to gather valuable input, gain support, and foster partnerships. This collaborative approach ensures that the development and implementation of intelligent water systems take into account diverse perspectives, needs, and interests of stakeholders, leading to better acceptance, adoption, and overall success of the initiatives.
- **Phased Approach and Implementation Roadmap:** Strategic planning allows utilities to embrace a gradual approach and create a step-by-step implementation roadmap for intelligent water systems. By dividing the development and implementation process into manageable phases, utilities can minimize risks, address technical and operational challenges in a step-by-step manner, and ensure a seamless transition. The roadmap sets out timelines, milestones, and key performance indicators, guiding the implementation process and providing utilities with a means to monitor progress and make adjustments as necessary.
- **Monitoring and Evaluation:** Strategic planning encompasses methods for monitoring

and assessing the performance and effects of intelligent water systems. By employing predefined metrics and performance indicators, utilities can keep track of the effectiveness, efficiency, and sustainability of these systems. Regular monitoring and evaluation empower utilities to pinpoint areas for enhancement, optimize system performance, and make data-driven decisions to guarantee the continued success of intelligent water systems.

In conclusion, the establishment of strategic planning and implementation plans offers utilities a well-organized framework to define objectives, evaluate requirements, allocate resources, involve stakeholders, and guide the gradual development and implementation of intelligent water systems. By incorporating intelligent water systems into strategic plans, utilities can guarantee alignment with their vision and goals, optimize resource distribution, foster collaboration, and enable efficient monitoring and evaluation. This comprehensive approach leads to the successful implementation and long-term sustainability of intelligent water systems in the water and wastewater sector.

This section outlines the three main pillars of iWISE strategic planning and implementation. The first pillar deals with the creation of a strategic plan. The second pillar addresses the challenges related to the managerial and technical aspects of implementation plans. The third pillar emphasizes the strategies necessary for ensuring the long-term success of the implementation plans. These pillars are depicted in Figure [3.7](#).

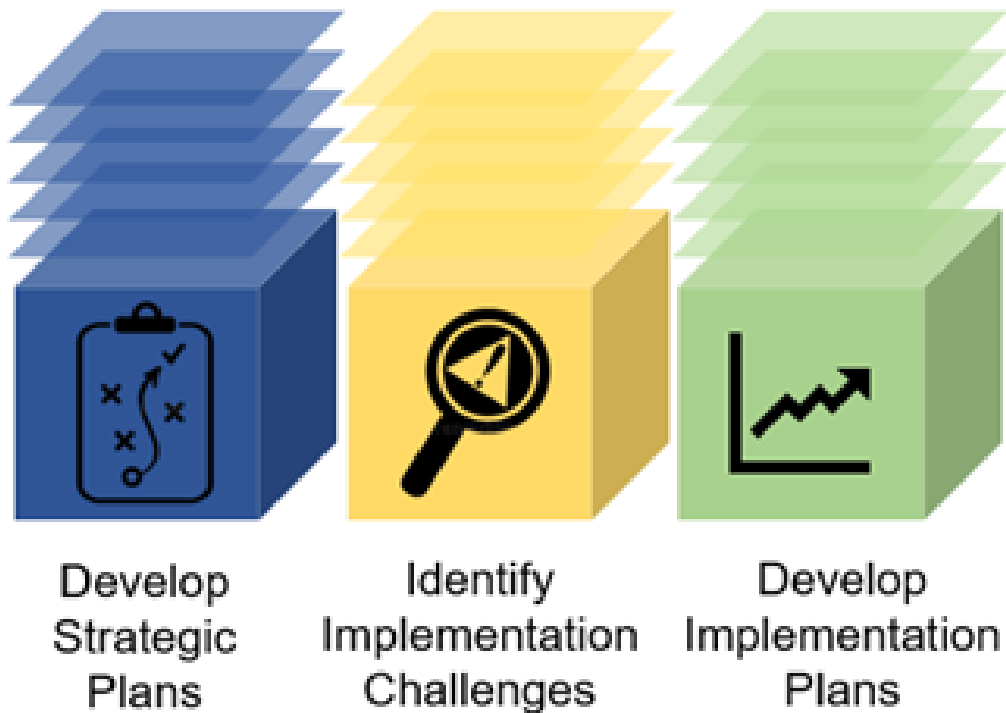


Figure 3.7: Pillars for Planning and Implementation Building Block

Pillar 1: Develop Strategic Plan

Strategic plans serve as long-term visions spanning 5 to 10 years, designed to support Intelligent Water Systems (IWS) operations and management objectives. These plans identify essential strategies that can be applied at a sewershed scale to address crucial technical and institutional requirements. The proposed framework for a strategic plan, as outlined in Figure 3.8, is presented in this research. It's important to note that an IWS program is an ongoing process and is subject to continuous re-evaluation. The suggested components of the iWISE strategic plan should be perceived as a continuous loop with feedback at each stage. Additionally, the strategic plan should outline the frequency and methods for gathering and incorporating feedback.

1. **Definition, Building Blocks, Scope and Benefits:** The utility should establish a

clear definition of what Intelligent Water Systems (IWS) mean to them, tailored to their specific needs. Discussing the unique challenges faced by each utility will emphasize the importance of developing a strategic plan to ensure the successful implementation of IWS solutions. The definitions and building blocks provided in this report can serve as a valuable reference in this process.

2. **Organizational Initiatives:** The necessary organizational changes concerning strategic planning, governance and policy, workforce development, and communication strategies should be thoroughly discussed, strategized, and put into action. During this process, utilities should prioritize the challenges they encounter, which fosters trust among stakeholders during the transition to IWS.
3. **Identify and Assess IWS Technologies:** Utilities should have a comprehensive understanding of existing technologies and keep themselves informed about the latest advancements that can automate repetitive tasks, enhance productivity, and support operational and management decisions. Once a sufficient level of understanding is attained, utilities can address specific problems by selecting the most suitable technological approach for each situation. Regularly updating and maintaining knowledge of available technologies can be achieved by evaluating best practices and studying relevant use cases.
4. **Coordinate and Lead iWISE:** Create action teams and designate main coordinators and leaders to oversee coordination efforts and decision-making. The core team members should be subject matter experts in their respective areas.
5. **Demonstrate iWISE Benefits:** The iWISE implementation teams should develop comprehensive value proposition plans to identify the favorable outcomes and illustrate the benefits to secure the necessary support from stakeholders. Key performance

indicators (KPIs) can be employed to assess and measure these advantages.

6. **Support iWISE Implementation:** To facilitate IWS implementation, enforcement protocols can be established through consensus with stakeholders. This entails identifying and consulting relevant stakeholders to obtain their support and buy-in for IWS policies. Presenting the enabling outcomes and benefits of IWS solutions can bolster this support. It is vital to secure long-term backing from stakeholders, as IWS implementation is an ongoing and continuous process, not a one-time solution.
7. **iWISE Implementation Plan:** iWISE plans are designed for the long-term, necessitating sustainable resource availability for successful implementation. To ensure enduring social support for iWISE plans, a sustainability plan can be devised.

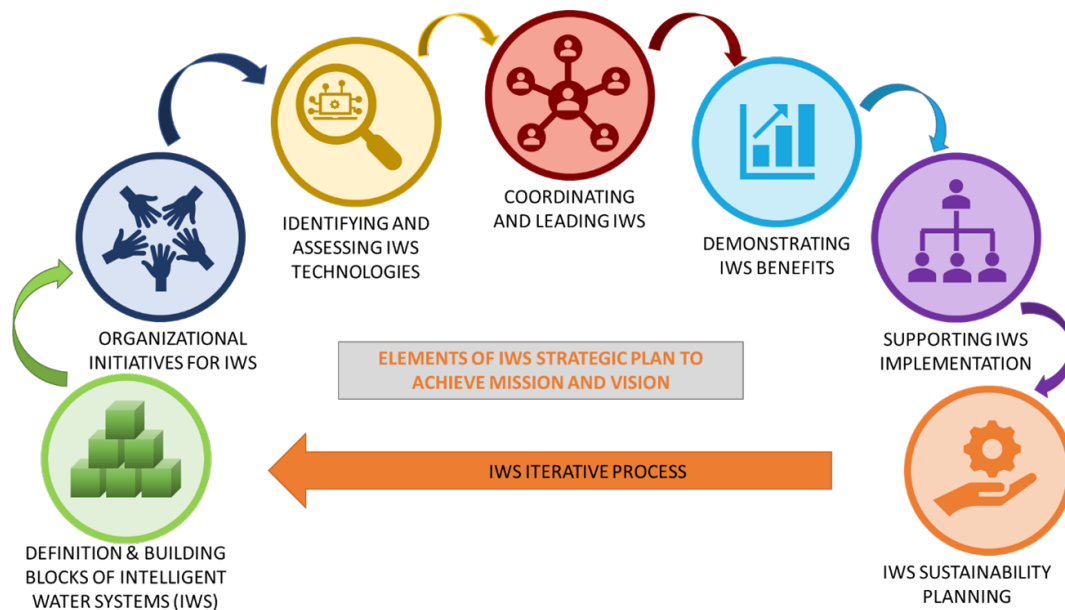


Figure 3.8: Strategic Plan for iWISE Implementation

Pillar 2: Identify Implementation Challenges

In implementation plans, the managerial aspects place significant emphasis on financial matters, contracts, and engagement with diverse stakeholders and customers. Meanwhile, the

technical aspects concentrate on assembling a skilled human workforce proficient in engineering design, operations, data analytics, and decision-making. This section also suggests adopting an iterative approach, wherein utilities progressively construct their implementation plans, guided by the iWISE building-block framework and desired outcomes.

Managerial Aspects

To achieve a successful iWISE implementation, comprehensive management is crucial to meet the satisfaction of all stakeholders. Initially, management must ensure the existence of a well-defined project plan and its adherence throughout implementation. The plan should encompass sufficient detail for all participants to comprehend their responsibilities, timelines for completion, interdependencies among project activities, and the availability of external resources, if needed. The managerial aspects typically involve the following activities:

- Establishing and overseeing contracts with suppliers, system integrators, IT, and communications providers.
- Implementing financial protocols, such as funds disbursement based on completed work.
- Engaging stakeholders to maintain transparent communication regarding iWISE implementation progress and any deviations from the planned schedule, while addressing any concerns they may have.
- Managing relationships with customers and the media, providing appropriate information, both positive and negative, about the project.

The extent of managerial activity required will vary based on the scale and complexity of the iWISE implementation. Factors such as the number and scope of building blocks for the utility and the geographical coverage of the sewershed infrastructure will play a

significant role. Additionally, the number of stakeholders, suppliers, IT, and communications providers involved will also influence the size of the activity. Certain preliminary tasks may be necessary, such as setting up a control center, installing sensors in various locations, or removing and properly disposing of existing sensors.

Technical Aspects

The implementation of iWISE building blocks involves intricate tasks that require utilities to consider appointing an expert to oversee the technological aspects at the sewershed scale. This expert should possess a comprehensive understanding of crucial technical aspects, including the sewershed system, its components, dependencies, and interdependencies, data collection and management tools, modeling techniques (including AI/ML), cybersecurity, and the principles behind reliable decision-making.

To ensure successful implementation of these complex technology tasks, the expert leader should adopt an agile implementation approach. This agile approach for iWISE emphasizes collaboration and communication among the technical and operational teams responsible for implementation. It involves prioritizing and resolving critical issues while concurrently delivering greater value to the utility.

As the iWISE implementation progresses, it will pass through the foundational, organizational, and technical building blocks. These categories will necessitate a multi-disciplinary team, led by the expert, equipped with a diverse range of skills and experience, encompassing system design, operational knowledge, data analytics, decision support, and management.

Pillar 3: Develop Implementation Plans

The agile approach for ensuring long-term success involves conducting frequent, regular, and rapid assessments of progress and utilizing the feedback obtained to enhance the IWS implementation plan. These reviews can occur as frequently as every day or on a monthly

basis for broader stakeholder review. By conducting these reviews, issues and opportunities for course correction can be identified.

To ensure the successful implementation of IWS, it is essential to establish short-term, medium-term, and long-term plans. These plans provide a clear vision and ensure sustained efforts toward IWS implementation.

Near-term actions (for 1-2 year timeframe):

1. Formulate and implement an IWS policy directive that encourages stakeholders in sewersheds to embrace practices facilitating integrated wastewater management across their natural, built, and social sewershed sub-systems.
 - a. The policy directive should require stakeholders to identify value propositions aligned with the context of the communities.
 - The policy directive should outline pathways for communities, offering guidance for their transition towards implementing IWS at the sewershed scale. This includes identifying challenges and improvements, as well as mapping existing and optimized digital and data infrastructure assets.
2. Create a central organization (e.g., an Office of IWS) that operates based on the IWS policy directive and a federated data governance framework. This organization will be responsible for coordinating information exchange and facilitating the involvement of various data hubs in both public and private sectors to establish IWS hubs. While allowing each hub autonomy over its data resources, the organization's primary objective is to foster collaboration among these hubs and leverage global expertise from other organizations to support its establishment.
3. Identify specific use cases and case studies at the sewershed level, where pilot projects

can be initiated to document and assess stakeholder, technical, and organizational strategies for IWS governance and implementation.

Medium-term actions (for 3-5 year timeframe):

1. For efficient implementation of an IWS governance policy directive in sewershed communities, it is advised to establish working groups focused on essential policies, disciplines, and specific geographical areas. Additionally, a decision-making structure should be formed, comprising technical officials and a political steering committee with key representatives who can collaborate and establish a shared understanding of objectives.
2. Determine approaches to transform culture and policies, placing emphasis on digitalization, data sharing, and integration in both public and private sectors. Focus on increasing transparency in the public domain by openly communicating goals, processes, and outcomes related to sewershed data.

Long-term actions (for 5-10 year timeframe):

1. The organizational transformation should prioritize fostering trust through open knowledge exchange between established IWS hubs. This involves sharing best practices and actively engaging in workshop sessions to collaboratively define and refine joint propositions. The focus should be on identifying existing or new challenges and devising short-term, medium-term, and long-term goals and actions to overcome them.
2. Provide sustained support for acquiring reliable data and information to aid in setting goals, managing resources, and implementing governance and implementation strategies in both resource-rich and resource-poor communities across urban and rural regions of the country.

3. Measure and report results through benchmarking at the regional and national level.

The IWS program conducts thorough assessments to verify the accomplishment of short- and long-term deployment objectives. These evaluations assess the effectiveness and advantages of implemented IWS solutions, as well as the return on investments made in the IWS Program. They ensure that progress is being made toward the ultimate vision of integrated IWS. Evaluations are performed in the following four ways:

1. **IWS Performance Evaluation.** Establishes a qualitative and quantitative point of reference for evaluation of implemented IWS solutions. Solutions failing to achieve the performance goals will need countermeasures to achieve success.
2. **IWS Program Evaluation.** Establishes a program-wide point of reference to refine the IWS roadmap.
3. **Knowledge Management.** Turns the wealth of insights and results from surveys and evaluations into a broad and deep knowledge base to support current and future IWS deployments.
4. **Knowledge Transfer.** Develops databases and other easily accessible materials for use in decision-making, training, and providing guidance

3.3 Data Governance

The complexity of sewershed System-of-Systems (SoS) arises from the interdependence of its subsystems and their components. To manage this complexity, a structured approach to collecting accurate data from each subsystem is crucial. This approach enhances the ability to measure, analyze, and effectively manage the system. Thus, a well-structured data collection

process, including identifying data parameters, data sources, and implementing data quality control protocols, is essential for reliable system-level modeling and data analytics. These analytics aid in capturing the interdependent characteristics and developing efficient and resilient models for successful implementation of IWS tasks. This building block outlines the three pillars of data collection for the subsystems and their associated components within the context of SoS, as depicted in Figure 3.9. These pillars detail how to identify required data parameters, locate data sources, and establish data quality protocols.

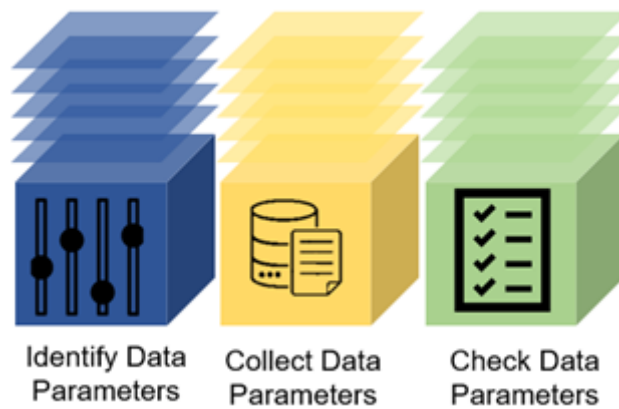


Figure 3.9: Pillars for Data Governance Building Block

Pillar 1: Identify Data Parameters

Having accurate data parameters at the appropriate time enhances the understanding and analysis required for effective sewershed operations. The previous building block's identification of elements provided a structured comprehension of the data parameters essential for reliably measuring these elements within the sewershed system using available technologies for analysis. Figure 3.10 outlines the key areas from which parameters should be collected, encompassing the natural, built, and social subsystems.

The data parameters needed from the natural subsystem's water components primarily focus on measuring the contamination levels of surface water, groundwater, and runoff water

Sewershed-Scale System			
Natural Sub-System	Built Sub-System		Social Sub-System
<p>Water</p> <p>Contamination of surface water, groundwater by discharge and runoff water Inflow & Infiltration</p>	<p>Household/ Commercial/ Industrial</p>	<p>Wastewater Infrastructure</p>	<p>Stormwater Infrastructure</p>
<p>Land</p> <p>Contamination of surface and groundwater due to runoff from landfills and agricultural activities</p>	<p>ASSET INVENTORY</p> <p>Asset ID, Geospatial location and other identification data of all managed assets including but not limited to manholes, gravity pipes, network structures (lift station, siphon, junction box, etc.)</p>		
<p>Climate</p> <p>Frequency and duration of extreme events in the sewershed</p>	<p>ASSET PERFORMANCE</p> <p>Asset current and historical condition and functional adequacy data used to support renewal decisions</p>		
	<p>ASSET RENEWAL</p> <p>Historical information of renewal activities (including forensic data) to identify trends and patterns to support renewal decisions</p>		
	<p>ASSET RISK</p> <p>Consequence of Failure parameters (including TBL impacts) for risk-based renewal prioritization (*Likelihood of Failure parameters are covered in Asset Performance)</p>		
	<p>ASSET FINANCE</p> <p>Costs involved in every stage (design, construction, installation, O&M, renewal & disposal) of the lifecycle of an asset to support comparative analysis of replacement alternatives</p>		
	<p>Community</p> <p>Modeling of system demand and social conditions of the residential, commercial and industrial population of a sewershed</p>		<p>Laws and Policies</p> <p>Analysis of management practices, organizational structure and regulatory impacts on water utility management</p>
	<p>Finance & Economic</p> <p>Life cycle assessment modeling and analysis of sources of funding (community willingness to pay, private and government funding)</p>		

Figure 3.10: Data parameter categories for sewershed subsystem components

characteristics. Likewise, for the land component, the metrics mainly assess the contamination caused by runoff from landfills and agricultural activities in surface and groundwater. Frequency and duration of extreme events in the sewershed are key metrics for the climate component in the natural subsystem.

Regarding the built-layer components, the main parameters to be collected fall into five categories: Asset Inventory, Asset Performance, Asset Renewal, Asset Risk, and Asset Finance. The social subsystem's parameters measure population characteristics, system demand, and revenue from customers within the service area. Additionally, it is important to capture revenue from different sources that fund sewershed operations and the applicable laws and regulations for treated wastewater quality and CSO/SSO events in the finance and economic domain of the social layer.

A comprehensive list of essential, preferable, and desirable parameters has been prepared to assist utilities in conducting a comprehensive analysis of sewershed management. These parameters have been categorized into natural, built, and social subsystems, accompanied by metadata, and organized based on their importance. The list is available in Appendix A.

Pillar 2: Collect Data Parameters

The collection and compilation of big data to facilitate the transition to IWS introduce complexities related to the "5 V" characteristics:

1. Volume (size) - the sheer amount of data to be managed.
2. Variety - dealing with both structured and unstructured data.
3. Veracity - ensuring data reliability and determining its origin.
4. Value - leveraging data for various analytical purposes such as predictive analytics, statistical analytics, correlations, hypothesis testing, etc.
5. Velocity - handling data in real-time, near-real-time, batch processing, and streams.

The importance of data sources lies in their influence on data quality. Understanding data sources becomes crucial in comprehending data complexity, identifying relationships between datasets, and establishing rules for data integration and preprocessing, as explained in pillar 3. The various categories of data sources and their corresponding metadata information are depicted in Figure 4.5. This figure illustrates the categorization of data from different sources within a sewershed and outlines the specific metadata that should be collected for each type of data source.

Pillar 3: Check Data Parameters

Quality assurance/quality control measures involve assessing the accuracy and precision of collected data. Quality assurance (QA) encompasses a comprehensive plan for maintaining quality across all aspects of a program. This plan outlines protocols for data collection, including proper documentation of procedures, workforce training, study design, data management, analysis, and specific quality control measures. On the other hand, quality control















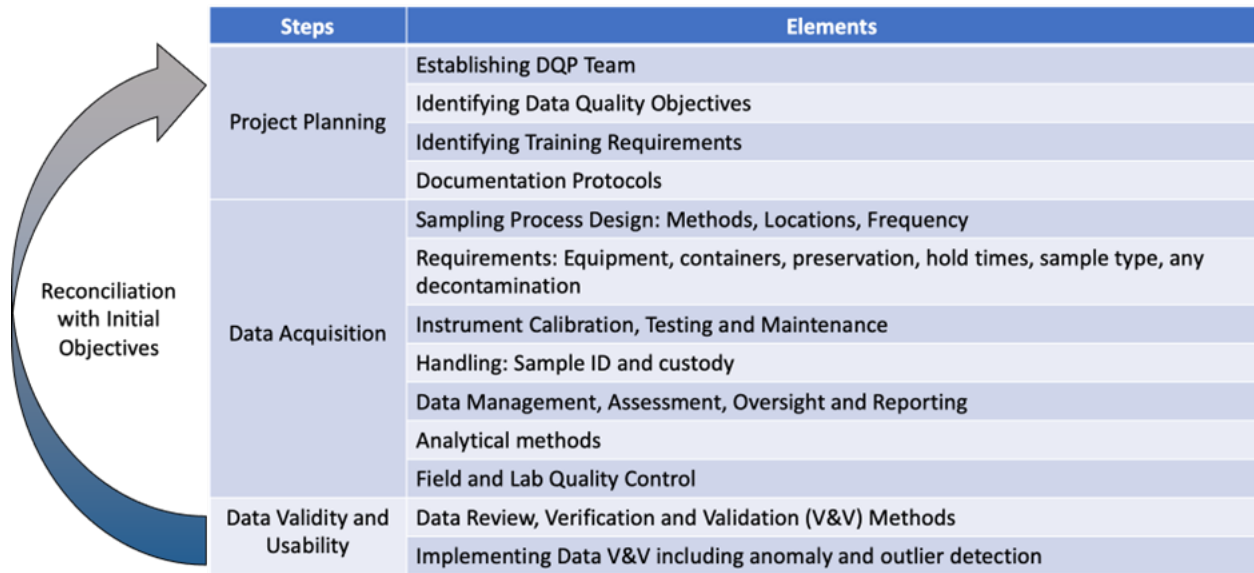
	Metadata	Sources
Utility Instrumentation Data	<ul style="list-style-type: none"> • Purpose of installing/using the device • Measurement characteristics: Resolution, measurement unit, measurement principle, data velocity (static, real/near-real time), historical outliers • Signal characteristics for recording, transmission, and storage. This can also indicate historical anomalies in signal patterns for O&M. • Hardware: Manufacturer, Sensor model • Cost: Installation Costs, Maintenance Costs • O&M: Installation Date, Maintenance Records, Historical Failure 	 CCTV  Meters  Sensor  Other IoT Devices
Utility Operational Data	<ul style="list-style-type: none"> • Purpose of collecting utility data • Privacy: Identification of access levels for different stakeholders and privacy levels within organization • Consistency: The interoperability of datasets from different platforms (which may contain lab generated, machine generated or manual data) need to be evaluated in terms of ease of integration into other datasets for analytical purposes. • Standardization and Preprocessing Needs: The preprocessing required to prepare integrated datasets for analytics. 	<ul style="list-style-type: none"> • Enterprise Asset Management (EAM) • Workforce data • Laboratory Information Management System (LIMS) • Geographic Information Systems (GIS) • Sample Manager • Supervisory Control and Data Acquisition (SCADA) platform • Hydraulic Modeling Platform • Pipe information system • Customer Data
External Data	<ul style="list-style-type: none"> • Purpose: This requires a needs analysis of data for supporting dataset creation and enabling more complex parameterized models for complex analysis. • Database selection: Identification of most reliable and consistent data sources from sources. • Preprocessing Needs: Many external sources exist in a variety of formats often dated due to legacy platforms. These needs more processing to bring it to consistent standards. 	 USGS  National Wetland Inventory  EPA  CSO/SSO Regulations  NCLD and Soil Characteristics  NOAA  CDC  United States Census Bureau  Testing Protocols and Disease Outbreak Data  Socio-economic Data

Figure 3.11: Data sources and their corresponding metadata

(QC) involves validating specific sampling and analytical procedures to ensure their validity. Additionally, a quality assessment can be conducted to verify the overall precision and accuracy of the collected data after performing the analyses.

The IWS framework proposes a step-by-step approach, as shown in Figure 3.12, to develop comprehensive Data Quality Plans (DQPs) that can be applied to various sub-system data management tasks in Intelligent Water Systems at a sewershed scale. DQPs can be categorized for different stages of the data lifecycle, such as data collection project planning, data acquisition, and data validity and usability stages. The Project Planning step involves tasks like establishing a DQP team, identifying data quality objectives, and defining training requirements and documentation protocols. The Data Acquisition step includes making decisions on sampling methods, the need for equipment calibration and testing, and establishing oversight requirements and responsibilities. The Data Validity and Usability step includes defining protocols for data review, verification, validation, and detecting anomalies and outliers.



Steps	Elements
Project Planning	Establishing DQP Team
	Identifying Data Quality Objectives
	Identifying Training Requirements
	Documentation Protocols
Data Acquisition	Sampling Process Design: Methods, Locations, Frequency
	Requirements: Equipment, containers, preservation, hold times, sample type, any decontamination
	Instrument Calibration, Testing and Maintenance
	Handling: Sample ID and custody
	Data Management, Assessment, Oversight and Reporting
	Analytical methods
Data Validity and Usability	Field and Lab Quality Control
	Data Review, Verification and Validation (V&V) Methods
	Implementing Data V&V including anomaly and outlier detection

Figure 3.12: Data quality protocols

3.4 Data Analytics

Modeling and analyzing IWS at the sewershed scale is a complex and multifaceted task that requires a deep understanding of various dimensions involved. These dimensions encompass the level of application (system, sub-system, element), the domain of insights (informational, engineering, management), and the mathematical approaches employed (deterministic, probabilistic, and AI), among others. Gaining a comprehensive knowledge of the specific techniques and problem areas in a sewershed context lays a strong foundation for developing new models. Additionally, implementing robust verification and validation (V&V) protocols for these models enhances the reliability of the results, provides insight into the model’s decision-making process, and instills confidence in utility decision-makers regarding the model’s efficacy. This building block elaborates on the three pillars, which involve identifying existing analytical and modeling techniques, understanding modeling dimensions, and conducting model verification and validation, as depicted in Figure 3.13.

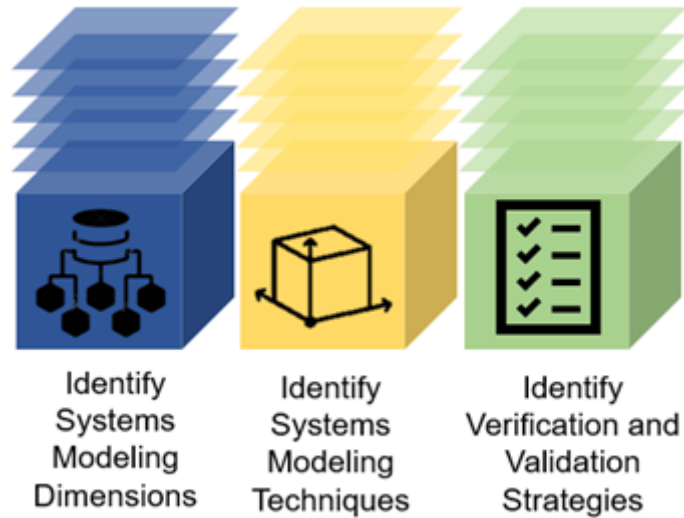


Figure 3.13: Pillars for Data Analytics Building Block

Pillar 1: Identify Systems Modeling Dimensions

Diverse modeling techniques are employed to analyze sewershed operations and extract meaningful insights to facilitate informed decision-making. These models also encompass the interconnectedness of various components through model parameters, weights, and rules. It is essential to comprehensively capture these interdependencies based on a thorough review of existing literature and industry practices, as depicted in Figure 3.14. This figure illustrates the diverse analytical techniques and relationships explored in sewershed modeling endeavors.

Models have been developed using various techniques for different components within a sewershed. These modeling efforts have focused on areas such as surface water contamination resulting from CSOs/SSOs, among others, employing a wide range of techniques. The models have been crafted to address the system level (sewershed), sub-system level (natural, built, and social), and component level (e.g., surface water, wastewater pipes, public perception). Figure 3.15 presents a compilation of the various analytical and modeling focus areas for the different components within each sub-system.

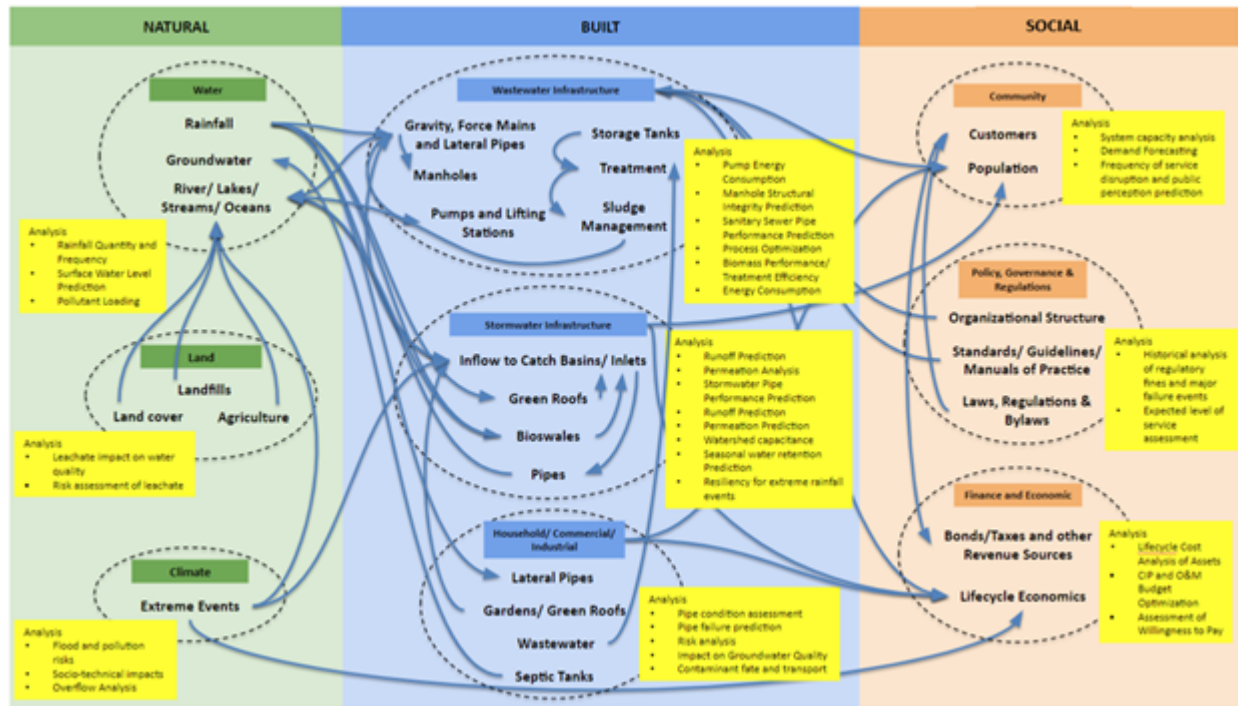


Figure 3.14: Different modeling techniques used in practice

In the natural subsystem, typical areas of modeling include wastewater quality analysis, rainfall quantity and frequency analysis, contaminant fate and transport, examination of leachate and its impact on groundwater quality, and assessments of the impacts of extreme climate events.

Within the built subsystem, key areas of modeling involve asset performance, asset renewal, asset risk, and asset finance modeling.

For the social subsystem of a sewershed, critical modeling areas encompass lifecycle economic assessments, analysis of public perception and feedback, as well as the social impacts of policy, governance, and regulations.

A comprehensive list of modeling techniques developed in literature and used in practice has been prepared to assist utilities in identifying the best practices for modeling the various components and processes for sewershed scale wastewater management. These modeling

techniques have been categorized into natural, built, and social subsystems, accompanied by their focus area, parameters required and the model type. The list is available in Appendix B.

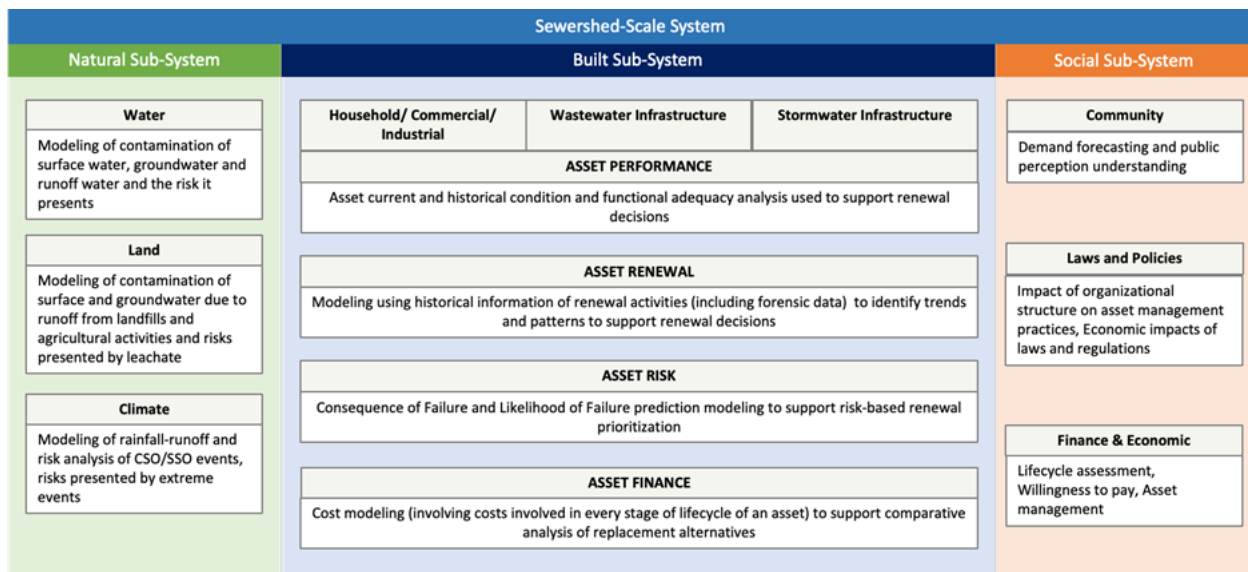


Figure 3.15: Different focus areas for modeling the various subsystems of a sewershed and their components

Pillar 2: Identify Systems Modeling Techniques

Modeling is a complex task that can be performed in a variety of ways depending on the problem being solved and which can be represented in the form of different techniques. Figure 3.16 demonstrates that a modeling strategy must start with the identification of the different techniques of modeling available.

When selecting a model for a sewershed system, several viewpoints should be considered. One perspective is the level of analysis, ranging from individual component-level to a system-level, as the sewershed system is a complex System of Systems (SoS).

Another important aspect is the domain of insights provided by the model, which can be categorized as informational, engineering, or management. Informational-level analyses deal with

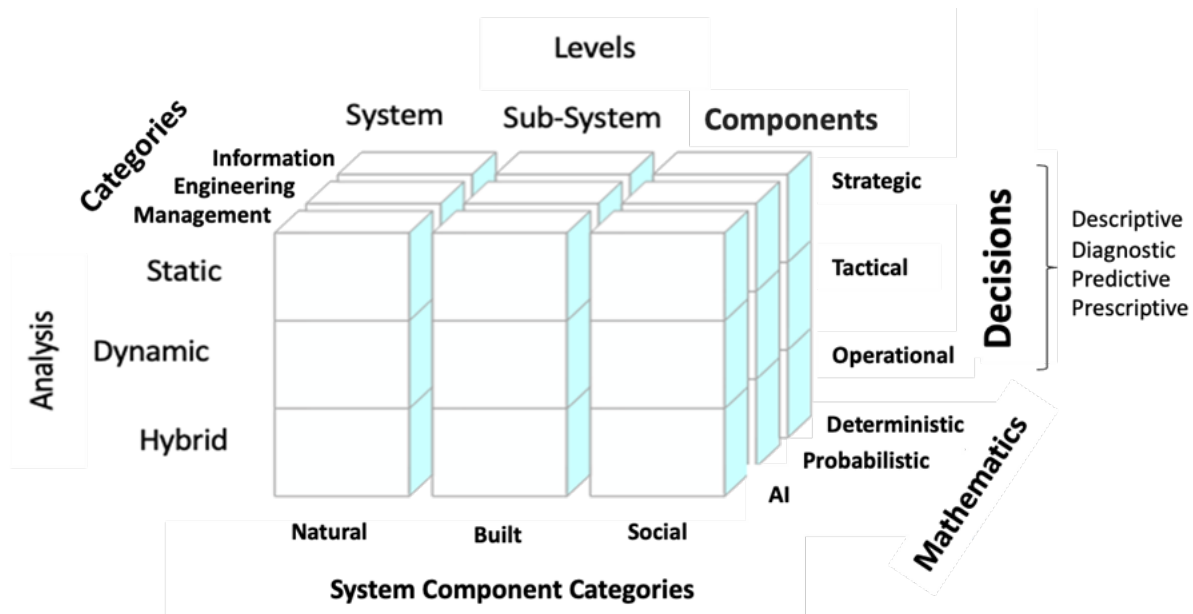


Figure 3.16: Modeling techniques, dimensions and methods

higher-level abstractions and provide basic system-level information, such as pipe mileage distribution. Engineering-level analyses involve specific and technical aspects of the built sub-system, like asset-level finite element models for structural performance, and natural sub-system analyses. Management-level analyses focus on generating information useful for utility managers, such as economic predictions and renewal prioritization.

Models can also be classified based on the decision domains they support, including strategic-level models for long-term decisions, tactical-level models to identify problem areas, and operational-level models for individual asset analysis.

The decision objectives of the modeling exercise can be categorized as descriptive, diagnostic, predictive, and prescriptive. Descriptive models provide a comprehensive view of the system, diagnostic models help identify the causes of issues, predictive models offer forecasts and projections, and prescriptive models recommend actions to achieve specific outcomes.

Furthermore, the mathematical techniques employed for modeling need to be determined,

which include deterministic, probabilistic, and AI methods. Deterministic models are formulaic and provide a fully determined output based on parameter values and initial conditions. Probabilistic models incorporate randomness and produce a range of outputs with a given confidence level. AI methods, such as expert systems and machine learning algorithms (e.g., Artificial Neural Networks, regression, random forest), learn from data and improve abstractions over time.

Finally, models can be described based on the sub-systems within a sewershed, which were defined earlier as natural, built, and social subsystems.

Pillar 3: Identify Verification and Validation Strategies

Modeling involves creating a simplified representation of the real world, and during this process of abstraction, there is a possibility of introducing inaccuracies. Verification and validation (V&V) is a systematic approach used to test whether the abstraction process was carried out correctly and if the model effectively addresses the problem. V&V serves several purposes and helps users understand the following aspects:

- **Model's internal logic:** This helps identify whether the model works as it was intended by the modeler.
- **Quantifying uncertainties:** This helps measure whether the developed model can measure the intended metric more precisely.
- **Model stability and robustness:** This can help identify scenarios where the model fails to accurately represent the intended system.

The accuracy of models depends on the quality of the data and knowledge used to develop them, and they cannot be expected to be more accurate than the errors present in the input and observed data. Since the measurements used for describing and evaluating a

model are problem-specific, there is no universally accepted statistic or test to validate a model. Typically, a combination of methods such as expert review, graphical comparisons, and statistical tests is employed, using both quantitative and qualitative measures. This approach is often referred to as the "weight-of-evidence" approach. The overall process for verification and validation (V&V) during the modeling process is depicted in Figure 3.17.

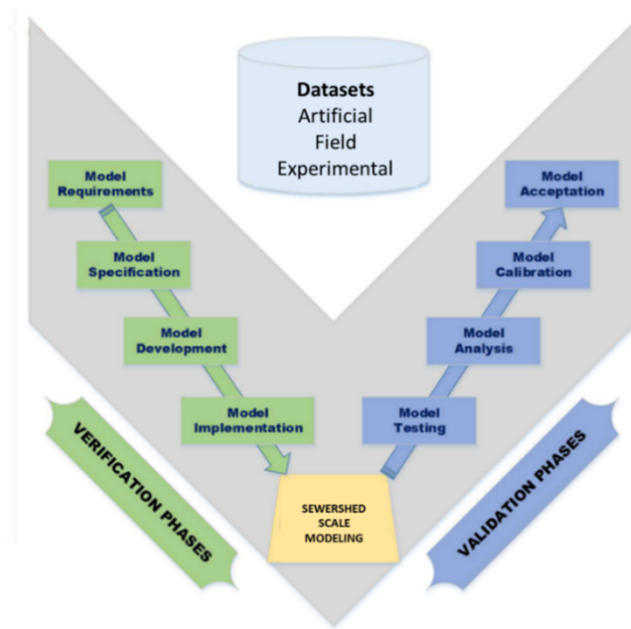


Figure 3.17: Model verification and validation process

V&V can be viewed as an ongoing feedback loop aimed at continuously calibrating and enhancing the model as part of the model governance cycle, rather than a simple pass/fail test. As a first step, it is crucial to ensure the model's foundational setup is accurate. Verification involves confirming whether the model was implemented correctly according to the intended design. This process may include software checks, debugging, and validating the model logic. For sewershed-scale models, internal verification can be performed through various methods, some of which are as follows:

- Checking model logic: Using artificial data and common knowledge for checking whether

best, moderate, or worst input values represent the best, moderate, and worst results, respectively.

- Checking parameter influence: This can be performed using techniques such as sensitivity or correlation analysis of input and output parameters to measure the influence of parameters on the final model output.

While verification can be conducted using artificial data and expert opinions, model validation demands the use of ground truth metrics to establish reliability, accuracy, and confidence in the model. This can be achieved through the following methods:

- Establishing ground truth metrics: The data used as the input to the model as well the final model output should be represented using the best measurable metric. Here, measurability is based on the availability of resources in the form of domain experts, specialized equipment, and time. The chosen metric, especially the model output, should accurately capture the intended purpose of the model to establish real-world usability.
- Competing methods: The chosen output metric can be measured using laboratory tests or a previously validated model developed by the utility or found in scientific publications. Generally, laboratory tests are considered more robust as they can provide accurate measures with robust protocols. However, one disadvantage of laboratory tests is that testing in a laboratory setting represents a closed system and may be too simple to represent the real-world environments.
- Statistical and graphical tests: The results from the developed model and the competing methods can be compared using qualitative contextual information and quantitative statistical or graphical tests to establish reliability and accuracy of the proposed models.

3.5 Decision Support System

Creating Decision Support Systems (DSS) is essential to extract value from data collection and modeling efforts, ultimately aiding in the management of sewershed systems. This building block focuses on three key pillars of the decision support process, depicted in Figure 3.18. These pillars involve techniques for developing a robust DSS, implementing effective visualization methodologies, and ensuring the trustworthiness of Intelligent Water Systems (IWS) applications.

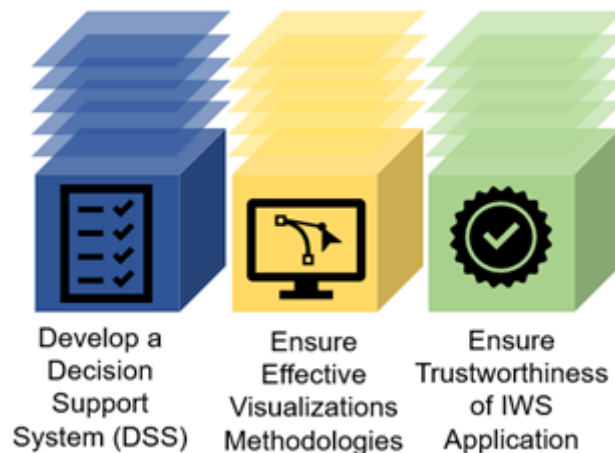


Figure 3.18: Pillars for Decision Support System Building Block

Pillar 1: Develop a Decision Support System (DSS)

Several approaches can be utilized for a decision-making process. However, to decide whether a DSS needs to be developed, a utility can consider the following aspects:

- **Level of complexity:** A higher level of complexity in a problem, system, or decision calls for the implementation of a Decision Support System (DSS). Given the intricate nature of a sewershed as a complex system, the use of a DSS becomes essential to enhance decision-making capabilities in managing its operations.

- **Need for timely decisions:** In situations where the decision-making process is straightforward, a Decision Support System (DSS) may still be necessary to handle frequently occurring issues that demand quick and immediate decisions.
- **Expertise availability:** Having a readily available pool of diverse experts may render a Decision Support System (DSS) unnecessary. However, in many cases, especially when dealing with complex and interconnected impacts of wastewater-related problems, this is not the norm.
- **Specificity required:** Having a readily available pool of diverse experts may render a Decision Support System (DSS) unnecessary. However, in many cases, especially when dealing with complex and interconnected impacts of wastewater-related problems, this is not the norm.

”Human-In-The-Loop” Decision Support

A Decision Support System (DSS) designed for sewershed level decisions can offer various levels of outputs, impacting the choice of visualization tools and DSS complexity. It is essential for utilities to maintain a ”Human-in-the-loop” approach, where human intervention is required at each stage of the DSS workflow, as depicted in Figure 3.19. This ensures the reliability of the decisions made by the DSS and prevents full autonomy.

Pillar 3: Ensuring Effective Visualizaiton Techniques

To determine the optimal visualization approach, it is crucial to gain a comprehensive understanding of the problem’s nature and how a DSS can effectively support its resolution. Factors to be taken into account include the organizational structure and culture, the reliability and accuracy of available information, the associated risks, and the specific characteristics of the problem at hand.

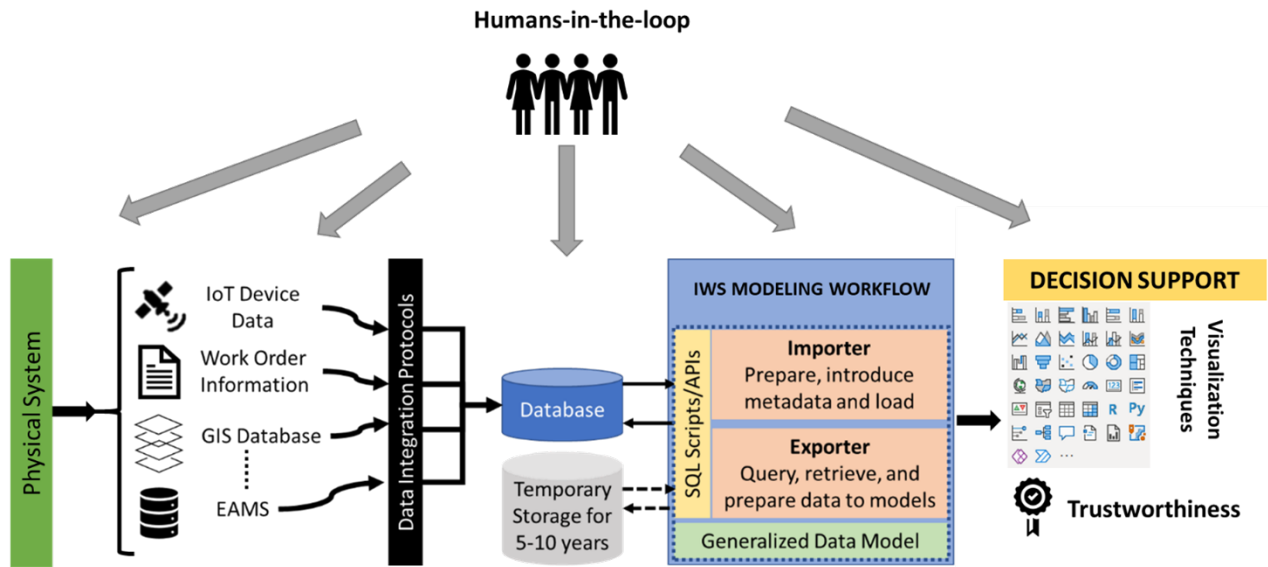


Figure 3.19: Human-in-the-loop decision making workflow

Visualization methods employed in Decision Support Systems for sewersheds can effectively present model-derived information to utility operators, aiding them in making informed decisions. Utilities commonly utilize a range of visualization techniques, including the following:

1. **Geographic Information System (GIS):** GIS software facilitates the integration of diverse spatial data layers, encompassing wastewater infrastructure networks, sewer lines, treatment plant locations, and sensitive areas. Through GIS, interactive maps, spatial analysis, and modeling can be generated, supporting decision-making processes concerning wastewater system planning, asset management, and environmental impact assessments.
2. **Data Visualization Software:** Visualization software allows for the generation of charts, graphs, and interactive dashboards to illustrate wastewater-related data. These tools provide an intuitive means to examine trends, patterns, and relationships in parameters such as flow rates, pollutant concentrations, treatment efficiency, and water

quality.

3. **Process Flow Diagrams (PFDs):** Process Flow Diagrams (PFDs) are visual representations that depict the flow of wastewater and the processes engaged in its treatment. These diagrams utilize symbols, arrows, and labels to illustrate the different treatment steps, equipment, and control systems involved. PFDs are valuable tools for visualizing the complete wastewater treatment process, aiding in comprehension, optimization, and problem-solving.
4. **3D Visualization and Modeling:** Three-dimensional (3D) visualization and modeling tools are utilized to present wastewater treatment plants and associated infrastructure in a realistic and interactive format. With these tools, virtual walkthroughs of treatment processes can be conducted, equipment layouts can be visualized, and operational scenarios can be simulated. They are valuable for design, planning, and training purposes.
5. **Time Series Visualization:** Time series visualization techniques are employed to examine and present data collected over time for a sewershed. Line charts, area charts, and stacked area charts are frequently utilized to illustrate trends, variations, and irregularities in parameters like flow rates, pollutant concentrations, and treatment efficiency across different time intervals.
6. **Interactive Web-based Platforms:** Web-based platforms and tools are employed to develop interactive visualizations that can be accessed and shared online. These platforms often combine data from various sources, enabling users to explore layers of wastewater-related information, such as treatment plant locations, effluent quality, and compliance with regulatory standards.
7. **Real-time Monitoring and Control Systems:** Sophisticated visualization tools are

utilized alongside real-time monitoring and control systems in wastewater treatment facilities. These tools offer real-time graphical representations of process variables, alarms, and trends, enabling operators to monitor the system's performance, make well-informed decisions, and promptly address any issues that may arise.

8. **Virtual Reality (VR) and Augmented Reality (AR):** Virtual Reality (VR) and Augmented Reality (AR) technologies are gaining traction in the wastewater industry. They are used to create virtual simulations of wastewater treatment processes and plant environments, offering immersive and interactive experiences for training, optimization, and maintenance purposes.

Pillar 3: Ensure Trustworthiness of IWS Application

Trust plays a crucial role in the decision-making process for managing sewersheds. While humans have relied on machines for decision-making for a considerable time, the introduction of new technologies in the wastewater sector adds complexity and necessitates a level of trust with users to foster a cultural shift and facilitate the digital transformation.

The European Union has provided clear guidelines for designing and developing trustworthy AI systems. However, these principles extend beyond AI trustworthiness and can be applied to ensure trust in the application of any Decision Support System (DSS) for sewershed management. To ensure trustworthiness, utilities should adhere to the following four ethical principles:

1. **Human Agency and Oversight:** Decision Support Systems (DSSs) should be designed to enhance the decision-making process and empower human beings rather than completely replacing them. The level of autonomy of the DSS should be determined by the risk and potential impact of incorrect decisions. By doing so, humans remain an integral part of the decision-making loop and maintain control over the process.

2. **Prevention of Harm:**

- (a) **Technical Robustness and Safety:** Decision Support Systems (DSSs) should exhibit accuracy and reliability, fulfilling their intended tasks effectively. They must demonstrate robustness to handle errors in data and modeling workflows, as well as security measures to protect against external threats. Additionally, DSSs should ensure the reproducibility of their results, providing consistent and dependable outcomes.
- (b) **Privacy and Data Governance:** To maintain the confidentiality of sensitive data used in sewershed management, strict governance and controls must be implemented throughout the workflows to prevent any unauthorized or improper use of the data.
- (c) **Societal and Environmental well-being:** DSS should not cause any harm to society, and the natural environment in which it is supposed to be used.
- (d) **Accountability:** The decisions from the DSS should be justified. Accountability also demands that a proper mechanism or structure should be followed through which people are responsible for the correct and incorrect judgments delivered by the DSS.

3. **Fairness:** a. **Diversity, Non-Discrimination and Fairness:** DSSs should treat all sections of society equally without any form of discrimination. It should also ensure that the DSS and its services are available or applicable to all the entities of society.

4. **Explicability:** Transparency refers to the explainability, interpretability, and reproducibility of decisions. Transparency should be ensured in the following steps in the workflow:

- (a) **Transparency in Inputs:** The data collected and compiled in utility database

should be justified with details like how the data was collected, processed, and organized.

- (b) Transparency in Outputs: The performance of DSSs will be based on the reliability of data. Utilities should perform sufficient testing to assess the generalizability and efficiency of the DSS.
- (c) Transparency in Interpretations: There are many different stakeholders in a watershed. As utilities strive to create more informative dashboards for different stakeholders, it should be ensured that the DSS outputs are interpretable by all potential viewers of the dashboard.

Chapter 4

Results

In this section, we will answer the three research questions presented in this work that support the development of the iWISE Framework.

To verify and validate the framework, we conducted pilot interviews and developed questionnaires that were sent to utilities across the United States to obtain feedback from a real-world perspective. The objective of conducting these interviews and questionnaires was to capture the current intelligent water practices in utilities, understand the challenges they face and see how willing they are to implement intelligent water practices to tackle these challenges.

The questionnaires developed were based on each of the building blocks proposed in this framework. The questionnaire was designed to be discussed with the research and innovation officers of water utilities. However, it was found that many small, medium, and even some large utilities did not have dedicated staff responsible for research, innovation, or implementing Intelligent Water Systems (IWS). In this section, we will present the results and analysis derived from the questionnaire responses obtained from various water utilities across the country. To accommodate the varying levels of resources available within utilities, the target utilities were categorized into three segments: Small utilities, Medium utilities, and Large utilities. The water and wastewater systems in the United States exhibit diverse characteristics and face different challenges due to variations in customer base, wastewater volume, infrastructure complexity, and regulatory oversight.

- **Small Utilities** - Small water utilities generally cater to populations of fewer than 50,000 and are commonly found in rural regions. They typically have less complex treatment processes and distribution systems, with a smaller number of wells, pumps, and storage tanks. Challenges faced by small utilities include geographical location, availability of workforce, and financial funding mechanisms. These utilities may be managed by local governments, private companies, or cooperatives, and they may encounter difficulties in securing funding and sustaining their infrastructure.
- **Medium Utilities** - Medium water utilities generally cater to customer bases ranging from 50,000 to 250,000 and are situated in suburban areas or smaller cities. They possess a more extensive wastewater infrastructure system compared to small utilities, comprising multiple water supply sources, treatment plants, and storage facilities. Typically managed by public agencies, such as municipal or county governments, medium utilities are subject to regulatory oversight and reporting obligations.
- **Large Utilities** - Large utilities cater to populations exceeding 250,000 and are located in larger cities or metropolitan areas. These utilities possess intricate treatment processes and distribution systems, comprising multiple water supply sources, treatment plants, and storage facilities. The size and complexity of large utilities can present challenges in effectively managing their infrastructure and meeting the diverse needs of their customer base. However, their larger scale often allows them to have more resources available for implementing advanced technologies, such as AI/ML, to enhance their operational efficiency and decision-making processes.

For small utilities, where resources and knowledge of intelligent water practices might be limited, online responses were not sought. Instead, the questionnaires were discussed during 1-hour long workshops, providing an opportunity for the research team to gain insights into

the perspectives of small utilities regarding current and future IWS implementation.

Medium utilities, on the other hand, were invited to participate in the survey through brief online conference calls with utility experts who had some experience in data analysis.

For large utilities, the questionnaire was shared with the teams responsible for managing sewershed operations, which often included staff members working on IWS applications, including AI/ML.

In cases where the responses were unclear or inadequate, follow-up meetings were conducted with key contacts from the utilities to ensure the quality and reliability of the collected data for analysis.

General information was collected from utilities and it was found that all those who responded were public utilities. Out of all the participating utilities, 2 were small utilities, 3 were medium utilities and 14 were large utilities. The distribution of utilities who filled the questionnaires by scale is depicted in Figure 4.1.

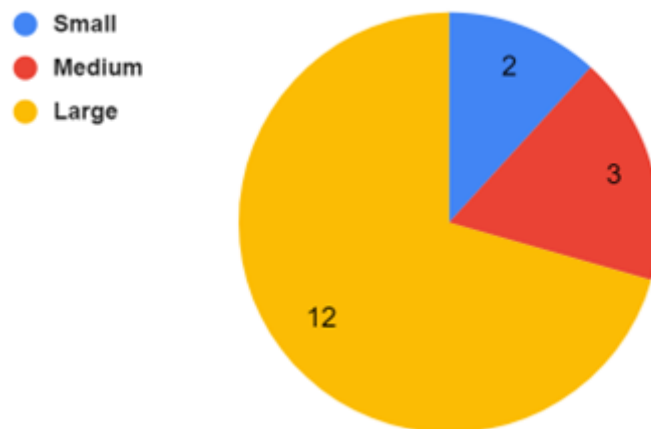


Figure 4.1: Distribution of utilities by scale

4.1 RQ1: Are utilities currently implementing intelligent water practices, and to what degree?

The aim of this research question was to investigate to what level utilities are currently implementing intelligent water practices in their sewer shed management. Through the questionnaire, utilities were asked what stage they would evaluate themselves at in terms of iWISE implementation and were as follows:

- Preliminary: The level before any significant steps are taken toward implementing digitization. Exploring the options, developing a strategy, and conducting isolated pilots to test technology and processes.
- Intermediate: Having a clear utility-wide strategy and investing in pilots based on the strategy. Merging technologies and processes across the utility and demonstrating cross-functional measurable benefits.
- Advanced: Fusing information across the utility and potentially beyond the utility (e.g., customers, regulators) to increase measurable benefits. Innovating as an industry leader.

The distribution of responses from utilities is shown in Figure 4.2.

With respect to the scale that specifies the level of iWISE implementation that utilities fall under, smaller systems see themselves in the basic to preliminary stage of the ‘digital transformation’ journey where they are exploring options and developing strategies for implementing some technical aspects like data collection, modeling, visualization platforms, data governance, and cybersecurity.

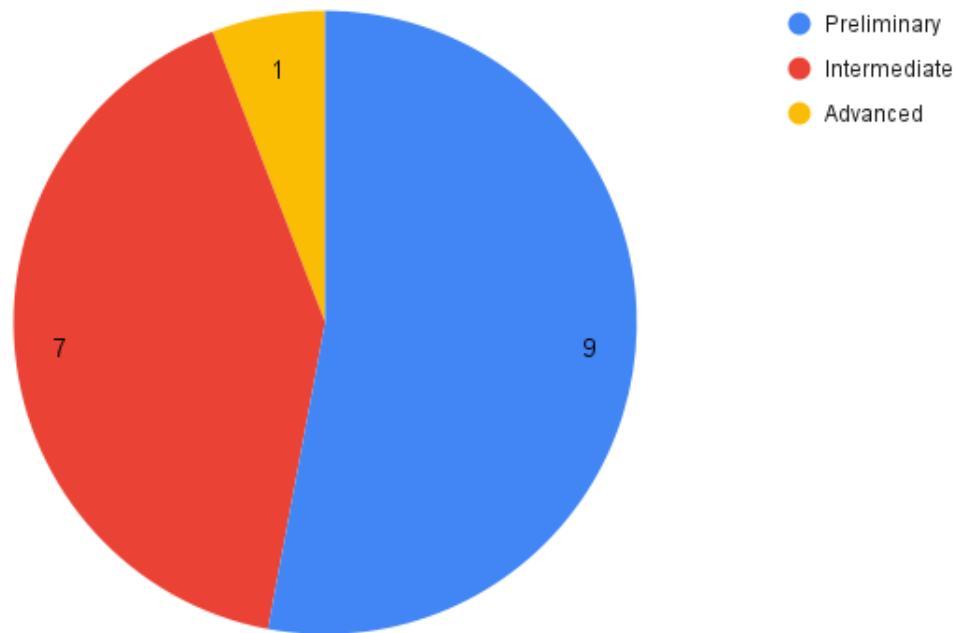


Figure 4.2: Level of implementation of iWISE across utilities

With respect to the scale that specifies the level of iWISE implementation that utilities fall under, medium utilities are in the preliminary to intermediate stage of the ‘digital transformation’ journey. They have some practices that support their efforts to implement new technologies and practices but face some challenges that oppose these efforts.

Large utilities usually have the budget for implementing new technologies and investing in intelligent water practices. The current level of implementation of intelligent water practices across large utilities falls under the intermediate to proficient level, as per the specified scale in the iWISE framework.

With respect to the technical building blocks discussed in this study, the maturity level of utilities at different scales was evaluated through the questionnaires shared and interviews conducted. The findings of these interviews and the responses of utilities from the questionnaires are discussed as part of sections 4.2 and 4.3.

4.2 RQ2: How do utilities of different scales compare to each other in terms of IWS implementation?

Small utilities recognize the benefits of implementing smart and intelligent technologies in their systems and are not opposed to taking up such projects to enhance their sewer shed operations. Since small systems identify the benefits that intelligent water systems have to offer, funding these projects can also be justified, which can further support efforts to finance such projects. When it comes to data collection, small utilities only collect data that is process specific and required by regulations for them to collect. They mainly collect data from the built and natural systems that belong to their service area, and only collect data from outside their service area based on specific project requirements. Their analysis and data collection are governed by day-to-day requirements, with no long term applications and is limited to built component level analysis that supports decision making for specific built assets only. They make use of GIS to visualize data which is considered as a preliminary level visualization. The findings from the interviews conducted with small utilities show that they do not have a separate visualization decision support platform. All these practices further confirm that the efforts of small utilities with respect to the iWISE framework fall in between the basic to preliminary level of iWISE implementation.

Medium sized water utilities are located in suburbs or smaller cities, they may have many small utilities in nearby towns and rural areas. As a result, they recognize the importance of collecting data of influencing factors from natural systems that fall outside their built service area for specific tasks like water contamination levels to protect downstream areas. Their data collection is fairly preliminary as they only collect what is required for analysis of specific assets within their service area. Their databases are generally siloed and are not automated, they manually integrate data as and when required for specific applications. They

do not have automated data lifecycles or interoperability for their database information systems. Their decision-making aid them in both enduring and daily decision-making, and their models provide them with understanding for both their overall sewershed performance and individual built assets. This assists them in forming strategies not only for daily activities but also for the enduring viability of their operations and the integration of novel technologies aimed at enhancing the resilience of their infrastructure. Some of the participating medium utilities had decision support systems in place while others do not. Medium utilities acknowledge the necessity for a cultural transition within their workforce to establish roles for individuals possessing the necessary expertise to deploy advanced technologies and drive digital evolution. These utilities proactively engage in workforce development initiatives to achieve this objective. Although medium sized utilities are in the preliminary to intermediate stages of digital transformation, they do recognize the need to use the accessible technological tools in a systematic way to help them improve their utilities' operational and management efficiency.

Large utilities typically have resource and funding availability to support intelligent water projects and out of all the large utilities who responded to the questionnaires, they are all engaging in these projects in some aspect of their sewershed management.

Large utilities currently do not have a well-defined strategic plan for iWISE implementation. From the questionnaires, we have concluded that they are in the knowledge compilation and knowledge transfer phase regarding iWISE solutions and are still identifying and assessing the available iWISE technologies and identifying the organizational initiatives they can take to begin their journey towards implementing iWISE solutions as part of their sewershed management.

When it comes to applying smart water solutions, major utility companies are currently in the early phases of initiating the iWISE (Intelligent Water Infrastructure Solutions and

Engineering) implementation. They are focused on internal communication within the organization to handle the iWISE implementation process. This involves tasks like establishing management contracts, setting up financial procedures, and involving relevant stakeholders. However, they haven't started communicating with customers and the public through media channels to share information about these projects. On the technical side of things, these utility companies are currently in the process of learning and gathering the necessary knowledge to offer guidance on technical aspects, which is essential for their planning efforts. These initial trials by the large utilities are backed by their short-term and mid-term plans for implementation. The utilities were asked if they consider near-term, medium-term and long-term plans for implementation to ensure long-term sustainability of their implementation plans for their intelligent water projects, the results of which are shown in Figure 4.3.

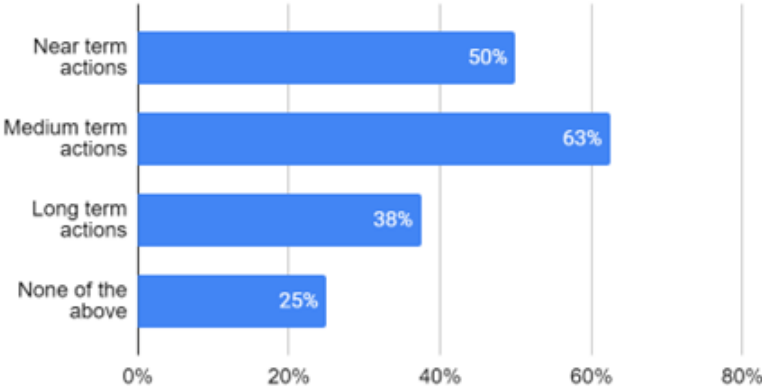


Figure 4.3: Planning for long term sustainability of iWISE implementation plans

Large utilities typically have a holistic data collection process and collect data parameters from all three subsystems. The results from the questions asked regarding the subsystems that utilities collect data from is shown in Figure 4.4.

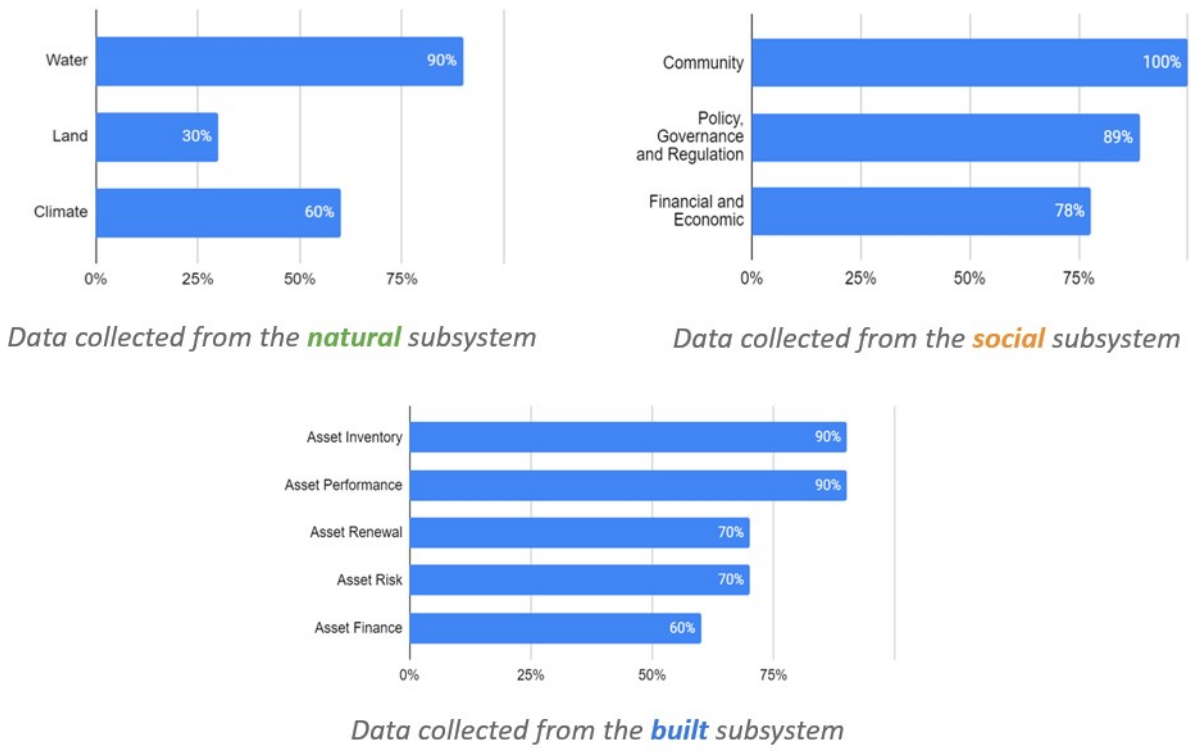


Figure 4.4: Data collected from the different subsystems for the sewershed scale

The finding that large utilities have a holistic data collection process is further supported by the responses from the questionnaire when asked if they categorize their data by the data source. These results are shown in Figure 4.5.

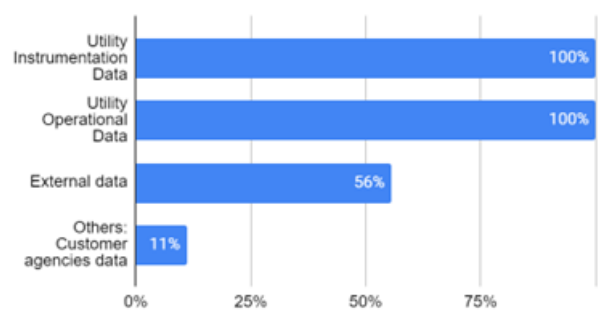


Figure 4.5: Data sources

Most utilities have some level of data quality assessment protocols, barring a few exceptions. These DQ/DA steps are done as part of their regular processes and do not have a dedicated

project planning step prior to quality assessment. This is shown in Figure 4.6. Most large utilities do not have a holistic data governance and database management strategy. Most utilities either only identify sources of data or do not have a data mapping or data cataloguing process altogether.

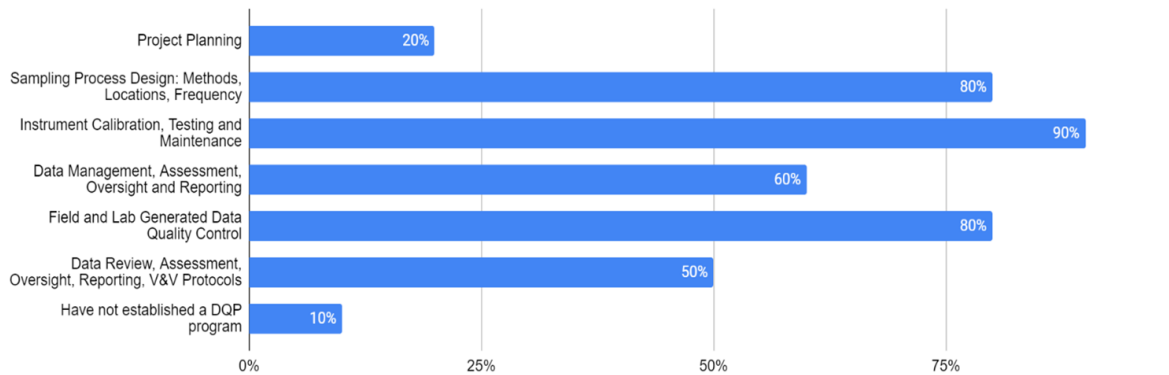


Figure 4.6: DQP protocols followed by utilities

Large utilities use a number of types of analytical models to understand their natural, built and social subsystems and support their decision-making process. The level of analysis varies from utility to utility. As shown in Figure 4.7, majority of large utilities carry out component level analysis, which support decisions to manage specific problems. Some large utilities also carry out system and sub-system level analysis that support decisions at the sewershed scale which supports holistic decision making.

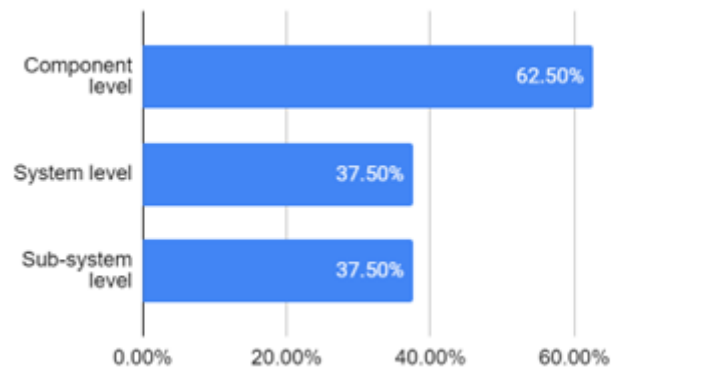


Figure 4.7: Levels of Analysis

Analysis carried out by most utilities support tactical decision making which is meant for identifying hot spots and problem areas to seek patterns in datasets. Large utilities also conduct analysis that supports operational decision making, for day-to-day decisions at an asset level. Some of the large utilities have also adopted strategic level decision making which supports long term policy and financial decisions. This is shown in Figure 4.8.

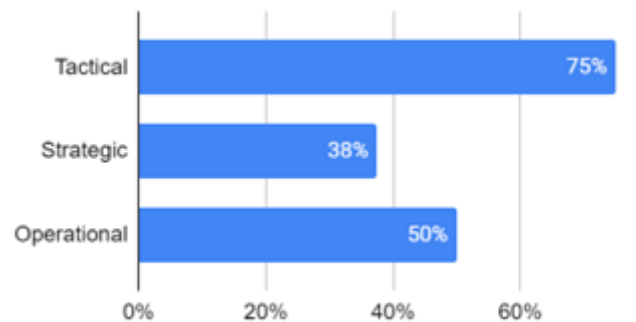


Figure 4.8: Domains of decisions that models are applied to

There are different levels of insights that modeling and analysis carried out by wastewater utilities can support. These include -

- Information level: higher level insights for general overview of sewershed performance.
- Engineering level: insights based on modeling of individual built assets

- Management level: economic and financial insights for management level staff

All the participating large utilities selected engineering level insights, while most utilities selected information and management level insights. These results are shown in Figure 4.9.

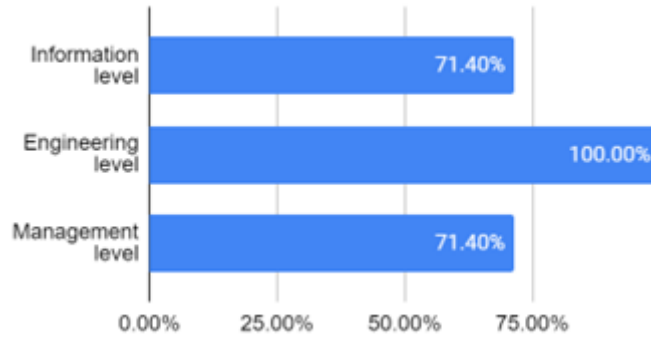


Figure 4.9: Categories of insights offered by models

The subsystems considered for modeling varies from utility to utility. Some concentrate their model development for their built and social sub-systems, while others concentrate on their built and natural sub-systems. All of the participating utilities develop models for analysis of their built assets. These results are shown in Figure 4.10.

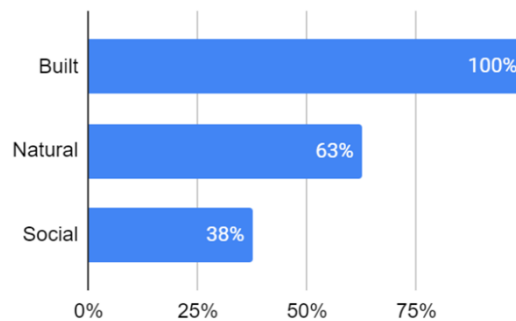


Figure 4.10: Subsystems considered for modeling

The distribution of types of mathematical techniques that utilities consider for their models is shown in Figure 4.11. Similar to their smaller and medium counterparts, large utilities also do not perform analysis using AI models as of yet, but are in the early stages of planning

and budgeting for such projects. Majority of their models are probabilistic, showing that their analyses support predictive and dynamic modeling that can support real-time decision-making.

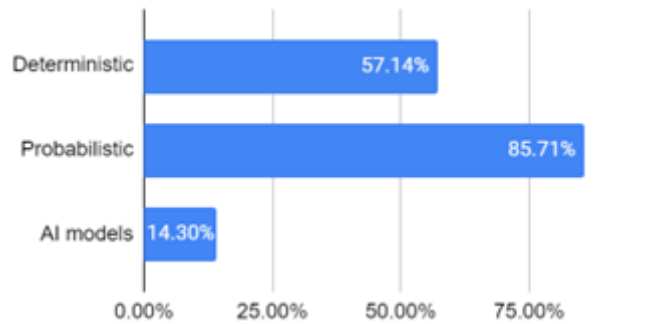


Figure 4.11: Mathematical techniques used for modeling

Utilities were asked which aspects they consider for development of a decision support system. Results from this question show that majority of large utilities do not have a decision support system (DSS) in place. The utilities that do have a DSS place equal importance on the various aspects to consider before the development of a DSS, barring the specificity required in the results. This supports the finding that the participating large utilities are in the preliminary stages of developing and refining their decision support systems. These results are shown in [Figure 4.12](#)

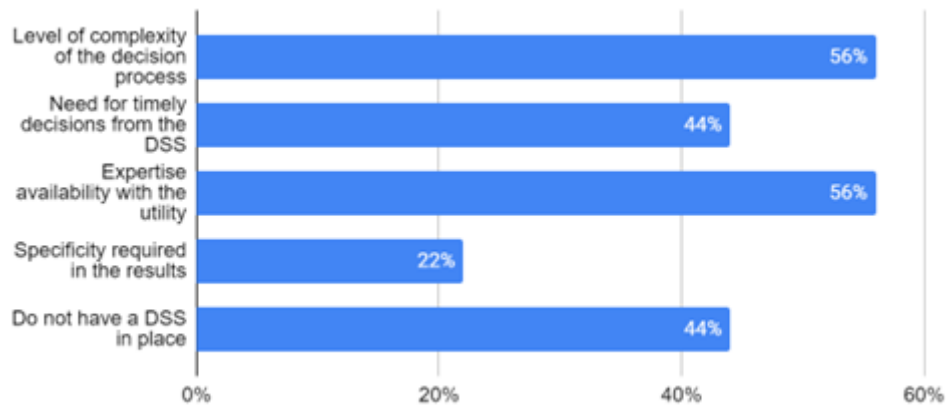


Figure 4.12: Development of a DSS

4.3 RQ3: What aspects of IWS implementation present as major challenges to utilities?

Small utilities encounter four main challenges when it comes to implementing Intelligent Water Systems projects. Firstly, they often lack access to the same level of technical expertise and support available to larger systems. While they can secure funding and justify such projects from state and federal resources, the design, implementation, and maintenance of complex systems are hindered due to the shortage of skilled and experienced workforce. Moreover, small utilities face difficulties in retaining their existing staff, as employees often leave for better opportunities in bigger cities with improved healthcare, school systems, and higher pay.

Secondly, small systems grapple with a lack of trust in the reliability of newly available technological solutions and modeling techniques, as they have not been thoroughly tested for applicability to smaller setups.

Thirdly, these utilities suffer from data limitations, as they do not possess datasets of the same volume or quality as larger systems. This scarcity of data hampers their ability to

develop advanced analytics, models (including AI), and data-driven strategies.

Lastly, small systems may encounter unique regulatory challenges that can complicate the implementation of Intelligent Water projects, particularly in states with varying regulatory requirements. These regulatory complexities can add to the overall challenges faced by small utilities in adopting Intelligent Water Systems.

The discussion with medium-sized utilities revealed that they encounter similar challenges as their smaller counterparts in terms of having a workforce with the necessary skills for implementing AI and other intelligent water technologies.

While medium-sized utilities are in the early to intermediate phases of digital transformation, they acknowledge the importance of utilizing available technological tools systematically to enhance operational and management efficiency. However, they may lack the resources available to larger utilities, which can pose challenges in financing new capital improvements and IWS projects. Furthermore, medium water utilities may face difficulties in attracting and retaining qualified personnel for their digital transformation efforts due to competition from larger utilities and private companies.

Major challenges faced by prominent utility companies encompass a lack of trust in emerging technologies, the necessity for a cultural transformation to instill a different perspective, a shortage of new skilled personnel joining the workforce, and the establishment of cyberattack-resistant digital elements within their wastewater systems. A shared thread among utilities, spanning beyond just the larger ones, involves the skepticism surrounding new technologies and the deficit of skilled workforce. Many novel technologies, such as AI, are often introduced as plug-and-play systems, and utilities lack the workforce equipped with the necessary expertise to effectively maintain these solutions over the long term.

Chapter 5

Discussion

Water utilities across the US are beginning their journey towards digital transformation and through this research it can be said that the water sector recognizes the advantages that advanced technologies offer. Through the first research question, which investigates the level of IWS implementation in utilities, we found that utilities are implementing intelligent water practices in their sewershed management across different departments and are in the preliminary stages of implementing these practices in a more holistic manner, that integrates their various operations and produces reliable and more intelligent results. Utilities recognize the importance of system of systems thinking and its application in sewershed management.

Through the second research question, we found the different areas in which utilities are implementing these practices and how they compare with each other across small, medium and large scale utilities. The questionnaires helped us investigate their level of IWS understanding and practices with respect to each building block, which divides the vast number of operations managed in a utility systematically and helped us evaluate both the current practices as well as verify the steps and guidelines proposed in this framework.

As noted in the third research question, which identifies the challenges faced by utilities in this digital transformation, we found that utilities are not opposed to adopting intelligent water practices but require the resources, both financial and in the workforce, to ensure reliability of these practices and their implementation can be done sustainably. A primary challenge across small, medium and large scale utilities is the lack of trust in new technologies

and a lack of workforce that have the required skills to maintain these practices. This lack of trust can be owed to the lack of strategic planning when it comes to implementation. The water sector can benefit in many ways from an integrated approach to intelligent water practices and this can be facilitated by a formal set of guidelines to help utilities navigate their journey to digital transformation.

Chapter 6

Future Work

The iWISE framework in its entirety includes the application of intelligent water practices not only in the technical aspects of sewer shed management, but also the organizational aspects. These include areas such as workforce development strategies, creating a culture of diversity and inclusion, encouraging stakeholder engagement and the facilitation of innovation ecosystems. This study includes the recommendations and guidelines for the technical building blocks of the framework. Utilities should diversify their investments in intelligent water projects beyond technical aspects to include the proposed organizational aspects.

Chapter 7

Conclusions

In this research study, we propose the iWISE framework to support the implementation of intelligent water systems. Several pilot interviews were conducted and the framework was verified and validated through questionnaires that were sent to utilities across the United States. We obtained feedback through these methods, and gained valuable insights on the current level of IWS implementation, the associated challenges and verified the exhaustiveness of methods proposed in each building block of the framework. The feedback shows that the proposed framework can be utilized by any wastewater utility and systematically implemented for each building block.

Small and medium size utilities are somewhere between the preliminary to intermediate stages of iWISE implementation, whereas their larger counterparts are in the intermediate to advanced phases of iWISE implementation, depending on the utility. Small and medium utilities are both applying intelligent water practices in a limited capacity and mainly to their technical operations. Larger utilities, however, have a more holistic approach and are adopting the system of systems approach that is recommended in this framework.

Similar to their smaller and medium counterparts, large utilities also do not perform analysis using AI models as of yet, but are in the early stages of piloting and budgeting for such projects. Majority of their models are probabilistic, showing that their analyses support predictive and dynamic modeling that can support real-time decision-making.

Through this study, the iWISE framework has been validated as a valuable source for guidance in the implementing of intelligent water systems and ensuring efficient and reliable wastewater management. The recommendations from this framework can serve as a blueprint for wastewater utilities and can be extended to other sectors of water distribution as well.

Appendices

Appendix A

Recommended Data Parameters

The following figures present the recommended data parameters that were developed based on the literature reviews, case studies developed and discussions with participating utilities. The parameters are organized based on the three subsystems as defined in this framework - natural, built and social. These subsystems were further divided into the components and their individual elements that belong to their respective subsystems.

Figures [A.1](#), [A.2](#) and [A.3](#), [A.4](#), [A.5](#), [A.6](#) and [A.7](#) show the recommended parameters to collect from the water, land and climate components of the natural sub-system for sewershed-scale modeling.

WATER				
Component	Parameter	Unit	Brief Explanation	Level of Importance
Surface Water	Temperature	Celcius	Higher water temperatures close to the effluent outfall and decreasing temperatures downstream	Preferable
	Total Suspended Solids	mg/l	SS concentration stabilizes downstream of effluent outfall but it is high near the utfall	Preferable
	pH	0-14	Relatively stable (ranged from circumneutral i.e. 5.5-7.2 to slightly basic) along gradients downstream of effluent outfall	Preferable
	Dissolved Oxygen	mg/l	Lower DO immediately below effluent outfall, higher DO as flow moves downstream	Preferable
	Electric Conductivity	Ds/cm	Higher electric conductivity at effluent outfall, and then remaining relatively stable along downstream gradient and across seasons	Preferable
	Alkalinity	meq/l	Higher alkalinity near effluent outfall, but then decreasing values further downstream from outfall	Preferable
	Nitrates	mg/l	Higher nitrate near the effluent outfall, lower nitrate as flow moves downstream affected by chemical, biological and physical (dilution) processes. In some cases, nitrates can increase downstream due to evaporation and low or no dilution	Preferable
	Ammonia	mg/l	High ammonia con-centrations (e.g. >2 mg/L for chronic exposure and >17 mg/L for acute exposure: US EPA, 2013) are particularly influential, reducing growth rates and reproductive success or causing direct mortality in aquatic invertebrates and fish (Constable et al., 200	Preferable
	Ammonium	mg/l	Higher ammonium near effluent outfall, lower as flow moves downstream	Preferable
	Phosphate	mg/l	Higher phosphate near the effluent outfall, lower phosphate as flow moves downstream	Preferable
	Heavy Metals	mg/m3	Elevated heavy metal concentrations near effluent outfall from treatment facilities receiving industrial waste	Preferable
	Bacteria (E. Coli)	units/ml	Relatively low concentrations of E. coli contributed from treated effluent outfall. Nonpoint source loads were the primary source of bacteria loading	Preferable
	Antibiotic Resistant Coliform Bacteria	colonies/100 ml of water	Higher populations of antibiotic-resistant coliform bacteria in reaches downstream of effluent outfall as compared to those upstream	Preferable
	Endocrine Disruptors (EDCs)	mg/l	Undetected or very low levels upstream of effluent outfall, but detected, and often in high levels, at sites below effluent outfall. Some EDCs attenuated to undetectable concentrations within 11 km	Preferable
Pharmaceuticals	mg/l	Undetected or very low values upstream of effluent outfall, and frequently higher at sites below effluent outfall. Pharmaceutical attenuation during stream transport was detected. Some active compounds can decrease almost 4-fold within 30 km distance from effluent outfall	Preferable	
Biocides	mg/l	Elevated concentrations about 2-fold of biocide compounds found downstream of effluent outfall	Preferable	

Figure A.1: Surface Water Parameters

WATER				
Component	Parameter	Unit	Brief Explanation	Level of Importance
Runoff Water			Collection systems can be damaged when they are forced to transport more flow than they are designed to handle. Increased volume also raises costs for wastewater treatment facilities, because harmless stormwater mix with sewage.	
	Inflow	GPD/inc h-mile	Inflow is stormwater that enters the sewer system through rain leaders, basement sump pumps or foundation drains illegally connected to the sewer.	
	Infiltration	GPD/inc h-mile	Infiltration occurs when groundwater seeps into sewer pipes through cracks, leaky pipe joints and/or deteriorated manholes	
	Soil Infiltration Rate	in/hr	Rainfall exceeding infiltration capacity becomes surface runoff	Desirable
	Rainfall/Storm Intensity	in/day	Amount of precipitation in the sewershed, excess precipitation contributes to runoff. Rainfall: Rain Gage data and Gage-adjusted Radar Rainfall (GARR)	Essential
	Evapotranspiration	in/day	Remaining moisture after deduction of evapotranspiration loss flows into the soil moisture store and affects extent of runoff	Desirable
	Soil Moisture	in	Total amount of water that is stored in the soil within the plant's root zone	Essential
	Soil Type	Type	Infiltration is more rapid in coarser soils (e.g., medium to coarse sands or gravels) than in fine grained soils (e.g. silts and clays)	Essential
	Total Suspended Solids (TSS) and Turbidity	mg/l	TSS concentration stabilizes downstream of effluent outfall but it is high near the outfall	
	COD	mg/l	Harmful chemicals like pesticides may wash into stormwater during storm events and lead to higher COD	
	Fecal bacterial coliform	units/ml	Bacterial coliform may wash into stormwater during storm events and elevate the fecal bacteria concentrations in stormwater	
	Phosphate	mg/l	Leaf litter, landscape trash, lawnmowing may increase phosphate content causing unwanted algal blooms	
	Nitrates	mg/l	Fertilizers used in agricultural activities and human waste flowing in stormwater may increase the nitrate concentration	
			Preferable	

Figure A.2: Runoff Water Parameters

WATER				
Component	Parameter	Unit	Brief Explanation	Level of Importance
Groundwater	Hydraulic head (h)	m	Groundwater flows from positions of high hydraulic head to positions of lower head. The rate of flow is proportional to the rate at which head decreases with distance along the path from high head to low.	Desirable
	Specific storage coefficient (S)	NA	Storativity or the storage coefficient is the volume of water released from storage per unit decline in hydraulic head in the aquifer, per unit area of the aquifer. Storativity is a dimensionless quantity, and is always greater than 0.	
	Transmissivity (T)	gpd/ft	Transmissivity is the rate at which water passes through a unit width of the aquifer under a unit hydraulic gradient.	
	Chloride	mg/l	Chloride is one of the most common anions in uncontaminated groundwater	
	Boron	mg/l	Boron and borates are used in manufacturing glass, ceramics, soaps, laundry detergents, bleach, cosmetics, medications, pesticides, personal care products, and other.	Preferable
	Phosphorous	mg/l	Higher phosphate near the effluent outfall, lower phosphate as flow moves downstream	
	VOCs	mg/l or ppm	Exposure risk is determined based on the individual constituents of the VOC compound, with each having the potential to trigger different symptoms, human health effects, or illnesses.	
	Sulphate	mg/l	Sulfate is a major anion in most groundwaters. There is no primary drinking-water standard for sulfate	
	pH	0-14	There are no health-based drinking-water standards for pH. However, pH values that are not near neutral can lead to high concentrations of metals for which there are drinking-water standards and associated health effects.	Essential
	Conductivity	Ds/cm	Ability of water to transmit an electric current. Water with high conductivity may have objectionable taste, cause staining, and precipitate scale in pipes and containers.	
	Total dissolved solids	mg/l	Measure of the dissolved combined content of all inorganic and organic substances present in a liquid in molecular, ionized, or micro-granular suspended form	
	Alkalinity (HCO ₃ ⁻)	mg/l	Capacity of the water to neutralize acid	
	Total hardness	mg/l	Capacity of water to precipitate an insoluble residue when soap is used. Hard water reduces the ability of soap to clean clothes; leaves a sticky film on skin, clothes, and hair; and deposits scale in water heaters, boilers, and industrial equipment.	
	Calcium	mg/l	Calcium and magnesium are found in ground water that has come in contact with certain rocks and minerals	
	Magnesium	mg/l	Magnesium absorption ratio calculated from this (MAR)	
	Sodium	mg/l	Sodium absorption ratio and soluble sodium percentage calculated from this measurement	
	Potassium	mg/l	Potassium is a common dissolved mineral present in groundwater	
	Chloride	mg/l	Chloride is one of the most common anions in uncontaminated groundwater	
	Fluorides	mg/l	Fluoride is a minor anion, usually present at less than about 1 mg/L in groundwater. Natural sources of fluoride include the mineral fluorite, which is common in carbonate rocks. The major contaminant sources are discharges from fertilizer- and aluminum-production facilities.	
	Sulphates	mg/l	Sulfate is a major anion in most groundwaters. There is no primary drinking-water standard for sulfate	
Nitrates	mg/l	Nitrates are a common dissolved mineral present in groundwater		
Hydraulic Conductivity K	m d-1	Hydraulic conductivity of the surrounding homogeneous soil		

Figure A.3: Groundwater Parameters

LAND				
Component	Parameter	Unit	Brief Explanation	Level of Importance
Landfills (Leachate)	Depth of landfill site	m	Depth of landfill (height)	Desirable
	Suspended Solids	mg/l	As a liquid passes through matter and extracts soluble or suspended solids it forms leachate.	Desirable
	Color	Yes/No	The physical appearance of leachate when it emerges from a typical landfill site is a strongly odoured black-, yellow- or orange-coloured cloudy liquid. As it becomes oxygenated it tends to turn brown or yellow because of the presence of iron salts in solution and in suspension.	Desirable
	Sulfate	mg/l	High concentrations of sulphur compounds in leachate hinder wastewater treatment as a biologically and it resulted that low production of methane gas. This phenomenon results from the anaerobic reduction of sulphates into sulphides	Desirable
	Chloride	mg/l	The high concentration of chloride (Cl ⁻) ions in leachate often has negative effects in their harmless treatments, and the common treatments containing the ion exchange method consume excessive antichlors due to their large particle sizes and unfavorable morphologies	Desirable
	BOD5	mg/l	Amount of oxygen consumed by bacteria and other micro organisms in a leachate sample	Desirable
	COD	mg/l	Initial COD concentration of leachate affects runoff contamination	Desirable
	Moisture content	%	Moisture content of landfill waste affects runoff properties	Desirable
	Temperature	Celcius	Temperature conditions around landfill affects runoff properties	Desirable
	pH	0-14	Quantitative measure of the acidity or basicity of the leachate affects runoff properties	Desirable
	Suspended Solids	mg/l	As a liquid passes through matter and extracts soluble or suspended solids it forms leachate.	Desirable
	Turbidity	NTU	Turbidity is caused by particles suspended or dissolved in water that scatter light making the water appear cloudy or murky	Desirable
	Conductivity	Ds/cm	Ability of water to transmit an electric current. Water with high conductivity may have objectionable taste, cause staining, and precipitate scale in pipes and containers.	Desirable

Figure A.4: Landfills Parameters

LAND				
Component	Parameter	Unit	Brief Explanation	Level of Importance
Land Cover	Land use type	type	Runoff amount, runoff process and sediment discharge are influenced by land use and forest type	Essential
	Area	sq-ft	Runoff amount, runoff process and sediment discharge are not only influenced by land use and forest type, but also by terrain feature like length, area and width at watershed scale	Essential
	Rainfall/Storm Intensity	in/day	Amount of precipitation within the area used to determine runoff, taking into consideration the impact of extent of forest coverage	Essential
	Runoff Volume	m3	With increase in forest coverage there is a decrease in runoff volume during rainy seasons	Desirable
	Soil Moisture	in	Total amount of water that is stored in the soil within the plant's root zone	Essential

Figure A.5: Land Cover Parameters

LAND				
Component	Parameter	Unit	Brief Explanation	Level of Importance
Agricultural Activities	Soil moisture	%	Moisture content of the soil	Essential
	Soil erodibility	K	Soil erodibility (K) is the intrinsic susceptibility of a soil to erosion by runoff and raindrop impact.	Essential
	Slope length	L	Slope gradient measurements used for conceptual soil erosion modeling	Essential
	Slope steepness	S		Essential
	Drainage Practices	Type	Conservation drainage describes practices including modifying drainage system design and operation, woodchip bioreactors, saturated buffers, and modifications to the drainage ditch system	Desirable
	Till Frequency	Frequent/Occasional/Rare	Farmers can reduce how often and how intensely the fields are tilled. Doing so can help to improve soil health, and reduce erosion, runoff and soil compaction, and therefore the chance of nutrients reaching waterways through runoff.	Desirable
	Presence of Yearly Crop Cover Duration	Yes/No	Farmers can plant cover crops or perennial species to prevent periods of bare ground on farm fields when the soil (and the soil and nutrients it contains) are most susceptible to erosion and loss into waterways.	Desirable
	Presence of Field Buffers	Yes/No	Farmers can plant trees, shrubs and grasses along the edges of fields; this is especially important for a field that borders water bodies. Planted buffers can help prevent nutrient loss from fields by absorbing or filtering out nutrients before they reach a water body	Desirable
	Fertilizer Application Method	Type: Subsurface injection (Best) >plowed under (Moderate) >surface broadcast with no incorporation (Worst)	Nitrogen and phosphorus are less likely to be lost by erosion or runoff if they are banded directly into the soil or incorporated. However, incorporation disturbs the soil, which promotes soil erosion. Although surface application of nitrogen and phosphorus without incorporation is the least desirable fertilizer application method, it is often used for pastures, lawns, turf, other perennial crops, and in conservation-tilled fields because it is the easiest and least disruptive method. Nitrogen tends to move down into the soil as rainwater infiltrates, so the application method (surface applied or banded) has little effect on losses of nitrogen by leaching. However, nitrogen and particularly phosphorus applied to the soil surface are more susceptible to being transported by runoff and less likely to become attached to soil particles or be taken up by plant roots. For this reason, nitrogen and phosphorus should be incorporated into the soil before crops are planted/established or banded, even if using conservation tillage. Where surface application is unavoidable, minimize the use of phosphorus.	Desirable
	Presence of fencing to restrict surface water access	Yes/No	Farmers and ranchers can install fence along streams, rivers and lakes to block access from animals to help restore stream banks and prevent excess nutrients from entering the water.	Desirable

Figure A.6: Agricultural Activities Parameters

CLIMATE				
Component	Parameter	Unit	Brief Explanation	Level of Importance
Precipitation	Annual Rainfall Event Frequency	Number	Frequency of 2hr, 6hr and 24hr rainfall events captures number of important event for planning wet-weather operations	Essential
	Duration of Rainfall Events	Days	Duration of rainfall events categorized into 2hr, 6hr and 24hr events	Essential
	Average Annual Rainfall Volume	in/year	Rainfall infiltration is the leading cause of sanitary sewer overflows (SSOs) and combined sewer overflows (CSOs)	Essential
Temperature	Range (Winter)	Fahrenheit	Temperature affects runoff characteristics (due to evapotranspiration), can indicate rainfall patterns and climatic conditions (tropical, temperate, arid, frigid, etc.)	Essential
	Range (Summer)	Fahrenheit		Essential
Extreme Events	Relevant Threatening Extreme Events	Type (100 year storm events, hurricanes, sea level rise)	Understanding of main threats from climate for WW and SW infrastructure systems may be in the form of 100 year storm events, hurricanes, sea level rise, etc.	Essential
	Frequency of 100-year storm events	Number	Frequency indicates the importance of having formalized wet-weather operations	Essential
	Peak Intensity	Type (Volume of rainfall, sea level rise)	Peak intensity helps identify the boundary conditions for planning wet-weather operations	Essential
	Inter-event Time	Days	This indicates the level of saturation in soil to absorb impact of extreme events	Essential

Figure A.7: Climate Parameters

From the built subsystem, the parameters for septic tanks are shown in [A.8](#). The parameters for various wastewater infrastructure like force mains, gravity mains, catch basins and treatment plants are shown in Figures [A.9](#), [A.10](#), [A.11](#), [A.12](#), [A.13](#), [A.14](#), [A.15](#), [A.16](#).

The parameters for various stormwater infrastructure like stormwater pipes and green roofs are shown in Figures [A.17](#), [A.18](#), [A.19](#), [A.20](#).

HOUSEHOLD/ COMMERCIAL/ INDUSTRIAL				
Component	Parameter	Unit	Brief Explanation	Level of Importance
Septic Tanks	Average flow	l/p/d	Average flow of sewage (daily per capita) depends on the user group such as houses, shops, schools etc	Desirable
	Hydraulic retention time	days	The time that septic effluent spends in the septic tank before flowing out to the drainfield.	Desirable
	Minimum capacity	m ³	The total capacity of the tank consists of the capacity needed for sludge and scum storage and capacity for liquid retention	Desirable
	Ventilation pipe diameter	m	Diameter of ventilation pipe	Desirable
	Ventilation pipe height	m	Height of ventilation pipe from the bottom of the tank	Desirable
	Free board	mm	Free board is the height between the top water level and the soffit of the cover slab of the septic tank	Desirable
	Liquid depth	m	Depth of liquid inside the septic tank	Desirable
	Percolation rate	mpi (mins per inch)	The soil percolation rate indicates how quickly water moves through soil and helps evaluate the ability of the soil to absorb and treat effluent — wastewater that has received preliminary treatment in a septic tank.	Desirable
	Distance to a water well	m	Distance between septic tank and nearest water well	Desirable
	Pipe blockage	Yes/ No - Type	A healthy grass cover should be maintained over the drainfield to prevent soil erosion, and trees and shrubs should not be planted too close to the drainfield because roots may eventually damage or block the distribution lines.	Preferable
	Pump Condition	Good/ Fair/ Poor	Failure to have the septic tank pumped out regularly causes damage to the system.	Preferable
	Frequency of inspection	No. per year	Owner of the septic tank system (homeowner, property owner, homeowner's association, or other responsible management entity) is responsible for the overall operation, maintenance, and upkeep of the system, including repairs or replacement.	Preferable
	Presence of Site Drainage	Yes/ No	Drainage can be improved by directing gutters and downspouts away from the septic tank and drainfield. The drainfield area should be graded so that it sheds, rather than accumulates, rainwater in low areas or depressions.	Preferable
	Wastewater Flow	cu-ft	Reducing the amount of wastewater that goes to the septic system is one of the simplest ways to prolong the life of the system.	Preferable
	pH	0-14	Depends on pH and alkalinity of water supply, typically 5-9	Preferable
	Floating material	Yes/No	Presence of any object(s) floating in the tank	Preferable
	Turbidity	NTU	Turbidity is caused by particles suspended or dissolved in water that scatter light making the water appear cloudy or murky	Preferable
	Fats, oil and grease	mg/l	Concentration of FOGs	Preferable
	Settleable solids	mg/l	Suspended solids that will settle out of suspension within a specified period of time	Preferable
	TSS	mg/l	Increased erosion of banks of rivers and streams can increase the TSS level in water	Preferable
	BOD	mg/l	Amount of oxygen consumed by bacteria and other micro organisms in a water sample	Preferable
	COD	mg/l	Estimate of oxygen required for the portion of organic matter in wastewater that is subjected to oxidation	Preferable
	Total Nitrogen	mg/l	Total concentration of organic nitrogen and ammonia	Preferable
Total Phosphorus	mg/l	Measure of all the forms of phosphorus, dissolved or particulate, that are found in a sample	Preferable	
Total Coliforms	CFU/100ml	Total coliforms are a group of bacteria that are widespread in nature	Preferable	
Fecal Coliforms	CFU/100ml	Fecal Coliform provides a risk because of the many diseases that spread through fecal transmission	Preferable	
Residual Cl ₂	mg/l	The amount of available chlorine present in wastewater after a given contact time under specific environmental conditions	Preferable	
Color	Pt-Co	Analysis to evaluate pollution levels in wastewater in the septic tank	Preferable	

Figure A.8: Septic Tanks Parameters

WASTEWATER INFRASTRUCTURE				
Component	Parameter	Unit	Brief Explanation	Level of Importance
Catch basins/Inlets	Catch Basin Performance Parameters			
	Location	Coordinates	Location of the catch basin/inlet in the stormsewer system	Preferable
	Peak flow rate	ft ³ /hr	Flow rate of wastewater at the inlet	Preferable
	Capacity	cubic ft	Volumetric capacity of the catch basin/inlet	Preferable
	Flooding issues	Yes/No	Does the catch basin/inlet have flooding issues	Preferable
	Catch Basin Renewal			
	Renewal Date	MM/DD/YYYY	Historical information of past renewal helps identify trends and patterns for supporting decisions	Essential
	Renewal Type	Type	Type of renewal-repair, rehabilitation, replacement	Essential
	Response Time	hr	Time taken to respond to event	Essential
	Renewal Time	hr	Total renewal time reduces the overall consequences of disruption	Essential
	Catch Basin Risk			
	Direct Cost of Renewal	Low, Medium, High on 1-3 Likert scale	Direct costs include direct and indirect labor costs, materials and equipment purchases, construction, engineering, repaving, landscaping, other contract repair costs, and laboratory services.	Essential
	Flooding issues	Low, Medium, High	Flooding due to blockage can affect nearby households, industrial and commercial operations and also introduce health risks	Preferable

Figure A.9: Catch Basins Parameters

WASTEWATER INFRASTRUCTURE				
Component	Parameter	Unit	Brief Explanation	Level of Importance
Storage Holding Tank	Storage Holding Tank Performance Parameters			
	Material Type	type	Material of storage holding tank must be selected to withstand traffic loading, internal loading, external loading and other stresses depending on location of installation (buried/above ground)	Desirable
	Pumping Capacity	gallons	Hydraulic models can help estimate asset capacity (Platforms like InfoWorks ICM)	
	Pumping Frequency	No/Year	Holding Tanks need to be pumped regularly to make sure there is capacity for containing future sewage flows	Preferable
	Storage Holding Tank Renewal Parameters			
	Renewal Date	Date	Historical information of past renewal helps identify trends and patterns for supporting decisions	Essential
	Coating Inspection	Type	Holding Tanks require some specialized structural inspections and especially inspections for protective coatings	
	Renewal Type	Type	Type of renewal-repair, rehabilitation, replacement	Essential
	Storage Holding Tank Risk Parameters			
	Direct Cost of Renewal	Low, Medium, High on 1-3 Likert scale	Direct costs include direct and indirect labor costs, materials and equipment purchases, construction, engineering, repaving, landscaping, other contract repair costs, and laboratory services.	Essential
Flooding issues	Low, Medium, High	This is the cost of any legal issues due to flooding of residential, commercial or industrial areas following a failure event.	Preferable	

Figure A.10: Storage Holding Tanks Parameters

No	Parameter	Unit	Brief Explanation
Physical/Structural			
1	Node Identification Number	Node	ID for each pipe segments (Manhole-Manhole) between nodes
2	Pipe Material	Type	Different pipe materials deteriorate at different rates
3	Pipe Diameter	Inch	Different pipe sizes may fall in different failure modes
4	Pipe Age	Year	Older pipes may deteriorate faster than newer pipe
5	Pipe Depth	Feet	Pipe Depth affects pipe loading and deteriorating rate
6	Pipe Wall Thickness	Inch	Wall thickness affects rupture resistance and corrosion penetration rates
7	Pipe Location	Area	Some locations may receive roadway salt intrusion; urban, sub-urban, rural, costal, etc.
8	Pipe Shape	Type	Different pipe shapes may result in different failure modes and deterioration
9	Pipe Joint Type	Type	Some types of joints may undergo premature failure
10	Pipe Bedding	Type	Inadequate bedding may cause premature pipe failure, special bedding use
11	Trench Backfill	Type	Some backfill materials are more corrosive or frost susceptible
12	Pipe Slope	Gradient	Slope affects the velocity of gravity flow and may result in different pipe deterioration rates
13	Design Life of Pipe	Year	The pipe design life
14	Design Strength of Pipe	psi	Original design strength of each pipe.
15	Node Length	Feet	Length of Node (Manhole-Manhole)
16	Pipe Lining	type	Presence of pipe lining significantly reduces internal corrosion
17	Pipe Lining pH	pH	The low pH of the pipe liners indicate deterioration of the liners

Figure A.11: Force Mains Physical and Structural Essential Parameters

Operational/Functional			
18	Operational & Maintenance Practices	Type	Poor practices can compromise structural integrity and water quality; very good, good, fair
19	Pipe Renewal Record	Type	All records of pipes renewal- type of renewal method
20	Pipe Defect Type	Type	Record of Defects observed
21	Pipe Defect Level	Level	The level of defects observed at pipe.
22	Pipe Defect Location	Orientation	Locations of the defects observed
23	Blockage/stoppage	Yes/No-Type	Blockage make the pipeline network inoperative, sewer pipe is no longer functional
24	Sediments	Ton/Feet	Sediments per unit length
25	Inspection record	Type	Record of inspection, method use, date of inspection
26	Water Corrosivity	level	Water present may be corrosive and may affect pipe material
27	Hazen Williams C Factor	c factor	Hazen Williams C factor is used to determine the head loss in flow
28	Operation Pressure	psi	Operational pressure pipe is designed for.
29	Pipe Break	Number	The historical break records can be used to assess the probability of failure
30	Pipe Break<5 Years	Yes/No	The current pipe breaks indicate an ongoing problem with the pipe.
31	Leak	Gal/Min	The presence of leak indicates exfiltration
32	Tuberculation	Yes/No	The presence of tuberculation indicates a surface wear/internal corrosion problem
33	Pressure Exceeded	Yes/No	Pipes operating on higher pressure is prone to structural failures
34	Pressure Surges	Yes/No	Pipes operating on higher pressure is prone to structural failures
35	Distance to WWTP	Miles	The distance to the Wastewater treatment plant indicate the time spend by the conveyed water in the system.
36	Surcharging	Yes/No	The presence of surcharging indicate capacity and blockage problems.
37	Number of Gas Pockets	Number	Number of gas pockets indicate gas accumulation and internal corrosion problems
38	Length of Gas Pockets	Feet	Length of gas pockets indicate gas accumulation and internal corrosion problems

Figure A.12: Force Mains Operational and Functional Essential Parameters

Environmental			
40	Soil Type	Type	Corrosive, expansive, & compressible; hydrocarbons & solvents cause deterioration
41	Soil Corrosivity	Level	Condition of the soil related to pipe deteriorate; low, medium, high
42	Soil Moisture Content	Percent	Moisture percentage in the soil may affect loading and pipe deterioration
43	Stray Currents	Yes/No	Stray currents may cause electrolytic corrosion of metal pipes
44	Groundwater Table	Feet	affecting soil loading on the pipes and pipe deterioration rate; above, below sewer, fluctuating
45	Ground Cover	Type	Paved ground or vegetation cover result in different deterioration mode and rate
46	Loading Condition (Dead Load)	Lbs/sq.ft.	Death load can be determined from infrastructure loading
47	Loading Condition (Live Load)	ADT-Level	Live load can be determined from average daily traffic volume and railway loading etc.
48	Rainfall/Precipitation	Inch/year	Rainfall in the areas should be monitored
49	Climate - Temperature	°F	Frost action in cold regions and seasonal soil water content variation in warmer regions
50	H2S	ppm	Concentration of Hydrogen Sulfide can increase pipe internal deterioration rate
51	Frost Penetration	Yes/No-depth	Soil ever frozen around the pipe, depth of penetration in feet.
52	Tidal Influences	Yes/No	Sewer in Coaster area may be subjected to tidal influence affecting bedding of the pipe
Financial			
53	Annual Capital Cost	\$/Year	Utility annual capital Cost and allocation criteria
Other			
54	FOG	Level	Fats, Oils, and Grease entering the sewer system

Figure A.13: Force Mains Environmental, Financial and Other Essential Parameters

No	Parameter	Unit	Brief Explanation
Physical/Structural			
1	Node Identification Number	Node	ID for each pipe segments (Manhole-Manhole)between nodes
2	Pipe Material	Type	Different pipe materials deteriorate at different rates
3	Pipe Diameter	Inch	Different pipe sizes may fall in different failure modes
4	Pipe Installation Year	Year	Older pipes may deteriorate faster than newer pipe
5	Pipe Depth	Feet	Pipe Depth affects pipe loading and deteriorating rate
6	Pipe Wall Thickness	Inch	Wall thickness affects rupture resistance and corrosion penetration rates
7	Pipe Location	Area	Some locations may receive roadway salt intrusion; urban, sub urban, rural, other
8	Pipe Shape	Type	Different pipe shapes may result in different failure modes and deterioration
9	Pipe Joint Type	Type	Some types of joints may undergo premature failure
10	Pipe Bedding	Type	Inadequate bedding may cause premature pipe failure, special bedding use
11	Trench Backfill	Type	Some backfill materials are more corrosive or frost susceptible
12	Pipe Slope	Gradient	Slope affects the velocity of gravity flow and may result in different pipe deterioration rates
13	Design Life of Pipe	Year	The pipe design life
14	Design Strength of Pipe	psi	Original design strength of each pipe.
15	Node Length	Feet	Length of Node (Manhole-Manhole)
16	Pipe Lining	type	Presence of pipe lining significantly reduces internal corrosion
17	Pipe Lining pH	pH	The pH of lining can be used as an indicator for the deterioration.

Figure A.14: Gravity Mains Physical and Structural Essential Parameters

Operational/Functional			
18	Pipe Hydraulics	Gallon/Min	Capacity of the sewage gravity conveying pipe
19	Pipe Surcharging	Yes/No.	Surcharging in gravity sewers in dry & wet weather should be considered
20	Operational& Maintenance Practices	Type	Poor practices can compromise structural integrity and water quality
21	Pipe Renewal Record	Type	All records of pipes renewal-type of renewal method
22	Pipe Defect Type	Type	Record of Defects observed
23	Pipe Defect Level	Level	The level of defects observed at pipe.
24	Pipe Defect Location	Orientation	Locations of the defects observed
25	Infiltration/Inflow	Level-Gal/Min	infiltration/inflow may cause soil erosion, and increasing flow volume
26	Exfiltration	Level	Exfiltration may cause erosion of soil and change soil loading on pipe
27	Blockage/stoppage	Yes/No-Type	Blockage make the pipeline network inoperative, sewer pipe is no longer functional
28	Sediments	Ton/Feet	Sediments per unit length
29	Inspection record	Type	Record of inspection, method use, date of inspection
30	Flow Velocity	Feet/Second	Low velocity accumulate deposits; excessive velocity accelerate deterioration at invert

Figure A.15: Gravity Mains Operational and Functional Essential Parameters

Environmental			
31	Soil Type	Type	Corrosive, expansive, & compressible; hydrocarbons & solvents cause deterioration
32	Soil Corrosivity	Level	Condition of the soil related to pipe deterioration
33	Soil Moisture	Percent	Moisture percentage in the soil may affect loading and pipe deterioration
34	Stray Currents	Yes/No	Stray currents may cause electrolytic corrosion of metal pipes
35	Groundwater Table	Feet	Affecting soil loading on the pipes and pipe deterioration rate
36	Ground Cover	Type	Paved ground or vegetation cover result in different deterioration mode and rate
37	Loading Condition (Dead Load)	Lbs. / sq. ft.	Dead load can be determined from infrastructure loading
38	Loading Condition (Live Load)	ADT-Level	Live load can be determined from average daily traffic volume and railway loading etc.
39	Rainfall/ Precipitation	Inch/year	Rainfall in the areas should be monitored
40	Climate Temperature	°F	Frost action in cold regions and seasonal soil water content variation in warmer regions
41	H2S	ppm	Concentration of Hydrogen Sulfide can increase pipe internal deterioration rate
42	Frost Penetration	Yes/No-depth	Soil ever frozen around the pipe, depth of penetration in feet.
43	Proximity to Trees	Feet	Average distance between sewer and trees
44	Tidal Influences	Yes/No	Sewers in Coastal areas may be subjected to tidal influence affecting bedding of the pipe
Financial			
45	Annual Capita cost	\$/Year	Utility annual capital Cost and allocation criteria
Other			
46	FOG	Level	Fats, Oils, and Grease entering the sewer system

Figure A.16: Gravity Mains Environmental, Financial and Other Essential Parameters

HOUSEHOLD/ COMMERCIAL/ INDUSTRIAL				
Component	Parameter	Unit	Brief Explanation	Level of Importance
Gardens/ green Roofs	Structural parameters			
	Green roof type	Extensive/ Intensive	Type of green roof area	Desirable
	Area of roof	%	Percentage of green roof area in total roof area	Desirable
	Green area of roof	m2	Green area of green roof	Desirable
	Green roof height	Level	Floor that green roof is located on	Desirable
	Substrate depth	cm	Depth of substrate	Desirable
	Continuous coverage of substrate	%	Percentage of area covered by substrate in green roof	Desirable
	Drainage	Yes/No	Presence of drainage system	Desirable
	Area exposed to sunlight	%	Percentage of sunlight-exposed concrete area in total hardscape area	Desirable
	Permeable surface area	%	Percentage of permeable surface area in green roof	Desirable
	Storage reservoirs	Yes/No	Existence of water containers, e.g. bird baths and barrels and ponds	Desirable
	Water Sources	Yes/No	Ponds, swimming pools, basins and water tap	Desirable
	Connectivity to natural habitat	Yes/No	The near green area at ground level within a 200m radius from green roof	Desirable
	Physical parameters			
	Soil pH	0-14	Indication of the acidity or alkalinity of soil and is measured in pH units	Desirable
	Light soil	Yes/No	Light soil refers to a soil high in sand relative to clay	Desirable
	Undisturbed soil	Yes/No	Open area that is not disturbed by vegetation or any constructions	Desirable
	Topographic variation	Yes/No	Topographic variation, e.g., sloped surfaces, different heights of garden beds, flowerpots and edging	Desirable
	Perching habitat	Yes/No	Provision of elements for attraction insects and birds to perch, e.g., branches, logs and rocks	Desirable
	Sunlight hours	hrs/day	Number of hours of sunlight per day	Desirable

Figure A.17: Green Roofs Parameters

STORMWATER SYSTEM PERFORMANCE PARAMETERS			
Physical/Structural Attributes			
Parameter	Unit	Range	Explanation
Pipe Material	Type	RCP, PVC, CMP, HDPE, Clay, Brick	Pipes made from different materials differ in design life, thickness, diameter and failure pattern
Pipe Diameter	inch	<12, 12-18, 18-36, >36	Rate of pipe failure and failure pattern vary with pipe diameters
Depth of Cover	feet	<10, 10-25, >25	The Depth from surface to crown of pipe determines the effect of the surface loading and protection from frost. It also effects the pipe failure mode and mechanism
Pipe Age	Years	<10, 10-24, 25-49, 50-75, >75	Effects of pipe deterioration becomes more apparent with time
Pipe length	feet	0-100, 100-200, 200-300, 300-400, >400	Long length pipes have a higher chance of being in poor condition due to the presence of more joints
Pipe Thickness	% loss	10%, 10%-20%, 20%-30%, >30%	
Pipe Shape	Type	Circular, rectangular, oval, egg, other	Different pipe cross-section shapes result in different failure modes and deterioration
Slope	gradient	Greater, Equal, Less - than the minimum required gradient	Slope effects the rate of gravity flow and may result in blockage or sedimentation. It also effects the deterioration rate
Pipe Joint	Type		A few type of joints might result in premature failure for example leadite joint
Pipe Coating	Yes/No		External protection provided on pipe to protect from corrosion
Pipe Lining	Yes/No		Internal lined pipes are less susceptible to corrosion and I&I
End section	Yes/No		End sections are discharge points of stormwater system. They are tracked, inspected and reviewed in a separate way from the pipe

Figure A.18: Stormwater Performance Essential Physical/Structural Parameters

STORMWATER SYSTEM PERFORMANCE PARAMETERS			
Environmental Attributes			
Parameter	Unit	Range	Explanation
Pipe Location	Area	Urban, Sub-urban, Rural, coastal, Industrial, agricultural	Location of pipe determines the amount of stormwater flowing into the pipe. Large water quantities can lead to high stress
Root Intrusion	Nominal Categorical	High, Medium, Less	Tree roots cause pipe blockages
Groundwater level	Nominal Categorical	In vicinity of invert, generally below invert, indeterminate	Presence of groundwater causes ground loss and subsequent lack of support to pipes. It also affects soil loading on pipe and pipe deterioration rate
Loading condition (Dead Load)	Nominal Categorical	High(increased significantly from the day of installation), Medium (changed from the day of installation), Low(did not change from the day of installation)	Depends on depth of pipe and infrastructure above
Loading Condition(Live Load)	Average Daily Traffic (ADT)	High (>6000 ADT), Medium(>1500 and <6000), Low(<1500)	Heavy live load like Traffic can result in high compressive stress on pipe walls
Rainfall Max	inch/year	> design storm, in the range of design storm, < design storm	Rainfall determines the amount of water that flows into the stormwater pipe and at what rate
Rainfall average	inch/year	> design storm, in the range of design storm, < design storm	
Frost penetration	Yes/No		Frozen soil leads to increase in pipe loading, which results in pipe dwindling or defects
Soil pH	Type	Moderate pH 5-9, aggressive (pH>5 and pH<9)	Low or High pH can accelerate the deterioration process
Pipe bedding	Nominal Categorical	Good, Bad, Poor	Improper bedding may result in premature pipe failure or beam stress
Backfill type	Type	clay, granular, variable soil, concrete, other unknown material	Some backfill materials are more corrosive and can experience significant volume changes that result in loading changes on the pipes
Change in Temperature	Nominal Categorical	High(>70F) , Medium (30 F-70 F), low (<30 F)	Change in atmospheric temperature can result in stresses to pipe and the soil surrounding it
Extreme Events	Description		Any natural calamity or extreme event effecting stormwater pipes
Soil Disturbance	Yes/No		Third party disturbance that led to direct or indirect damage to pipe

Figure A.19: Stormwater Performance Essential Environmental Essential Parameters

STORMWATER SYSTEM PERFORMANCE PARAMETERS			
Parameter	Unit	Range	Explanation
Operational/Functional Attributes			
Flow velocity	Nominal Categorical	High(> =15ft/s), Medium(4-14ft/s), Low(<=3ft/s)	Flow velocities should be greater than 2 ft/s, to avoid sedimentation. Also, excessive velocities are not recommended because they lead to surface wear
Overflow Frequency (no.of overflows per year)	Nominal Categorical	Frequent (weekly, monthly) & High magnitude, Frequent & low magnitude, occasional (1-12 times per year) & high magnitude, occasional & low magnitude, no	Overflows indicate the service failure of the stormwater pipe
Smell	Yes/No		Smell in the pipe indicates that debris is present which might be effecting the hydraulic capacity as well
Insects	Yes/No		Insects around the pipe indicate present of biodegradable waste which might be reducing the hydraulic capacity of pipe and also altering the water quality
Debris Level (leaf matter, trash or other material)	Nominal Categorical	Significant, Moderate, Minor	Blockage effects the hydraulic capacity of the stormwater pipe
Sedimentation Level	Nominal Categorical	High(76-99%), Medium(26-75%), Low(<=25%)	Sedimentation also effects the hydraulic capacity of stormwater pipe
Presence of stagnant water within structure	Yes/No		Important if the pipe material is Metal as it leads to increased rate of corrosion
Inflow/Infiltration	Nominal Categorical	High (>51%), Medium (26-50%), Low (<25%)	I&I effects the quality of stormwater
Maintenance methods	Type		Cleaning methods like jetting can compromise the structural integrity of pipe
Maintenance frequency	Nominal Categorical	Very often (1-3 years), Regularly (3-5 years), Rarely (> 5 years), Never	
Inspection/CCTV Record	Feedback	Excellent, Average, Poor	Pipe inspection provides information about pipe sections identified to be in poor condition
Pipe Renewal Record	Description		Record of pipe renewal type and year of renewal
Pipe Failure Record	Description		Record of pipe failure and year of failure
Runoff rate	Nominal Categorical	High, Medium, Low	Large velocities of the runoff can deteriorate the pipe
Complaints	Type	flooding, pollution, blockage	Complaints provide a fair idea of the problems associated with the pipe
Other Attributes			
Annual operational cost	Dollar/year		Cost spent for operating and functioning for the pipe segment
Annual maintenance cost	Dollar/year		Cost of maintenance like routine cleaning for the pipe segment

Figure A.20: Stormwater Performance Essential Operational/Functional and Other Essential Parameters

The recommended parameters to be collected from the social subsystem are shown in Figures A.21, A.22 and A.23.

COMPONENT		PARAMETERS	UNIT	EXPLANATION	LEVEL OF IMPORTANCE
Community	Residential, Commercial and Industrial Customers	Willingness to Pay	\$	Willingness of customers to pay decreases with increase in tariffs.	Essential
		Water Consumption Billing	\$	Annual revenue collected from tariffs helps fund the sewershed O&M operations. Water Consumption/billing: Water Consumption every 15 min is collected, however, aggregated monthly average water consumption is currently being used for analysis.	Essential
		Types of customers	Type, Number	Most watersheds contain multiple communities (overlapping boundaries of social organizations) that range from residential neighborhoods to industries to school districts and so on.	Essential
		Customer Feedback	1-5 level of satisfaction	The ability to meet customers needs is a direct reflection of the effectiveness of wastewater management operations. To represent these concepts requires mixed methods including historical archival analyses, sentiment analysis using AI, survey work, and in-depth interviews. This can be measured on a scale of 1 to 5 with 1 being the lowest and 5 being the highest level of satisfaction.	Essential
	Population	Overall Population	Number	A wide variety of secondary data on population and place characteristics are available for examining social and economic conditions. Population density is also used in determining wastewater utility asset and operation capacities.	Essential
		Current system demand	Annual	Allocation of water resources by population type and density.	Essential
		Stakeholder Type	Type	Wastewater operations affect a variety of stakeholders that may include regulatory groups, community groups, local authorities, contractors and suppliers, policymakers, employees, investors (if any), customers and also the environment	Essential
		Population Distribution	Number per type	Density of population in different parts of the service area dictates wastewater operations.	Essential

Figure A.21: Community Parameters

COMPONENT		PARAMETERS	UNIT	EXPLANATION	LEVEL OF IMPORTANCE
Policy/ Governance/ Regulations	Organizational Parameters	Types of Departments	Types	The types of departments and number of teams for specialized wastewater operations indicates the level of preparedness and organizational maturity. For example, presence of teams overlooking data analysis can indicate more data driven decision making in the utility.	Essential
		Sewershed Operations Team Strength	Number	Dedicated teams for managing sewershed can indicate structured management approach	Preferable
		Resource Availability	High/Medium/Low	Availability of staff, materials and equipment (for O&M) indicates the efficiency of sewershed management operations	Preferable
	Standards/ Guidelines/ Manual of Practice	Level of Service expectancy	Yearly Number of CSO and SSO Events	Level of Service expectancy among the customers indicates the performance standards expected out of the wastewater systems and can be indicated by the number of CSO and SSO events in a particular year	Preferable
		Presence of Asset Management Plans	Yes/No, Type	Asset management plans formalizes the sewershed management protocols based on reliability of the service and minimization of overflow events. This helps develop systematic plans to improve and sustain the performance of sewershed operations	Preferable
	Laws, Regulations and Bylaws	Applicable Regulations	Type	List of all federal, state, local regulations on the treatment and discharge of wastewater	Essential
		Regulatory compliance	Yes/No	Compilance on monitoring and reporting requirements from different federal, state and local regulations like the CWA and NPDES discharge limits	Essential
		Regulatory fines	\$	Regulation and enforcement are used to motivate sustainable practices.	Essential

Figure A.22: Policy, Governance and Regulation Parameters

COMPONENT		PARAMETERS	UNIT	EXPLANATION	LEVEL OF IMPORTANCE
Finance and Economic	Financial	Bonds	\$	Investments in water utilities are a source of their funding	Essential
		Federal Funds	\$	Funding given by the federal government allocated for wastewater operations.	Essential
		State Funds	\$	Funding given by the state government allocated for wastewater operations.	Essential
		Taxes	\$	Local and regional data are fragmented and depend on funding for systematic testing.	Essential
	Budgeting	Annual O&M Budget	Annual	Aggregated yearly budget allocated for funding O&M operations including asset renewal.	Desirable
		Annual CIP Budget	Annual	Aggregated yearly budget allocated for funding Capital operations including asset replacement.	Preferable

Figure A.23: Finance and Economic Parameters

Appendix B

Recommended Modeling Techniques

The following figures present the recommended modeling techniques for sewershed-scale modeling that were developed based on the literature reviews, case studies developed and discussions with participating utilities. The techniques are organized based on the three subsystems as defined in this framework - natural, built and social.

WATER					
Infrastructure Component	Focus Area	Parameters (with units)	Modeling Technique	Explanation	Modeling Type
Rivers/ Lakes/ Streams/ Oceans	Contaminant Prediction, Flow Prediction	Contaminant concentration, flow zone area, storage zone area, mass exchange rate, flow velocity, flow depth	Machine Learning	In this study, a framework combining Machine Learning (ML) and the Transient Storage zone Model (TSM) was developed to predict the spill location and mass of a contaminant source	Probabilistic
		Water quality parameters (BOD, COD, pH, conductivity, etc.)	Artificial Intelligence Algorithm	In this work, advanced artificial intelligence (AI) algorithms are developed to predict water quality index (WQI) and water quality classification (WQC).	Probabilistic
		BOD, metal concentrations, anionic and cationic concentrations, pH	Analytical Methods	Due to the urbanization and industrialization, new pollutants have been reported in the water bodies and explored for understanding the status of this contamination. The plan of water quality surveillance and checking programs is to pursue a stepwise methodology, given a rationale conspire.	Deterministic
	Pollutant transport	Concentration, mean flow velocity, distance from point of well mixing, fluid density, dynamic viscosity, etc.	Artificial Neural Networks, Mathematical Modeling	This study uses the results of ANN and finite element modeling as an input parameter in the numerical modeling of pollutant transmission in rivers.	Deterministic
		NO3 concentration, PO4 concentration, water flow rate, etc.	Mathematical Modeling	This study explores mathematical modeling and computer simulation of diffusion and transport of chemicals in rivers.	Deterministic
		Physical and chemical parameters of water quality (pH, conductivity, BOD, COD etc.)	Hydrological Modeling	Explains the basics and methods for advanced simulation models of pollutant transport in rivers and streams.	Review
	Risk Analysis	Pollution Parameters (Ammonia nitrogen, Nitrite nitrogen, BOD5, COD, Petroleum, and Potassium)	Modified Non-Linear Model	Risk analysis of a natural resource (river) of contaminants based on a non linear model in order to aid water management.	Probabilistic
	Rehabilitation	Flow Fields, Bottom Shear Stresses, Flow Velocity, Water Depth	Hydraulic-Habitat Modeling	The use of a combined 2D hydraulic modeling with habitat modeling in order to design the rehabiliation management for an urban river	Deterministic

Figure B.1: Modeling techniques for modeling of rivers/lakes/oceans/streams/oceans

Infrastructure Component	Focus Area	Parameters (with units)	Modeling Technique	Explanation	Modeling Type
Runoff Water	Surface Runoff Modeling	Precipitation, Retention Parameter, Initial Abstraction	ANN	This study compares the ANN and mathematical modeling techniques to cross evaluate the results and adopt a generalized ANN model.	Probabilistic
			TOPMODEL	TOPMODEL can be used in catchments with shallow soil and moderate topography.	Deterministic
			HBV	HBV gives satisfactory results for runoff modeling.	Deterministic
			MIKE-SHE	Requirement of large data and physical parameters makes the use of MIKE SHE model limited to smaller catchments.	Deterministic
			VIC	VIC performs well in moist areas and can be efficiently used in the water management for agricultural purposes.	Deterministic
			Stanford Watershed Model	This study applies the Stanford Watershed Model to estimate a rainfall-runoff relationship.	Deterministic
			KINEROS	The kinematic runoff and erosion model KINEROS is an event oriented, physically based model describing the processes of interception, infiltration, surface runoff and erosion from small agricultural and urban watersheds.	Deterministic
	Quality and Quantity Assessment		PRMS	The Precipitation-Runoff Modeling System (PRMS) is a deterministic, distributed-parameter, physical process based modeling system developed to evaluate the response of various combinations of climate and land use on streamflow and general watershed hydrology.	Deterministic
			HSPF	HSPF is used to simulate water quantity and quality processes on a continuous basis in natural and man-made water systems. It uses input meteorological forcing data and parameters related to system geometry, land use patterns, soil characteristics, and land use activities (e.g., agricultural practices).	Deterministic
			SMR	This study compares two models, HSPF and SMR, and found that overall hydrographs of this comparison had minimal differences, but SMR was more accurate in summer periods when saturation excess was a major factor in runoff generation.	Deterministic
	Stormwater Management		LID	Low impact development (LID) refers to systems and practices that use or mimic natural processes that result in the infiltration, evapotranspiration or use of stormwater in order to protect water quality and associated aquatic habitat.	Stochastic
Overflow Risk Forecasting	Stochastic Greybox Model	Probabilistic runoff forecasts generated by stochastic greybox models can be notably useful for the improvement of the decision-making process in real-time control setups for urban drainage systems because the prediction risk relationships in these systems are often highly nonlinear.	Stochastic		

Figure B.2: Modeling techniques for modeling of runoff

Infrastructure Component	Focus Area	Parameters (with units)	Modeling Technique	Explanation	Modeling Type
Groundwater	Pollutant Source Identification	Fluid viscosity, density, pressure, concentration, aquifer thickness, hydraulic head, etc.	Optimization Model	In this study, a source identification methodology is proposed that uses a classical nonlinear optimization model linked to a flow and transport simulation model. The groundwater flow and transport simulator is linked to the nonlinear optimization model as an external module.	Deterministic
		Transmissivity, Conductivity, Hydraulic head, volume flux per unit area, concentration, thickness of aquifer, etc.	ANN	This study uses artificial neural network (ANN) to identify the sources of groundwater pollutant in terms of its location, magnitudes, and duration of activity.	Probabilistic
	Flow and contaminant transport modelling	Transmissivity, Conductivity, Storage Coefficient	Finite Difference Method, Finite Element Method, Analytical Element Method	Groundwater models are being applied to predict the transport of contaminants for risk evaluation. They describe the groundwater flow and transport processes using mathematical equations based on certain simplifying assumptions.	Deterministic/Probabilistic
	Groundwater Infiltration	Porosity, Defect Sizes, Hydraulic Conductivity, Groundwater Head, Sewer Radius	GWl Prediction using calibration	Collection systems in coastal cities are often below the groundwater table, leading to groundwater infiltration (GWl) through defects such as cracks and poor lateral connections. A method has been developed to predict GWl when groundwater levels change using calibration with sewershed flow monitoring data.	Deterministic
	Groundwater Quality Assessment	Groundwater concentration, flow velocity, distance of considered area from pollutant source, dispersion coefficient	Numerical Modeling	In this research, a long term groundwater quality assessment in heterogenous soil model is proposed. Two numerical models are introduced, the traditional forward time centered space finite difference technique is used to approximate the groundwater pollutant concentration in an area around a landfill and the new fourth-order finite difference technique with Sauljev method is also employed to approximate the solution.	Deterministic
		Water Quality Parameters	Water Quality Index method (WQI)	This study assesses the suitability of groundwater collected from South West Delhi, India, for irrigation and drinking purpose on the basis of various water quality indices.	Deterministic
	Risk Assessment	Groundwater quality and quantity parameters, Best Management Practices	Groundwater Risk Assessment Model (GRAM)	This study uses GRAM based on a multi-barrier approach using likelihood of release, contaminant pathway and consequence equation. It incorporates multiple parameters relating to groundwater quality, quantity, management practices and emergency measures to reduce parameter uncertainty.	Deterministic
		Depth to water table (D), net Recharge (R), Aquifer media (A), Soil media (S), Topography (T), Impact of the vadose zone (I), and hydraulic Conductivity (C)	Fuzzy Comprehensive Evaluation using DRASTIC model	In order to deal with the uncertainty in the risk assessment of groundwater contamination, this study proposes an approach with analysis hierarchy process and fuzzy comprehensive evaluation integrated together.	Probabilistic

Figure B.3: Modeling techniques for modeling of groundwater

Infrastructure Component	Focus Area	Parameters	Modeling Technique	Explanation	Modeling Type
Wastewater	WASTEWATER QUALITY ASSESSMENT				
	Quality assessment	Water quality parameters (BOD, COD, pH, Turbidity, etc.)	Non-Linear Regression Model	In this study a regression-based nonlinear model was developed to predict BOD effluent concentration from the proposed VFCW system.	Probabilistic
		Physical and chemical water quality parameters	Qualitative and Quantitative Assessment	Assessment of grey water measurement and quality measurement	Deterministic
	Contaminant fate and transport	Source, and the regional climate and hydrogeological conditions	Industrial Waste Management Evaluation Model (IWEM)	IWEM is a screening level ground water model developed to evaluate ground water impacts from industrial waste management practices or the beneficial reuse of industrial materials. The software helps determine the most appropriate liner design for a waste management unit that is protective of human health as well as ground water resources.	Deterministic
	Risk Assessment	COD, BOD, nitrates, total nitrogen, phosphorus, ammonia, suspended solids	Statistical Analysis	This study presents a framework to evaluate the risk presented by industrial wastewater at wastewater treatment plants using statistical methods and Failure Mode and Effect Analysis (FMEA).	Probabilistic
Gardens/Green Roofs	GREEN ROOF PERFORMANCE				
	Water retention efficiency	Flow Factor, Roof Thickness	Geospatial analysis, deterministic modeling	Retention efficiency of the rain garden/green roofs can be modelled and assessed.	Deterministic
	Hydrologic Performance	Rain gauge data, Land Use, Manning Coefficient	Hydrological Modeling	Hydrological modelling of green roof performances using historical rain gauge data	Probabilistic

Figure B.4: Modeling techniques for household/commercial/industrial wastewater infrastructure

Infrastructure Component	Focus Area	Parameters	Modeling Technique	Explanation	Modeling Type	
LATERAL PIPE PERFORMANCE						
Lateral Pipes	Pipe Failure Prediction	Pipeline attributes, environmental factors and historical pipeline broke/breaks records	AutoML	AutoML is able to predict the pipe age vs failure count from historical data	Probabilistic	
	Pipe Condition Assessment	Length, Dia, Material, Age, Slope	Markov Chains	This paper uses the Markov chain method to conduct performance prediction to pipes.	Probabilistic	
		Length, Dia, Material, Age, Bedding material, Depth	Back propagation and probabilistic neural network	This paper presents a study which uses artificial neural networks to investigate the importance and influence of certain characteristics of sewer pipes upon their structural performance, expressed in terms of condition rating.	Probabilistic	
	LATERAL PIPE RENEWAL					
	Renewal Techniques	Number of burst pipes, Pipe Diameter, Age, Length	Genetic Algorithm	This paper presents a decision support tool for replacement of damaged water mains based on a multi-objective strategy developed as a genetic algorithm.	Probabilistic	
Failure Rate and Rehabilitation Time Estimation	Historical failure, Pipe characteristics, hydraulic pressure, soil type and pipe locations	Artificial Neural Networks	This paper presents an application of Artificial Neural Networks (ANN) to model the failure rate and estimate the optimal replacement time for the individual pipes in an urban water distribution system.	Probabilistic		
SEPTIC TANK RISK						
Septic Tanks	Impact on Groundwater Quality	Saturated Hydraulic Conductivity, Longitudenal Dispersivity	Numerical Modelling	Contamination of groundwater from onsite disposal of septic tankeffluent is an increasing concern. Numerical models are useful tools for the quantitativeassessment of the impact of onsite systems on ground-water quality and the elucidation of the importance offactors that control contaminant concentrations in re-ceiving waters.	Deterministic	
	Risk Analysis	Drainfield type, Tank Capacity, Soil Topographical Index (STI)	Regression Analysis	This paper presents a novel GIS-based framework for assessing septic system vulnerability using a database of known septic system specifications and a modified Soil Topographic Index (STI) that incorporates seasonal high groundwater elevation to assess risks posed to septic sys-tems in coastal Georgia.	Probabilistic	

Figure B.5: Modeling techniques for household/commercial/industrial wastewater infrastructure

	PIPE PERFORMANCE				
Infrastructure Component	Focus Area	Parameters	Modeling Technique	Modeling Type	
Gravity, Force Mains	Structural Integrity, Hydraulic Performance	Internal pressure, traffic loading, corrosion, soil interaction, vibrations, natural effects,	Artificial Neural Networks, Bayesian Networks, Random Forest	Probabilistic	
	Capacity analysis	pipeline material, machining flaws, stresses within walls	Fuzzy Logic	Probabilistic	
	Leakage detection		Genetic Algorithm	Probabilistic	
	Sewer Pipe Condition Assessment	Roots, debris, encrustation, protruding,	Peak score (WRc)	Probabilistic	
	LoF Prediction	LoF, CoF, condition and risk scores	Mean score, Total score, Peak score	Probabilistic	
	Condition Prediction	Type, Length, Dia, Material, Age, Slope, Depth	Neural networks	Probabilistic	
	Condition Prediction	Age, velocity, flow	Logistic regression	Probabilistic	
	Condition Rating	Internal, External and Hydraulic factors	AHP	Deterministic	
	Operational Condition Failure	Flow, Infiltration, Gradient, Blockage, Root Intrusion, Condition, O&M History, Pumping Station/Screening Equipment Failure	Multiple regression	Probabilistic	
	Condition/Structural Performance Prediction	Length, Dia, Material, Age, Bedding material, Depth	back propagation and probabilistic neural network	AI	
	Deterioration Modeling	Length, Dia, Material, Age, Slope	Markov Chains	Probabilistic	
	Condition Scoring	Defect type	Intermediate aggregation approach—NASSCO	Deterministic	
	Corrosion Modeling	Concrete pipes, H2S concentration	Non-Linear Ordinary Differential Equations	Deterministic	
	Condition prediction	Age, diameter, traffic loading, material, soil condition, surroundings	Multicriteria decision making (fuzzy)	AI	
	Condition Scoring	Failure data, discounting rate	Mean time to failure (MTF)	Statistical Analysis	
	Condition Assessment	CCTV Image dataset: defect longitude, debris silty, joint faulty, joint open, lateral protruding, and surface damage	Convolutional neural networks	AI	
	Performance Prediction	pipe characteristics, internal and external environmental factors	Fuzzy Logic, Markov Chains	AI, Probabilistic	
	Failure Prediction	material, network type, soil type, water type and section type	Logistic regression, Genetic Algorithm	Probabilistic	
	Pipe Failure prediction	Pipeline attributes, environmental factors and historical pipeline broke/breaks records	AutoML	Probabilistic	
	PIPE RENEWAL				
	Ranking Modeling	Hydraulic, Structural performance and consequences	Fuzzy Logic	AI	
	PIPE RISK				
Criticality Assessment	GIS points and lines for graph edges and nodes, pipe characteristics	ordered weighted averaging (OWA), Graph theory	Probabilistic		
PIPE FINANCIAL					
Remaining Life Analysis	Physical, Functional, Environmental and Financial Parameters of wastewater pipes	Fuzzy Logic	probabilistic		

Figure B.6: Modeling techniques for gravity mains and force mains

Infrastructure Component	Focus Area	Parameters	Modeling Technique	Modeling Type	
Treatment & Types of Treatment Plants	Treatment Plants (all types)		Energy consumption, wastewater inlet volume, energy intensity, water quality parameters	Machine Learning	Probabilistic
		Cost Modeling	Management costs, sludge removal efficiency, components of sludge, etc.	Statistical Modeling	Probabilistic
		Risk Assessment	Legal Risks, Financial Risks, Management Risks, Design Risks, Ecological Risks	Statistical Analysis	Probabilistic
	Sewage Treatment Plants	Nitrogen Removal, UV absorbance, TOC, Turbidity	Nr removal, water quality, soil Nr accumulation, N2O emissions, emperical data	Bayesian Belief Nets	Probabilistic
		Risk Analysis	Type of Event, Type of Risk	Analytical Techniques	Probabilistic
	Effluent Treatment Plants	Short-term effluent prediction	influent pH, COD, total solids (TS), temperature (T), free ammonia (FA), ammonia nitrogen (AN) and total Kjeldahl Nitrogen (TKN)	SVM, Fuzzy Logic	Probabilistic
	Activated Sludge Plants	Optimization	Growth rate, VSS to COD ratio	Artificial Intelligence	Probabilistic
	Common and Combined Effluent Treatment Plants	Reliability and Performance Evaluation	BOD, COD, TSS	Mathematical Modelling	Deterministic

Figure B.7: Modeling techniques for wastewater treatment plant infrastructure

Infrastructure Component	Focus Area	Parameters	Modeling Technique	Modeling Type
Catch Basins/ Inlets	Conveyance, Capacity and Efficiency	Flow rate, Slope Gradient	Hydraulic Modelling	Probabilistic
	Efficiency	Inlet flow rate, flow captured by inlet, pass-over flow	Mathematical Modeling	Deterministic
CSO/SSO	Capacity and Condition Assessment		Synthetic unit hydrograph (SUH) approach for prediction	Probabilistic
	RDII/SSO reduction		Computer analysis (RTK method, Genetic Algorithm)	Probabilistic
	Extreme Rainfall Impact	Flow rate, Transmissibility, Flow Coefficient	RDII Modeling	Probabilistic
Manholes	Corrosion Analysis	VOC concentration, Sulphate Concentration, Biodeterioration	Finite Element Analysis, ANN	Probabilistic
	Geometrical Efficiency	Structural integrity	Mathematical Modeling	Deterministic
	Condition Assessment	Defective component of Manhole, Flow Type, Flow Rate	Data Analysis	Probabilistic
	Renewal Technologies	Structural Integrity, Defects	Physical Inspection	Physical
Pumps/Lifting Stations	Costs	Energy consumption types, cost breakdown, pump head, system pressure, sewer water quality	LCA/LCCA	Deterministic
			LCA/LCCA	Deterministic
	Flood prevention, reduced pollutant risk		Fuzzy Logic	Probabilistic
	Energy Cost Saving	Pump head, system pressure, sewer water quality	Genetic Algorithm	Probabilistic
	Performance Analysis	Energy consumption, wastewater flow rate, wet well elevation, speed of pumps	Data Mining Algorithms	Probabilistic
Reliability Analysis	Static head, pumping head, inlet & outlet flow rate	Hybrid Neural Networks, Genetic Algorithm	Probabilistic	

Figure B.8: Modeling techniques for catch basins, CSO and SSO events, manholes and pumps

Infrastructure Component	Focus Area	Parameters	Modeling Technique	Modeling Type
Stormwater Pipes	Performance Analysis	Pipe physical parameters, Climate characteristics, Flow Velocity, Overflow frequency etc.	Weighted Factor Framework	Deterministic
	Pipe Failure prediction	Pipeline attributes, environmental factors and historical pipeline broke/breaks records	AutoML	Probabilistic
	LoF Prediction	LoF, CoF, condition and risk scores	Intermediate aggregation approach - NASSCO	Deterministic
	Physical and Functional Performance Prediction	Capacity, Blackage, Surface Wear, Structural, Load/Deformation	Fuzzy inference method	probabilistic
			Analytic hierarchy process (AHP), weighted summation	Deterministic
			Weighted summation	Deterministic
	Condition Prediction	Age, Dia, Material, Traffic Loading, Condition, Surroundings	Multi criteria decision making	probabilistic
	Deterioration Modeling	diameter, construction material, soil type, and exposure classification	Markov Chains, Bayesian Probability	probabilistic
	Serviceability Deterioration	Size, age, depth, no. of trees around pipe, slope	Markov Chains	probabilistic
	Remaining Life Analysis	Physical, Functional, Environmental and Financial Parameters of wastewater pipes	Fuzzy Logic	probabilistic
	Inspection and Maintenance Prediction	CCTV data	Markov Chains, Monte Carlo Simulations	Probabilistic
	Performance Index	Physical, Environmental, Operational	Fuzzy Logic	AI
Mean Time to Failure and Condition Prediction	Break History	Mean Time to Failure (MTF)	Probabilistic	

Figure B.9: Modeling techniques for stormwater pipes

Infrastructure Component	Focus Area	Parameters	Modeling Technique	Modeling Type
Permeable Pavements	Hydraulic Behaviour	Hydraulic conductivity, Effective Saturation, Porosity	Reservoir Element Model	Deterministic
	Performance Analysis	Rainfall intensity, runoff coefficients, pavement design parameters	Hydrologic Modeling	Deterministic
	Life Cycle Analysis	Flooding parameters, Water purification parameters, water recycling parameters	Life Cycle Analysis	Probabilistic
Bioswales	Bioswale Efficiency	Width of flow, Skew factor, Slope, Imperviousness	SWMM	Deterministic
	Condition Assessment	Flow rate, thickness of soil, piezometric head, elevation head	SWMM	Deterministic
Gardens/Green Roofs	Water retention efficiency	Flow Factor, Roof Thickness	Geospatial analysis, deterministic modeling	Deterministic
	Green Roof Ecosystem Assessment	Structural, Physical, Biological and Management Factors of Green Roofs	Data Analysis	Deterministic
	Hydrologic Performance	Rain guage data, Land Use, Manning Coefficient	Hydrological Modeling	Probabilistic
Impervious Surfaces	Maintenance & Rehabilitation	Contour level, interval, index interval (heavy contours), label, colour, etc.	Road Surface Survey method	[a] Deterministic
	Impervious Surface Modelling	Efficiency during rainfall or extreme event	Impervious Surface Growth Model (ISGM)	Probabilistic
	Performance Analysis	Pavement thickness, climate characteristics, soil characteristics	Analytical Techniques	Deterministic/Stochastic

Figure B.10: Modeling techniques for various stormwater infrastructure

Infrastructure Component	Focus Area	Parameters (with units)	Modeling Technique
Community	Customers	Human impact on stormwater runoff	Conceptual Model
	Population	Metric Understanding	Community, Demographics, Public Perception
	Business		
Policy/ Governance/ Regulations	Organizational Structure	Impact of Organizational Structure on Asset Management	Maturity of Asset Management Plans
	Standards/ Guidelines/ Manual of Practice	Management Practices	Best Management Practices
	Laws, Regulations and Bylaws	Regulations, Economic Impacts	Regulatory Fines
Finance and Economic	Funding Sources	Asset Management	Asset Management Practices, Source of funding
		Willingness to Pay	Willingness to Pay
	Lifecycle Economics	Life Cycle Assessment	Potable water treatment volume, CSO/stormwater/combined sewage treatment volume

Figure B.11: Modeling techniques for social subsystem components

Appendix C

iWISE Framework Questionnaires

This questionnaire is an assessment tool to assess the readiness of a utility across all iWISE building blocks to help utilities prioritize focus areas and improve in line with the utilities' overarching iWISE ambitions at a sewershed scale. This questionnaire evaluates iWISE readiness and capability across the seven technical building blocks to create a holistic view of the utility's iWISE readiness.

1. Intelligent Water Systems Definition, Benefits and Enabling Outcomes

The first step to evaluate a water utilities current iWISE application level is to have a fundamental understanding of the term intelligent water, and what benefits and enabling outcomes it offers as a framework. Having a standard and clear definition of iWISE will aid water utilities in having a holistic understanding of iWISE that they can build on as per the recommendations and guidance offered by the building blocks in this framework.

- i. We have proposed the definition of iWISE systems to be **“A System-of-Systems” and “Digital-Approach” for smart, adaptive, and real-time management of engineered and natural water systems driven by societal needs for resilience, sustainability, affordability, reliability, and social justice**. Do you agree with this definition? If not, please provide your own definition/understanding of intelligent water systems in the option “Other”.

Refer to iWISE report: Definition, Benefits, and Challenges [3.1.1, Pg. 6]

- Yes
 No
 Other: Click or tap here to enter text.

- ii. What benefits and enabling outcomes do you wish to achieve from iWISE solutions? (Pick all that apply)

Refer to iWISE report: Definition, Benefits, and Challenges [3.1.2, Pg. 7]

- Right Information to Right People at the Right Time
 Better and Informed Decision-making
 Better Community & Stakeholders Engagement
 Better and Timely Regulatory Compliance
 Efficient and Cost-Effective Wastewater Services
 Better Asset Management & Optimize Capital Investments
 Sustainable & Resilient Water Infrastructure Systems
 Other: Click or tap here to enter text.

- iii. What challenges do you face in regards to implementation of iWISE? (Pick all that apply)

Please enter your answer in option “Other” if there are other challenges you wish to mention that are not mentioned in the options given.

Refer to iWISE report: Definition, Benefits, and Challenges [3.1.3, Pg. 7]

- Creating a cultural shift for a change in mindset
 Making the digital aspects of your wastewater systems resilient to cyber attacks
 Lack of trust in the reliability of new technologies
 Lack of communication among utilities and other stakeholders
 Lack of new talent entering the workforce
 Other: Click or tap here to enter text.

Figure C.1: iWISE Framework Questionnaire

2. Sewershed System-of-Systems Approach

The complex nature of sewershed system of systems comes from the dependent and interdependent characteristics of the subsystems and their components. These complexities need to be understood and considered for a more holistic iWISE approach. Please indicate your responses to the following questions.

- i. We have defined a sewershed boundary as a boundary defined by considering various elements of natural, built, and social sub-systems. Do you agree with this definition? If not, please provide your own definition/understanding of a sewershed boundary in the option "Other".
Refer to iWISE report: Sewershed System-of-Systems Approach [3.2.1, Pg. 8]
 - Yes
 - No
 - Other: Click or tap here to enter text.

- ii. What components do you consider as part of the sub-systems (natural, built and/or social) within the overall sewershed? If the components you consider are not mentioned in the options, please provide your answer in the option "Other".
Refer to iWISE report: Sewershed System-of-Systems Approach [3.2.2, Pg. 9]
 - Built components (built infrastructure assets owned and managed by the utility)
 - Built components and natural components (like surface water, groundwater, landfills, climate)
 - Built components, natural components and social components (like demand patterns, funding sources, policies and regulations)
 - Other: Click or tap here to enter text.

- iii. What types of sub-system/component interactions (interdependencies) within the sewershed system do you consider? (Pick all that apply)
If the interactions you consider are not mentioned in the options, please provide your answer in the "Other" category.
Refer to iWISE report: Sewershed System-of-Systems Approach [3.2.3, Pg. 11]
 - Natural-Social Interactions: Natural sub-systems provide resources for social sub-systems and natural sub-systems benefit from social stewardship.
 - Built-Natural Interactions: Built sub-systems directly affected quality of natural sub-systems, built sub-systems rely on resources from natural sub-systems.
 - Social-Built Interactions: Built sub-systems are designed to meet needs of the society, social sub-systems are dependent on the functioning of the built sub-systems.
 - Other: Click or tap here to enter text.

Figure C.2: iWISE Framework Questionnaire

3. Data Collection and Compilation

The complex nature of sewershed system of systems comes from the interdependent characteristics of the subsystems and their components. These complexities are captured by having a structured approach to collection data from each of these subsystems. The collection of accurate data results in improved ability to measure, analyze and manage the status quo. Therefore, a structured approach to data collection and QA/QC is essential for a reliable system level modeling and data analytics. These analytics can help capture interdependent characteristics and build efficient and resilient models for implementing Intelligent Water Infrastructure System Engineering (iWISE) tasks.

- i. What data parameters do you collect from the natural system? (Pick all that apply)
If the parameters that you collect are not mentioned in the options, please provide your answer in the "Other" category.
Refer to iWISE report: Data Collection and Compilation [3.3.1, Pg. 14]
 - Water (related to factors like contamination of surface water, groundwater and runoff water including inflow and infiltration)
 - Land (related to factors like runoff from landfills and agricultural activities)
 - Climate (related to factors like frequency and duration of extreme events)
 - Other: Click or tap here to enter text.

- ii. What data do you collect from the built system? Built system contains household/commercial/industrial customers, wastewater infrastructure and stormwater infrastructure. (Pick all that apply)
If the data that you collect are not mentioned in the options, please provide your answer in the "Other" category.
Refer to iWISE report: Data Collection and Compilation [3.3.1, Pg. 14]
 - Asset Inventory (locations and identifiers)
 - Asset Performance (current and historical condition)
 - Asset Renewal (historical renewal activity including forensic data)
 - Asset Risk (likelihood of failure, consequence of failure, redundancy and prioritization criteria)
 - Asset Finance (Lifecycle costs of assets)
 - Other: Click or tap here to enter text.

- iii. What data do you collect from the social system for supporting your iWISE operations? (Pick all that apply)
If the data that you collect are not mentioned in the options, please provide your answer in the "Other" category.
Refer to iWISE report: Data Collection and Compilation [3.3.1, Pg. 14]
 - Community (like system demand and revenue data based on customer base)

Figure C.3: iWISE Framework Questionnaire

- Policy, Governance and Regulation (data and information to show human and financial resource availability, applicable laws and regulations related to the sewershed)
 - Financial and Economic (like revenue, different funding sources and asset management budgets)
 - Other: Click or tap here to enter text.
- iv. Is your collected data characterized based on the source of the data? If so, what are the sources of these data parameters? (Pick all that apply)
If the data sources that you consider are not mentioned in the options, please provide your answer in the "Other" category.
Refer to iWISE report: Data Collection and Compilation [3.3.2, Pg. 15]
- Utility Instrumentation Data (CCTV, Meters, Sensors or other IoT devices)
 - Utility Operational Data (EAM, LIMS, GIS, SCADA, etc.)
 - External data (USGS, EPA, CDC, NOAA, etc.)
 - Other: Click or tap here to enter text.
- v. Does your utility have Data Quality Protocols (DQPs) to verify and improve the quality of the collected data? If yes, please indicate the aspects of DQP included. (Pick all that apply)
If the aspects of DQP that you consider are not mentioned in the options, please provide your answer in the "Other" category.
Refer to iWISE report: Data Collection and Compilation [3.3.3, Pg. 16]
- Project Planning (establishing DQP team, identifying data quality objectives, identifying training protocols, documentation protocols)
 - Sampling Process Design: Methods, Locations, Frequency
 - Instrument Calibration, Testing and Maintenance
 - Data Management, Assessment, Oversight and Reporting
 - Field and Lab Generated Data Quality Control
 - Data Review, Assessment, Oversight, Reporting and Verification & Validation (V&V) Protocols
 - Have not established a DQP program to verify and improve quality of collected data
 - Other: Click or tap here to enter text.

Figure C.4: iWISE Framework Questionnaire

4. Data Governance and Database Management

The collection of data at sewershed scale needs organization and management to ensure access for users, understand data flow within the utility, and protect data from external threats.

Mapping of the flow of data in the utility should be first performed to reduce any redundancies in generating data from same sources. Data cataloging helps describe data to enable utilization by anyone within and outside an organization without needing to read descriptions from the data source. It is also important to define the data integration protocols to enable efficient and accurate querying of information once it is stored safely in the database. Finally, having well defined data workflows helps the user directly access it from the visualization or analysis platform without needing to interfere with the database through queries.

- i. Which of the following tasks do you perform for your data mapping and data cataloging protocol? (Pick all that apply)

If the tasks that you perform are not mentioned in the options, please provide your answer in the "Other" category.

Refer to iWISE report: Data Governance and Database Management [3.4.1, Pg. 18]

- Identification of the different sources of data within a sewershed including any external database utilized for analytical purposes. These sources could be from field devices (like sensors and instruments), internal utility databases (like SCADA or LIMS), or external databases (from USGS, NLCD, NOAA)
- Identification of the different teams (like EHS, Treatment Operations, Modeling, Research, etc.) within the utility organization using sewershed data. These are the destination databases where data will live after transfer and processing.
- Identification of the metadata type, values, and the final format for mapped datasets.
- Develop data flow diagrams showing the flow of data between different departments and teams from the individual data sources.
- None of the above
- Other: Click or tap here to enter text.

- ii. What metadata do you collect and store for describing data as part of your data cataloging process? (Pick all that apply)

If the metadata that you collect are not mentioned in the options, please provide your answer in the "Other" category.

Refer to iWISE report: Data Governance and Database Management [3.4.1, Pg. 18]

- Sampling Characteristics like Site Name, Sewershed Name, Natural/Built/Socioeconomic components involved
- Project Characteristics like responsible contact, timestamp, location, project objectives
- Equipment characteristics like equipment model type, procedure used, maintenance, calibration and testing history
- Parameter characteristics like units, QA/QC history, short form codes, data entry contact
- None of the above
- Other: Click or tap here to enter text.

Figure C.5: iWISE Framework Questionnaire

- iii. Do you integrate different types of big data in your utility? If yes, what types of big data are you able to integrate? (Pick all that apply)
If the types of big data that you consider are not mentioned in the options, please provide your answer in the "Other" category.
Refer to iWISE report: Data Governance and Database Management [3.4.2, Pg. 20]
- Large data files (20 terabytes or larger)
 - Data from social networks
 - Unstructured data (e.g., video, open text, voice)
 - Geospatial/location information
 - Sensor data
 - Telematics/vehicular data
 - None of the above
 - Other: Click or tap here to enter text.
- iv. What aspects of data lifecycle are automated in your data workflow? (Pick all that apply)
If the aspects of data lifecycle that you automate are not mentioned in the options, please provide your answer in the "Other" category.
Refer to iWISE report: Data Governance and Database Management [3.4.3, Pg. 22]
- Data access and sharing
 - Data privacy, security and integrity
 - Integration, Interoperability and Reusability
 - Curation, Provenance and Findability
 - Analytics and Visualization
 - None of the above
 - Other: Click or tap here to enter text.
- v. What aspects of interoperability have you incorporated in your database Information Systems (IS)? (Pick all that apply)
If the aspects you incorporate are not mentioned in the options, please provide your answer in the "Other" category.
Refer to iWISE report: Data Governance and Database Management [3.4.4, Pg. 23]
- Data Standardization for all collected data
 - Metadata Management through clear and consistent metadata standards
 - Data Security and Privacy
 - Data Governance in the form of clear data policies
 - Interoperability Testing before Deployment
 - Stakeholder Engagement to ensure database meets needs of all users
 - Capacity Building to maintain databases
 - None of the above
 - Other: Click or tap here to enter text.

Figure C.6: iWISE Framework Questionnaire

5. Data Analytics, Modeling and AI

Modeling for iWISE at a sewershed scale is a complex task requiring the understanding of the various dimensions involved. These dimensions could be at the level of application (system, sub-system, element), domain of insights (informational, engineering, management), mathematics involved (deterministic, probabilistic and AI), to name a few. Supporting this understanding of modeling dimensionality with a knowledge of the specific techniques and problem areas explored previously in a sewershed creates a solid ground for developing new models. Finally, robust Verification and Validation (V&V) protocols for these models helps increase the reliability of the results, understanding of how the model reaches a result, and the confidence of the utility decision makers in the developed model.

The checklist is supported by the aiWATERS document, which details the AI applications for iWISE.

- i. For which types of problems in the natural system of your sewershed have you used analytical models? Natural sub-system includes elements from land, water, and climate. (Pick all that apply)
Refer to iWISE report: Data Analytics, Modeling and AI [3.5.1, Pg. 25]
 - Contaminant fate and transport
 - Modeling of contamination of surface and groundwater due to runoff from landfills, agricultural activities and risks presented by leachate
 - Modeling of rainfall-runoff
 - Risk analysis of CSO/SSO events
 - Mitigating extreme event risks
 - Other: [Click or tap here to enter text.](#)

- ii. For which types of problems in the built system of your sewershed have you used analytical models? Built system contains household/commercial/industrial customers, wastewater infrastructure and stormwater infrastructure. (Pick all that apply)
Refer to iWISE report: Data Analytics, Modeling and AI [3.5.1, Pg. 25]
 - Asset performance
 - Asset renewal
 - Asset risk
 - Asset finance
 - Other: [Click or tap here to enter text.](#)

- iii. For which types of problems in the social system of your sewershed have you used analytical models? Social system includes customers, financial, policy, governance and regulations. (Pick all that apply)
Refer to iWISE report: Data Analytics, Modeling and AI [3.5.1, Pg. 25]
 - Demand forecasting
 - Public perception understanding
 - Impact of organizational structure on asset management
 - Economic impacts of laws and regulations
 - Lifecycle assessment of built assets

Figure C.7: iWISE Framework Questionnaire

- Willingness to pay
 - None of the above
 - Other: Click or tap here to enter text.
- iv. At what levels are your models typically applied? (Pick all that apply)
Refer to iWISE report: Data Analytics, Modeling and AI [3.5.2, Pg. 27]
- System level generating results and supporting decisions at sewershed or watershed scale
 - Sub-system level generating results and supporting decisions for entire natural, built or socioeconomic scale
 - Component level generating results and supporting decisions to manage specific problems like renewal, capacity design, etc in particular assets like pipes, treatment plants, etc.
 - Other: Click or tap here to enter text.
- v. What decision domains are your models typically applied to? (Pick all that apply)
Refer to iWISE report: Data Analytics, Modeling and AI [3.5.2, Pg. 27]
- Strategic decisions (higher level decision making for supporting long term policy and financial decisions)
 - Tactical decisions (for identifying hot spots and problem areas to seek patterns in dataset)
 - Operational decisions (for day-to-day decision support at asset level)
 - Other: Click or tap here to enter text.
- vi. What categories of insights do your models offer? (Pick all that apply)
Refer to iWISE report: Data Analytics, Modeling and AI [3.5.2, Pg. 27]
- Information level analysis (higher level insights for general overview of sewershed performance)
 - Engineering level analysis (insights based on modeling of individual built assets)
 - Management level analysis (economic and financial insights for management level staff)
 - Other: Click or tap here to enter text.
- vii. What sub-systems do you consider as categories for modeling? (Pick all that apply)
Refer to iWISE report: Data Analytics, Modeling and AI [3.5.2, Pg. 27]
- Natural sub-system level (modeling stream flows, surface water quality models etc.)
 - Build sub-system level (modeling structural reliability of pipes, treatment plants, etc.)
 - Social sub-system level (modeling customer demand, management practices, economic impacts, etc.)
 - Other: Click or tap here to enter text.
- viii. What mathematical techniques do you consider as categories for modeling? (Pick all that apply)
Refer to iWISE report: Data Analytics, Modeling and AI [3.5.2, Pg. 27]

Figure C.8: iWISE Framework Questionnaire

- Deterministic models (formulaic models where the final output can be fully determined based on parameter values and initial conditions)
 - Probabilistic models (models that incorporate randomness and represent a range of outputs with a given confidence)
 - AI models (use methods based on classical expert systems like fuzzy logic, ANN, linear or logistic regression, random forest etc.)
 - Other: Click or tap here to enter text.
- ix. What types of analytical categories do you consider for modeling? (Pick all that apply)
Refer to iWISE report: Data Analytics, Modeling and AI [3.5.2, Pg. 27]
- Static analysis: Analysis performed for steady-state conditions
 - Dynamic analysis: Analysis performed with varying design parameters that can be used for real-time decision making
 - Hybrid analysis: Combination of static and dynamic modeling
 - Other: Click or tap here to enter text.
- x. What aspects of model Verification & Validation (V&V) does your utility follow? (Pick all that apply)
Refer to iWISE report: Data Analytics, Modeling and AI [3.5.3, Pg. 29]
- Checking model logic using artificial data or common knowledge
 - Checking parameter Influence through sensitivity or correlation analysis
 - Evaluating model results in comparison to competing methods or existing models
 - Statistical tests, graphical tests and contextual information to establish model reliability and accuracy
 - Establishing ground truth metrics to measure model performance reliably
 - Other: Click or tap here to enter text.

6. Visualization and Decision Support

The continuously changing drivers of the sewershed management industry, embodied by rigorous environmental and health regulations and the challenge of emerging contaminants, necessitates the development of better decision support systems using visualization platforms.

- i. What aspects does your utility consider before the development of a Decision Support System (DSS) for iWISE at a sewershed scale? (Pick all that apply)
If the aspects you consider are not mentioned in the options, please provide your answer in the "Other" category.
Refer to iWISE report: Visualization and Decision Support [3.7.1, Pg. 39]
- Level of complexity of the decision process
 - Need for timely decisions from the DSS
 - Expertise availability with the utility
 - Specificity required in the results
 - Do not have a DSS in place

Figure C.9: iWISE Framework Questionnaire

- Other: Click or tap here to enter text.
- ii. What levels of decision-making are your DSSs capable of? (Pick all that apply)
If the levels you consider are not mentioned in the options, please provide your answer in the "Other" category.
Refer to iWISE report: Visualization and Decision Support [3.7.2, Pg. 39]
- Manual: Handled by human workforce
 Autonomous: Handled by integrated algorithms with robust model outputs
 Hybrid: Model making recommendations for human decision makers
 Do not have a DSS in place
 Other: Click or tap here to enter text.
- iii. What stage of development are you in in terms of Decision Support System (DSS) development?
Refer to iWISE report: Visualization and Decision Support [3.7.3, Pg. 40]
- Problem and System Understanding
 Modeling (developing a working model for accurately representing knowledge, data and reasoning)
 Decision Optimization (to identify decision constraints, rating criteria, preliminary screening and breakdown of decisions based on modeling strategies)
 Usability (stage focused on improving usability of the model)
 Do not have a DSS in place
 Other: Click or tap here to enter text.
- 7. iWISE Implementation and Service Delivery**
- Implementation and service delivery strategies can be a set of key recommended activities in the form of near term, medium term and long-term activities that need to be undertaken for implementing the iWISE systems (people, processes, and technologies) in communities and at a national-scale.
- i. What managerial or non-technical aspects of implementation does your utility consider?
Please indicate the aspects that are considered.
If the aspects you consider are not mentioned in the options, please provide your answer in the "Other" category.
Refer to iWISE report: iWISE Implementation and Service Delivery [3.8.1, Pg. 41]
- Setting up and managing contracts for suppliers, system integrators, IT and communications providers
 Establishing financial protocols like funds disbursements based on work performed
 Engaging stakeholders to ensure communication related to the IWS implementation progress, any deviations from the planned schedule and addressing any concerns
 Managing relations with customers and media to provide appropriate information (good and bad) about the project
 None of the above
 Other: Click or tap here to enter text.

Figure C.10: iWISE Framework Questionnaire

- ii. What technical aspects of implementation does your utility consider in your IWS implementation plans? Please indicate the aspects that are considered.
Refer to iWISE report: iWISE Implementation and Service Delivery [3.8.1, Pg. 41]
- Understanding of the major technical aspects of IWS like the sewershed system, components, dependencies and interdependencies, data collection and management tools, modeling techniques (including AI/ML), cybersecurity and the basis behind reliable decision making
 - Adopting a collaborative and efficient agile approach in the technical team
 - Knowledge base development and knowledge sharing
 - None of the above
 - Other: Click or tap here to enter text.
- iii. Do you consider short-, medium- and long-term plans for implementation to ensure long-term sustainability of your implementation plans? If yes, please check the phases that you consider.
Refer to iWISE report: iWISE Implementation and Service Delivery [3.8.2, Pg. 43]
- Near term actions: 1-2 year implementation planning
 - Medium term actions: 3-5 year implementation planning
 - Long term actions: 5-10 year implementation planning
 - None of the above
 - Other: Click or tap here to enter text.
- iv. How does your utility evaluate the progress of IWS implementation? (Pick all that apply)
If the types of evaluation you consider are not mentioned in the options, please provide your answer in the "Other" category.
Refer to iWISE report: iWISE Implementation and Service Delivery [3.8.2, Pg. 43]
- Performance Evaluation: Tracking the success of research initiatives like sensor deployment, advanced analytics or decision support tools
 - Program Evaluation: Track alignment of the research initiatives with the industry guidelines
 - Knowledge Management: Analyzing the direct and indirect impacts of iWISE projects on the utility operations through surveys and data collection
 - Knowledge Transfer: Compiling the knowledge and data into databases for future reference
 - None of the above
 - Other: Click or tap here to enter text.

Figure C.11: iWISE Framework Questionnaire

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