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A System Dynamics Approach: For Modeling Natural Infrastructure Aging in Sustainable Urban Water Supply Systems

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Abstract

The provision of safe and reliable drinking water is fundamental to urban quality of life and sustainable economic development. However, aging water-supply infrastructure can progressively increase leakage, reduce service reliability, and intensify long-term asset-management pressures. This study develops a System Dynamics model that explicitly represents the natural aging of urban water-distribution infrastructure and evaluates its implications over a 50-year planning horizon. The model represents pipe cohorts by age and quantifies leakage fraction, serviceable life, and the proportion of infrastructure exceeding a 50-year service-life threshold. Two scenarios are evaluated: a newly developed network in which the 1,000-km network initially occupies the youngest age cohort, and a mature network in which the same total length is distributed equally among four age cohorts below 50 years. The simulations show that the Base Scenario leakage fraction increases from 0.10 to 0.70, whereas Scenario 1 increases from 0.35 to 0.81 by Year 50. Over the same horizon, the serviceable-life indicator increases from 6 to 42 years in the Base Scenario and from 25 to 46.5 years in Scenario 1. Despite the higher serviceable-life indicator in Scenario 1 at Year 50, its over-aged network fraction reaches 78%, compared with 54% in the Base Scenario. The results demonstrate that aggregate serviceable-life measures can mask the physical deterioration of aging infrastructure and should therefore be complemented by age-based condition and leakage indicators. The study provides a quantitative systems-thinking framework for long-term infrastructure planning and supports proactive asset replacement, condition-based rehabilitation, and evidence-based investment decisions.

Keywords: Sustainable Urban Water System; System Dynamics model; Infrastructure Aging; Installed Network Health Conditions

1. 1. Introduction

Water is indispensable for domestic use and constitutes a fundamental driver of national social and economic development, with profound implications for agricultural and industrial productivity.

In Pakistan, groundwater serves as a major source of domestic water for a large proportion of the population (ul Hasan and Fatima, 2025). Wherein, groundwater serves as the backbone of the domestic water-supply system. Groundwater is widely used for domestic supply, and the cited studies describe substantial dependence on groundwater resources in Pakistan. Studies highlighted that the country had heavy dependency on groundwater resources for meeting domestic water demands (Sheik et al., 2025; World Bank, 2021; Gajurel et al., 2024).

In 1990, Pakistan had touched the 'water stress line' while crossing the 'water scarcity line' in 2005, almost more than a decade ago, and it was predicted that Pakistan would become the most water-stressed country by the year 2040 in the region and stands at 27th worldwide. In addition, groundwater contamination also impacts the availability of freshwater. Emerging contaminants such as pharmaceuticals, personal care products, microplastics, and poly- and perfluoroalkyl substances (PFAS) have recently attracted substantial attention due to their persistence in ecosystems and potential ecological and health impacts (Ariffin et al., 2024).

Effective groundwater management and governance are crucial to ensure sustainable utilization of groundwater sources. In many regions, weak institutional measures, split responsibilities, and inadequate regulatory frameworks (Murad et al., 2007). Severely, impacts the effective management of the available groundwater. Limitations associated with monitoring and the unavailability of groundwater data, accompanied by poor enforcement of groundwater extraction regulations (Mukherjee et al., 2024). Adaptive governance approaches require linking groundwater management with broader water, land-use, and environmental policies, increasingly recognized as critical to achieve long-term groundwater sustainability and resilience under growing socio-economic and climatic conditions (Liu et al., 2025). Serving a complex socio-environmental challenge involving governance, land-use planning, population growth, and climate change relations (Kunwar et al., 2026; Singh et al., 2022).

The provision of safe, affordable, and consistent drinking water is a fundamental right. Maintaining a high quality of life supports sustainable economic growth in modern cities of developed and developing countries (De Loë, 1991). In many developing countries, Water Distribution Networks designed incorporating the principles of Continuous Water Supply and operate as intermittent water systems. Resulting, less supply of water to meet the demand requirement at the consumer end (Batish, 2003). Developing countries face either inadequate water quantity or other difficulties such as power cuts, etc., and it is critical to consider these realities while planning, designing, and operating water distribution networks (Vairavamoorthy et al., 2007). Aged and aging systems experience more frequent water-main breaks, severe overflows, localized flooding incidents, and the occurrence of discolored drinking water. In response, researchers and infrastructure experts highlighted an increasing backlog of deferred maintenance. Emphasizing the need for timely rehabilitation and immediate renewal of essential water infrastructure assets (Hukka and Katko, 2015; Mirza and Haider, 2003). To ensure sustainability in freshwater consumption, along with its environmental protection, water losses within the water-distribution systems are also assumed to be of utmost importance (Araujo et al., 2006). Reduction in water loss is to be considered one of the most critical techniques to improve the efficiency of water supply utilities and their services (Ahopelto and Vahala, 2020).

Besides, water losses, demographic characteristics (age, gender, and education of the household head), economic factors (households' total monthly income), time taken (distance travel) and the house hold size (number of persons in the household) (Kithinji, 2015). The urban water supply authorities continuously suffer from regulatory, community, customer service, and financial issues, accompanied by technological issues as a broader infrastructure challenge (American Water Works Service Co., 2002). It was reported that the rate of deterioration of water is not only a function of the pipe age. It is an accumulated function of the in-contact material mineralogy, temperature, and external forces acting upon it (Barton et al., 2020; Farh et al., 2023). In the current evaluation of the existing urban water supply pipe network, pipes with an age greater than seventy years were found in excellent condition, having minimal internal and external deterioration, and predicted to provide satisfactory service for another seventy years. On the other hand, a pipe aged fifty years was found to be in a severe corrosion condition, having a repeatedly high break rate (St. Clair and Sinha, 2012; Kleiner and Rajani, 2001; Rifaai et al., 2022).

Prevailing loading and environmental conditions, material properties, and the intrinsic characteristics of pipes cause failures in freshwater distribution pipes (Rezaei et al., 2015). An extremely complex situation arises when understanding impacts arises, due to the individual and dynamic nature and their interaction (Rajani and Kleiner, 2001; Folkman, 2018a). The resulting cyclic loading will then accelerate the chances and development of failures within the pipes (Walski and Chase, 1982).

The need for rehabilitation, replacement, and repair in existing water-distribution systems is of growing concern (Selvakumar et al., 2002). The cost of rehabilitation, replacement, and repair is totally dependent upon the different methods reported. Enables water utilities managers to select an appropriate method, ensuring financial sustainability (Najafi, 2005a; Van Houtte and Kirmeyer, 2002). Pipes can be rehabilitated through trenchless or open-cut rehabilitation. These rehabilitation techniques may be in the form of non-structural lining (corrosion-resistant material lining), i.e., cement mortar lining and epoxy lining. Structural lining comprises slip lining, cured-in-place pipe, fold-and-form pipe, and close-fit pipe lining techniques (Xing et al., 2025; Folkman, 2018b). In pipe replacement methods, trenchless replacement includes the pipe bursting technique, microtunneling, and horizontal drilling technique. While open trench replacement is the most common method, universally common and adopted (Najafi and Gokhale, 2005b; Selvakumar et al., 2002).

Water supply planning in developed countries has undergone a substantial revolution from conventional supply-oriented approaches to sustainability-determined approaches (Butler and Davies, 2018). In developed countries, increasingly integrate environmental considerations, water conservation measures, stakeholder participation, and adaptive management strategies to ensure long-term sustainability (Gleick, 1993). Integrated Water Resources Management and Integrated planning empower decision-makers to assess the critical mutuality between groundwater and surface water systems (Global Water Partnership, 2000; Radutu et al., 2022; Lewandowski et al., 2020; Baldwin and Hamstead, 2014). Adoption of demand-side interventions via conservation programs, leakage control, public awareness campaigns, use of economic instruments, and water pricing policies, instead of continuous water supply infrastructure expansion. Proven effective in reducing per capita water demand, also lowering the costs associated with infrastructure expansion, operation and maintenance, and water treatment operations (Brooks et al., 2009; Mayer et al., 1999).

Sustainable planning and development, accompanied by adopting proactive asset management strategies, results in life-cycle asset management practices in optimizing maintenance requirements, quick rehabilitation, and easy replacement decisions (Kleiner and Rajani, 2001; Bani Fawwaz et al., 2023; Asnaashari et al., 2010).

Water-sensitive urban planning and development distinguishes alternative water sources, i.e., rainwater harvesting and recycling techniques, as valuable components of urban water-supply systems (Wong and Brown, 2009). Advanced hydraulic modeling and analysis tools, Geographic Information Systems (GIS), remote sensing, smart metering systems, and decision-making support platforms enable utilities to monitor entire system performance, detect leaks, forecast demand, and evaluate planning alternatives more effectively (Vojinovic and Abbott, 2012).

Water supply planning and development in developing countries considerably differ from those in developed countries. Rapid population growth, unplanned and uncontrolled urbanization, limited financial resources for immediate maintenance, institutional weaknesses, inadequate infrastructure, and increasing pressure on available freshwater resources serve as major associated problems (World Health Organization [WHO] and United Nations Children's Fund [UNICEF], 2017).

Urban water supply distribution networks progressively deteriorate over time. As, a combined effects of material aging, corrosion of pipes, repeated hydraulic loading, soil type, loading conditions, environmental factors, and inadequate maintenance practices (American Water Works Association [AWWA], 2012; Burn et al., 2005). Aging of water infrastructure becomes a major challenge for many cities worldwide (Alegre et al., 2006; Marlow et al., 2013).

Efficient and well-maintained water distribution networks play a vital role, enhancing the serviceable life and performance of the entire urban water supply system. Several approaches for assessing the number of breaks, considering the proper length of pipe for certain years, may be followed in the literature, including the pioneering study of Shamir and Howard in 1979, presenting an approach to calculating the number of breaks in pipe per year per 1000 ft of pipe. The pipe break rate is determined using Eq. 1.

$$N_t = N(to)e^{A(t-to)} \ldots\ldots\ldots\ldots (1)$$

Where, t = time (years), to = the year in which the pipe was installed (data available), N_t = number of breaks in t years per 1000 ft of pipe, and A= growth rate coefficient having dimension 1 in year.

This equation provides credible results upon the provision of judgmental factors in relation to repairs, replacement costs, future funds availability, inflation rates, and failure rates in pipes (Shamir and Howard, 1979; Shirzad and Safari, 2019).

Assessment of pipe failure rate has been carried out using two case studies, including the data sets of water distribution networks of Mahabad city and Mashhad city of Iran (Shirzad and Safari, 2018). However, the pipe failure factor can be calculated by dividing the number of failures per annum by the total length of pipe. Providing a simple but effective indicator for infrastructure condition assessment and deterioration analysis (Fan et al., 2021; Winkler et al., 2018).

A similar approach for estimating pipe failure rates has been applied using long-term historical datasets, including a 30-year record from Cuyahoga County's water-distribution system. In this approach, the failure rate is calculated as the ratio between the total number of observed failures within a given season and the total length of the existing water distribution network (Harvey et al., 2014; Aydogdu and Firat, 2015). Based on extensive historical failure records, recent advancements in machine learning techniques have introduced new capabilities for accurately predicting pipe failure rates by capturing complex nonlinear relationships (Serafeim et al., 2024; Lambert et al., 2002).

Besides the conventional method of estimating pipe failure, alternative approaches are widely employed to assess system performance and water losses in distribution networks. The difference represents non-revenue water, which includes both apparent and real losses (Farley and Trow, 2003). Higher connection density is generally associated with increased leakage risk and higher non-revenue water volumes. Understanding system deterioration and overall performance of urban water distribution networks (Scheidegger et al., 2015; Barton et al., 2022).

Given the availability of sufficient and reliable data, simpler modeling approaches are often more practical and useful for policy-making and operational decision support compared to more complex methods such as Bayesian models and machine learning techniques (Wilson et al., 2017; Zuñiga-Uribe et al., 2026). As most of the studies do not clearly report model assumptions, uncertainties, or methodological limitations, which reduces the transparency and reproducibility of results (Weeraddana et al., 2021). These constraints increase; the reliability of simpler and more interpretable models is often preferred in practice, as they provide more robust and actionable insights under conditions of limited and uncertain data (North Western Energy Group, Inc., 2022).

In addition to failure-rate and deterioration-based methods. The straight-line depreciation approach and several approaches incorporating asset depreciation are also widely employed for evaluating the annual reduction in value of water and utility infrastructure systems (Gannett Fleming Valuation and Rate Consultants, LLC, 2022). The straight-line depreciation approach ensures systematic cost recovery of infrastructure investment. Aligning asset valuation with the physical and functional aging of utility systems (North Western Energy Group, Inc., 2023). By incorporating depreciation into asset management practices, utilities can better anticipate future replacement needs and allocate resources more efficiently to ensure continuous and reliable service delivery (South Dakota Association of Rural Water Systems [SDARWS], 2019; American Water Works Association [AWWA], 2012).

Straight-line depreciation serves as an effective tool for supporting sustainable asset management and maintaining the reliability of water supply systems throughout their operational life. Equation 2 is used by the Communication and Works Department, Khyber Pakhtunkhwa, for calculating the depreciation of buildings (Communication and Works Department [C&W], 2019).

$$DV = P \times \left[\frac{(L - N)}{L} \right][M-R] \qquad \text{............ (2)}$$

where:

DV= Depreciated value of the building
P= Original capital cost of the building
L= Expected life of the building (years)
N= Current age of the building (years)
M= Maintenance expenditure
R= Repair cost

2. System Complexity and Urban Water-Supply Systems

2.1 Sectoral Structure of Urban Water Supply Systems: A Developing-Country Perspective

In urban water-supply system comprises social, financial, and physical/technical sectors in developing countries such as Pakistan, as illustrated in Figure 1. The social sector further includes key sub-sectors such as population growth, customer satisfaction, and customer affordability (Cheng and Chang, 2011).

All these sectors and sub-sectors contribute to the urban water-supply system, leading the system towards a more complex and dynamic nature (Hudson et al., 1997). This approach is widely applicable across various infrastructure systems. Broadly stated, asset management seeks to integrate engineering expertise with sound economic and financial practices (Federal Highway Administration [FHWA],1999). Use of relational databases supports systematic registration, integration, and analysis of asset-related data. Supports improving data consistency, enabling efficient information retrieval, and facilitating more informed decision-making in maintenance, rehabilitation, and replacement planning (Younis, 2010; Halfawy and Figueroa, 2006).

Urban water-supply systems are characterized by strong interdependencies between technical, financial, and social components, which makes their management fundamentally different from conventional infrastructure planning (Rehan, 2011). Different complexities are involved in the management of freshwater distribution. Makes, it difficult to develop system dynamics models capable of accurately predicting future water availability while considering changing demand patterns (Qin et al., 2012). These circumstances led to substantial difficulty for planners to propose long-term water supply plans under dynamic environments (Winz et al., 2009; Ahmad and Simonovic, 2000; Sterman, 2000; Fagan et al., 2010).

The current planning framework for the provision of drinking water supplies to inadequately served areas or areas with no coverage is based upon the provision of new tube well-based systems to address the unmet water demand. Currently, a holistic quantitative analysis framework doesn't exist that takes into account the complexity and dynamic characteristics of the water supplies planning framework (Bala et al., 2017). A recently proposed qualitative System Dynamics model for sustainable urban water-supply systems presents a novel framework for understanding the complex interactions among the physical/technical, financial, and social sectors of urban water-supply systems, as shown in Figure 2. The model appreciates drinking water systems as complex socio-technical systems with interconnections and feedback loops among various systems, whether social, technical, financial, etc. (Hassan et al., 2025).

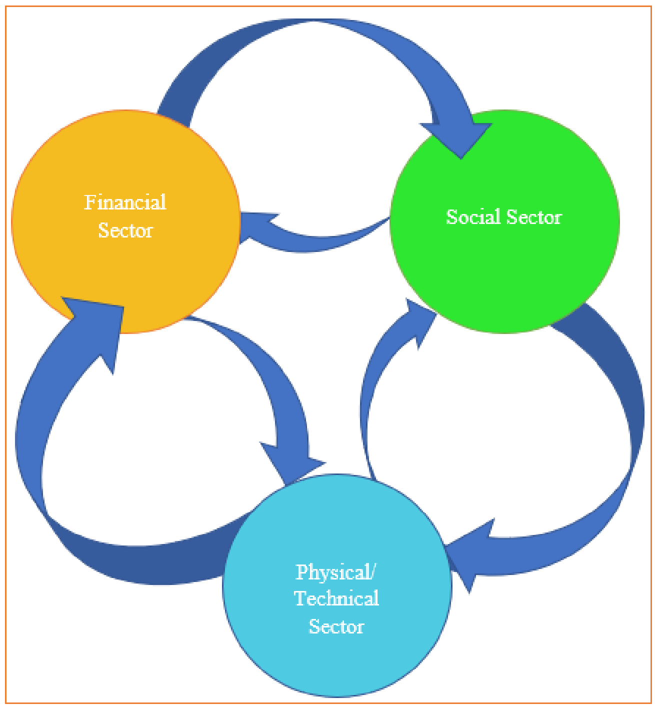

Fig. 1. Sectors involved in the urban water-supply system.

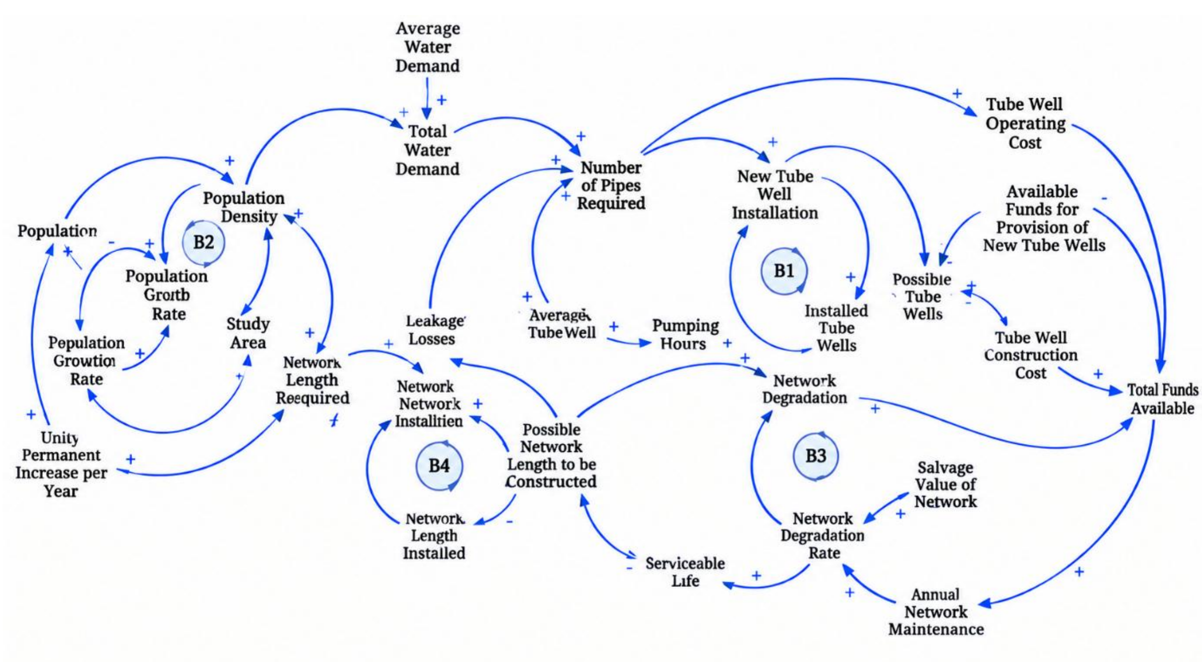

Fig. 2. Causal Loop Diagram for the sustainable urban water-supply system.

Causal Loop Diagram (CLD) is a qualitative system mapping tool that illustrates how different variables in a system are interrelated through causal links, forming closed loops of influence. Each link between variables is assigned a polarity (positive or negative), indicating how a change in one variable affects another. CLD serves as a qualitative system dynamics tool employed to represent and analyze the feedback structure of complex systems by presenting causal relationships among variables and the resulting reinforcing and balancing feedback loops. In a CLD, variables are connected through directed arrows indicating causal influence, where polarity signs (+/–) define whether changes in one variable lead to changes in the same or opposite direction in another variable. These causal links form closed feedback loops that are categorized as reinforcing loops, which amplify system behavior, and balancing loops, which counteract change and drive the system toward equilibrium. The concept originates from system dynamics theory developed by Forrester, who emphasized the importance of feedback structures in explaining the behavior of socio-technical systems (Mukherjee et al., 2024; Richardson and Pugh, 1981). CLDs are particularly useful in early stages of modeling because they help in conceptualizing complex interdependencies before developing quantitative stock-and-flow models. Improving problem structuring and policy analysis capabilities (Richmond, 1994). CLD is widely applied in fields such as urban water resource management, infrastructure planning, and environmental systems to identify leverage points and understand the long-term implications of policy interventions (Wolstenholme, 1999).

This study presents a qualitative system dynamics model for the physical/technical sector of an urban water-supply system. Explicitly incorporating the natural aging of installed pipe infrastructure throughout its proposed service life. The developed model captures the progressive deterioration of pipe networks and its implications for system performance. Providing a basis for assessing infrastructure sustainability and informed maintenance and replacement strategies.

2.2 System Complexity and System Dynamics

From 1516 to the mid-twentieth century, many researchers, i.e., Thomas More to pogo, acknowledged that people looking for solving problem often make it difficult to solve. Due to the impact of our unanticipated policies and their emerging side effects. Forrester (1961) termed this phenomenon as "Counterintuitive Behavior of Social Systems''. In which our efforts to restore the system stimulate reactions that make the system more complex in understand and properly manage. Such expected reactions from the real-world lead to inertia in the implementation of policies. Capabilities for interference may be delayed and diluted by the response of the system. System Dynamics is a methodology developed by Jay W. Forrester to understand and analyze the behavior of complex systems via interacting feedback loops, stocks and flows, time delays, and nonlinear relationships among system interlinked variables (Sterman, 2000; Fagan et al., 2010). The popularity of System Dynamics increased substantially following the publication of the seminal study "The Limits to Growth" by the Club of Rome in the early 1970s. Employed System Dynamics modeling, examining the long-term interactions among population growth, industrialization, resource consumption, food production, and environmental degradation (Forrester, 1961).

System Dynamics is widely applied to assess water demand and supply management, groundwater depletion, infrastructure deterioration, non-revenue water, water security, climate change adaptation, and long-term sustainability planning (Meadows et al., 1972). Integrating all these interconnected variables within a single modeling framework. System Dynamics assists planners and utility managers to identify sustainable strategies for balancing water availability, service reliability, and infrastructure investment requirements (de Araujo et al., 2019).

Integrating complex interactions among social, economic, environmental, and infrastructural components enables the model approach to capture the behavior of urban water systems and to evaluate the long-term impacts of management strategies and policy interventions (Wei et al., 2016; Zarghami and Akbariyeh, 2012; Grigg and Bryson, 1975).

The dynamic interdependencies that exist within urban infrastructure systems were highlighted by Kotz and Hiessl (2005). Employing an agent-based modelling approach for simulating technical innovation processes and their influence on system development (Kotz and Hiessl, 2005; Zarghami and Akbariyeh, 2012). A system dynamics model has been employed to capture these interrelationships and evaluate the long-term consequences of alternative management strategies (El Sawah et al., 2010; Guest et al., 2010). Ahmad and Prashar (2010) developed a system dynamics model to investigate the complex interactions among population growth, land-use change, water demand, and water availability. Adeniran and Bamiro (2010) developed a system dynamics model for urban water supply and wastewater systems. Comprising of numerous interrelated components, including water production, treatment, distribution, operation and maintenance, financial management, and customer demand (Wei et al., 2016; Ahmad and Prashar, 2010).

According to Sterman (2000), the behavior of complex systems arises from the interaction of reinforcing and balancing feedback loops, governing system structure and dynamics. When a change occurs in one component of a feedback loop, its effects propagate within the entire system and eventually influence the original component. Thereby creating dynamic patterns of behavior over time (Adeniran and Bamiro, 2010; Hannon and Ruth, 1994). Proper identification of issues related to water management is itself a challenging task. Particularly when attempting to assess the wide impacts of the system. Therefore, system dynamics serve as a critical need to adopt modelling methods and tools for analysis (Zare et al., 2019).

Rehan et al. (2011a) demonstrated the usefulness of system dynamics in assessing the sustainability of municipal water utility systems in Canada by linking financial flows with system operations and infrastructure conditions (Rehan et al., 2011b). The system dynamics approach has also been applied as a methodological framework to parameterize long-term simulation models (up to 100 years), enabling the evaluation of alternative operation and maintenance strategies for wastewater collection systems and supporting sustainable infrastructure planning (Rehan et al., 2011b). The interacting system dynamics framework is employed to develop simulation models. Supporting policy recommendations and decision-making for both short- and long-term objectives. Evaluating realistic and robust policy alternatives for the planning and management of water distribution networks (Rehan et al., 2014; Jensen and Wu, 2018).

The system dynamics approach, through simulation modelling, demonstrates that demand management can serve as an effective short-term strategy for coping with water scarcity (de Araujo et al., 2019). System dynamics has been established as a technique for addressing the imbalance between increasing freshwater demand and limited water availability under both current and future conditions (Xu et al., 2020). System dynamics models using simulations are widely employed to develop optimized scenario-based analyses for balancing water demand and supply (Richardson and Pugh, 1981). The ability of system dynamics to capture nonlinear interactions, feedback mechanisms, and delayed responses. Its use has become a well-established analytical tool for addressing complex challenges in urban water supply management, infrastructure planning, environmental systems, and resource sustainability (Richmond, 1994).

3. Materials and Methods

This study develops a system-dynamics model for the physical/technical component of an urban water-supply system. The methodological workflow comprises conceptualization of the system, causal-loop representation, stock-and-flow formulation, definition of age-dependent leakage and condition indicators, model validation, assumptions, and scenario simulation. The model boundary is restricted to the installed pipe network so that the long-term consequences of natural infrastructure aging can be examined consistently.

Stock-and-flow modeling is a fundamental concept in System Dynamics employed to represent and analyze how complex systems evolve over time. Through accumulation, depletion, and feedback processes. It provides a structured framework for understanding dynamic systems such as urban water-supply systems, population dynamics, economic systems, and infrastructure management. System dynamics is a feedback-based object-oriented modeling paradigm developed by Forrester (1958) to model complex systems (Meadows et al., 1972; Sterman, 2018; Rehan, 2011). The basic building blocks for system dynamics models are stocks, flows, converters, and connectors, as shown in Figure 3.

The stocks represent the accruals of both the physical and non-physical objects/sectors. Examples of physical stocks are length of road constructed, inventory of disabled children, quantity of water in reservoir, etc. The non-physical stocks are the riding quality of the road, consumer satisfaction, and level of pain a patient is suffering. The stocks represent the patterns of the activity over a period of time; the quantities may either increase or decrease within a specific interval of time. Flows represent the degree of change per unit time within the stock; examples are the length of road constructed per year, the number of disabled children born per year, quantity of water drained per year from a reservoir. The relationship of stocks and flows was mathematically described by (Sterman, 2000) in integral form for a time period ranging (Meadows et al., 1972; Sterman, 2018; Rehan, 2011).

$$Stock\,(to) = \int_{to}^{t}[Inflow(s) - Outflows(s)]ds + Stock(to) \quad \ldots\ldots (3)$$

$$d(\text{Stock})/dt = Inflow(t)\text{-}Outflow(t) \ldots\ldots (4)$$

Where ‘t’ in equations (3 and 4 represents the current time, while the t_o refers to the initial time, means starts of the simulation. Stock (to) is the initial quantity at t = t_o, and Stock (t) represents the values at any instant of time “t”. The inflow(s) and outflow(s) are the accumulation and drainage of stock for the time period (t_o to t), having units of stock(s) per unit time. Whereas Eq. 4 represents flow as the net rate of change in stock value with time. Arrows, the connectors, are the carriers of information, action, and decision as inputs via establishing a specific relationship among the different elements, sectors, and subsectors of the model. The circles, meaning converters, are the houses of intrinsic or extrinsic properties, patterns, actions, and decisions, i.e., water demand patterns, pumping hours, population growth rate, and population density, etc. Overall, stock-and-flow modeling provides a powerful, quantitative, analytical, and simulation-based approach for policy analysis, enabling researchers to evaluate alternative scenarios, understand feedback-driven behavior, and assess the long-term sustainability of urban infrastructure systems (Richardson, 1991).

3.1 Conceptual Framework and Stock-and-Flow Formulation

Causal Loop Diagram (CLD) was used as the qualitative conceptual framework for identifying the principal variables, causal relationships, and feedback structures governing natural infrastructure aging in the urban water-supply system. The CLD represents how changes in infrastructure condition, leakage, serviceable life, and network aging influence one another through reinforcing and balancing feedback relationships. This qualitative representation provides the conceptual basis for translating the system structure into a quantitative stock-and-flow formulation.

Figure 2 presents the causal-loop structure used to define the model boundary and identify the relationships subsequently represented in the stock-and-flow model. The CLD was therefore used as the first modelling stage, while the stock-and-flow formulation provides the quantitative representation used for simulation. The approach follows the system-dynamics principle that the behavior of complex systems emerges from interactions among stocks, flows, feedbacks, and auxiliary variables.

The conceptual framework focuses on the physical/technical sector of the urban water-supply system and explicitly incorporates the natural aging of installed pipe infrastructure throughout its proposed service life. The framework links pipe-age cohorts with leakage fraction, serviceable life, and accumulation of over-aged infrastructure, allowing the subsequent simulations to examine long-term deterioration under the defined scenarios.

3.2 Development of the Stock-and-Flow Model

The stock-and-flow model was developed from the causal-loop representation shown in Figure 2 using the standard system-dynamics building blocks of stocks, flows, converters, and connectors. The model was implemented in Vensim Research Version 9.2.3 x64 (Ventana Systems, Inc.). Figure 3 shows the principal building blocks used in model development. The resulting stock-and-flow structure is presented in Figure 5.

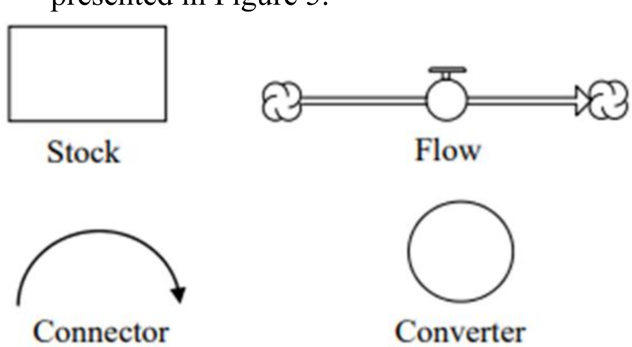

Fig. 3. Building blocks for development of the system-dynamics model.

Vensim was used as the object-oriented modelling and simulation environment for constructing and testing the system-dynamics model.

3.3 Physical/Technical Sector

The physical/technical sector represents the infrastructure components and operational condition of the urban water-supply system. The model boundary is restricted to the installed pipe network. Tube-well installation, average tube-well yield, study area, network density, and direct leakage-loss variables are outside the present model boundary; leakage losses are represented indirectly through the leakage-fraction indicator. The modeled variables therefore focus on installed network length, age cohorts, over-aged network fraction, serviceable life, and leakage fraction.

3.4 Model Variables and Performance Indicators

Leakage fraction is represented as a dependent variable. It is calculated as the weighted average of age-specific leakage factors, with the weight of each age category determined by its share of the total installed pipe-network length. The five modeled age categories are 0–12, 12–25, 25–37, 37–50, and >50 years. This formulation captures the cumulative effect of changing age composition on network leakage.

$$\text{Leakage Fraction} = \frac{\sum_i \text{IPN}_i \times \text{LF}_i}{IPN} \quad \text{.......... (5)}$$

Where IPN is the installed pipe-network length, LF is the leakage factor for the respective age group, and i denotes the modeled age category. The weighted-average formulation aggregates the contribution of heterogeneous age cohorts to the network-level leakage indicator.

3.5 Leakage Fraction and Leakage Factors

Age-specific leakage factors were determined using the pipe-aging relationship presented by Shamir and Howard (1979). Equation 6 defines the leakage factor for a pipe cohort as a function of its age; the resulting values used in the model are presented in Table 1 and Figure 4.

$$L_t = L(t_o)e^{A(t-to)} \quad \text{...........(6)}$$

Here 't' is time in years, t_0 is the installation/reference year, Lt is the leakage factor at time t for the specified pipe-age group, and A is the growth-rate coefficient. The model assigns the highest leakage factor to the >50-year cohort and the lowest factor to the 0–12-year cohort, consistent with the age-dependent deterioration assumption used in the simulation.

Table 1. Determined leakage factors for pipes of different age groups.

Pipe group having age (Years)	Depreciation/Deterioration	Network Condition	Leakage Factor	Average Time
0 -12	0%	100%	0.10	12
12-25	25%	75%	0.23	18.5
25-37	50%	50%	0.39	31
37-50	75%	25%	0.68	43.5
>50	100%	0%	0.90	50

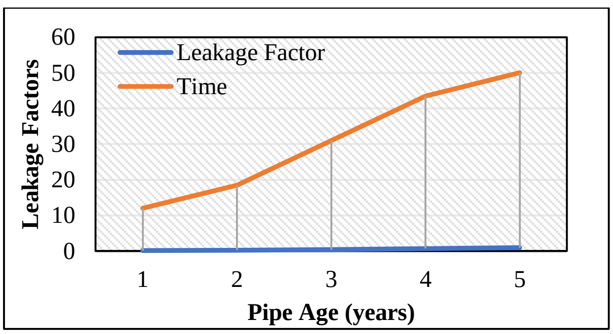

Fig. 4. Leakage factors assigned to different pipe-age groups.

The model uses the age-dependent leakage factors listed in Table 1. Pipes older than 50 years are assigned a leakage factor of 0.90, while pipes in the 0–12-year category are assigned 0.10. The simulation horizon is 50 years. Previous studies cited in the manuscript also identify pipe age, material deterioration, joint failure, corrosion, and operating pressure as factors affecting leakage and failure rates (van Zyl and Clayton, 2007; Berardi and Giustolisi, 2021; Wyatt, 2010; Ferrante et al., 2014; Serafeim et al., 2024).

3.6 Over-Aged Network Fraction (Installed Network Health Condition) and Serviceable Life

The installed network health condition is represented by the fraction of the total installed pipe network that exceeds the 50-year age threshold. Because a larger value indicates a larger proportion of over-aged infrastructure, this indicator is interpreted in this study as an over-aged network fraction. It is retained under the model label "Installed Network Health Condition" to remain consistent with the existing model terminology.

$$\text{Installed Network Health Condition} = \frac{IPN{>}50}{Pipe\ Network\ Installed} x100 \ldots\ldots\ldots\ldots (7).$$

The indicator is calculated as the length of pipe in the >50-year cohort divided by the total installed pipe-network length. It therefore serves as an age-threshold proxy for deterioration and rehabilitation backlog. The interpretation is consistent with the manuscript's discussion that aging assets are generally associated with higher failure risk and maintenance requirements (Sterman, 2000; van Sambeek and Berke, 2009).

$$\text{Serviceable life} = \frac{\sum_i \text{IPN}_i \times \text{MA}_i}{IPN} \ldots\ldots\ldots\ldots (8)$$

Serviceable life is calculated as the weighted average age of the installed pipe network, using the length of each age cohort as the weighting factor. The measure is therefore an aggregate network-level indicator and is interpreted jointly with leakage fraction and the over-aged network fraction rather than as a stand-alone measure of physical condition.

3.7 Model Validation

Model validation assessed boundary adequacy, structural consistency, dimensional consistency, parameter assessment, extreme-condition behavior, and sensitivity during model development. These checks support structural and behavioral credibility for the intended scenario-analysis application. The manuscript does not report independent field time-series data or numerical goodness-of-fit statistics; therefore, the simulations are presented as scenario-based system-dynamics projections rather than statistically calibrated forecasts. Detailed numerical outputs from sensitivity or validation tests should be added if available from the model files.

3.8 Assumptions for Model Development

The model allows the installed pipe network to age naturally without proactive replacement or rehabilitation. Pipes remain in service until they enter the >50-year category. The total installed network length is fixed at 1,000 km. In the Base Scenario, the complete network is initially assigned to the 0–12-year cohort. In Scenario 1, the 1,000-km network is initially distributed equally among the four active cohorts below 50 years—0–12, 12–25, 25–37, and 37–50 years—with 250 km in each cohort and no initial stock in the >50-year cohort. This initialization is consistent with the reported initial Scenario 1 leakage fraction of 0.35.

3.9 Simulation Scenarios

Two contrasting initial age distributions were simulated for 50 years. The Base Scenario represents a newly developed network in which the full 1,000 km is initially in the 0–12-year cohort. Scenario 1 represents an already developed network with 250 km initially in each of the four active cohorts below 50 years and no initial >50-year stock. The initial distributions are summarized in Table 2.

In Scenario 1, the 1,000-km installed pipe network was initially distributed equally among the four age groups below 50 years, with 250 km in each cohort. No pipe length was initially assigned to the >50-year cohort. This represents an already developed urban area with infrastructure of varying ages. The network was then allowed to age naturally through the successive age categories at the defined transition rate of 1/13 per year. The scenario therefore captures the compounding effect of an initially mature asset base on leakage, infrastructure aging, and long-term network condition.

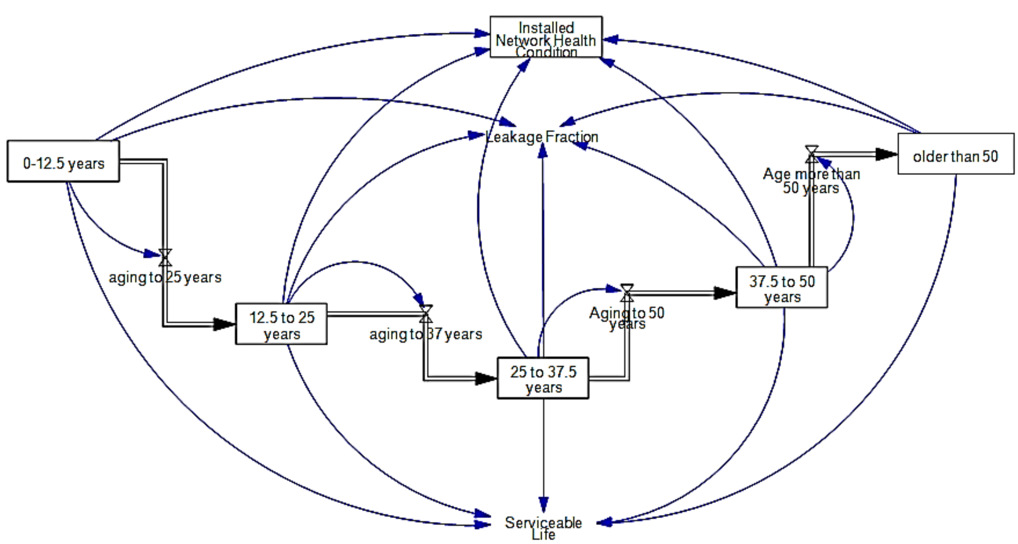

Fig. 5. Stock-and-flow model for natural infrastructure aging in the urban water-supply system.

Table 2. Simulation scenarios and initial distribution of the installed pipe network.

S. No.	Scenarios	Distribution of Installed Pipe Network Among Age Groups
1	Base Scenario (Up to 50-Years of Simulation)	1,000 km initially assigned to the 0–12-year age group.
2	Scenario 1	1,000 km distributed equally among the four age groups below 50 years (250 km in each cohort); 0 km initially >50 years.

4. Results and Discussion

4.1 Leakage Fraction

The 50-year simulation demonstrates a strong dependence of leakage on the initial age distribution. In the Base Scenario, the leakage fraction increases from 0.10 to 0.70 by Year 50, an absolute increase of 0.60 (600% relative to the initial value). Scenario 1 starts at 0.35 and reaches 0.81, an absolute increase of 0.46 (131.4%). Although Scenario 1 begins with a leakage fraction 0.25 higher than the Base Scenario, the difference narrows to 0.11 by Year 50. These results indicate that the initial age structure changes both the starting condition and the subsequent trajectory of network deterioration (Figure 6).

4.2 Serviceable Life

The serviceable-life indicator increases from 6 to 42 years in the Base Scenario and from 25 to 46.5 years in Scenario 1 over the 50-year horizon (Figure 7). The corresponding increases are 36 years (600%) and 21.5 years (86.0%), respectively. At Year 50, Scenario 1 retains a 4.5-year higher serviceable-life indicator than the Base Scenario. This higher aggregate value should not be interpreted as superior physical condition because the same scenario also has higher leakage and a larger over-aged network fraction. The result demonstrates the need to interpret serviceable life jointly with other condition indicators.

4.3 Over-Aged Network Fraction (Installed Network Health Condition)

The age-based condition indicator remains near zero in the early years of the Base Scenario because the network initially consists of young pipes. It subsequently rises to 54% by Year 50. Scenario 1 accumulates over-aged infrastructure much earlier and reaches 78% by Year 50. The Year-50 difference is therefore 24 percentage points, equivalent to approximately 44.4% more over-aged infrastructure relative to the Base Scenario (Figure 8). The result directly reflects the different initial age structures and the absence of replacement or rehabilitation.

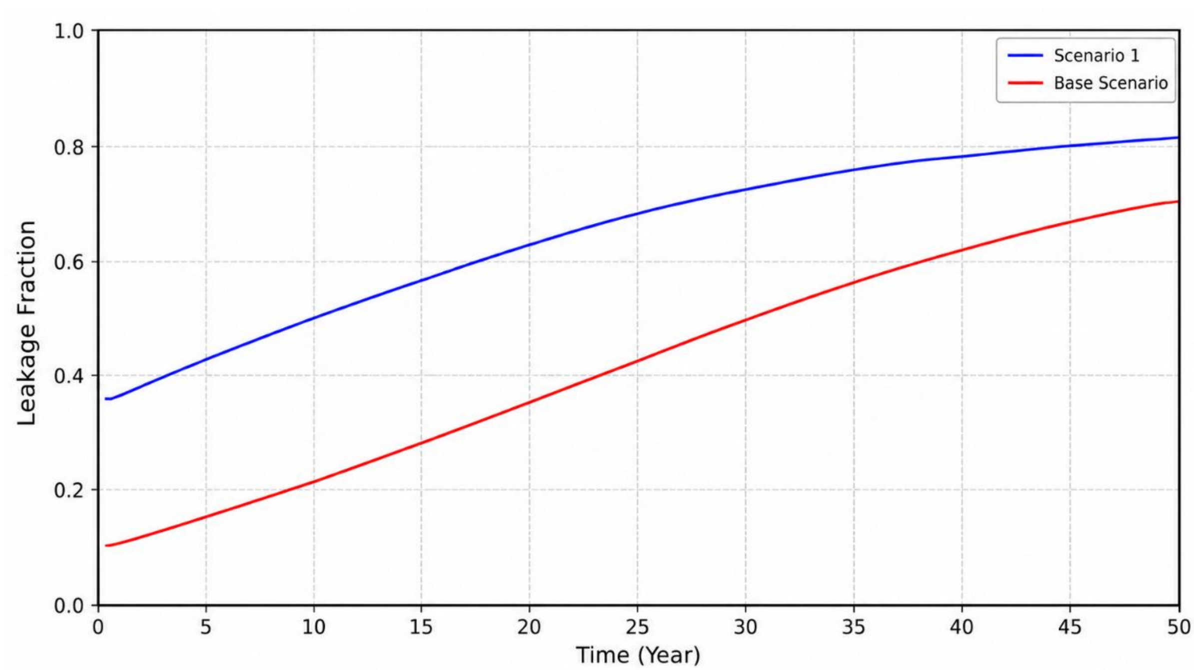

Fig. 6. Leakage fraction over the 50-year simulation period.

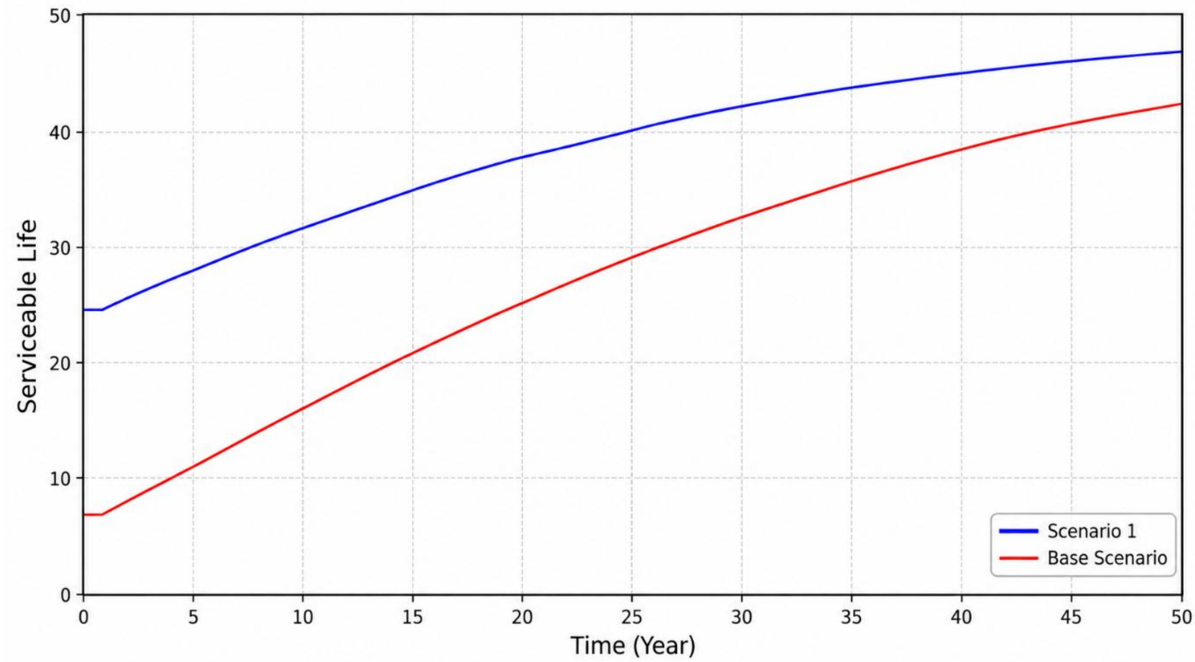

Fig. 7. Serviceable life over the 50-year simulation period.

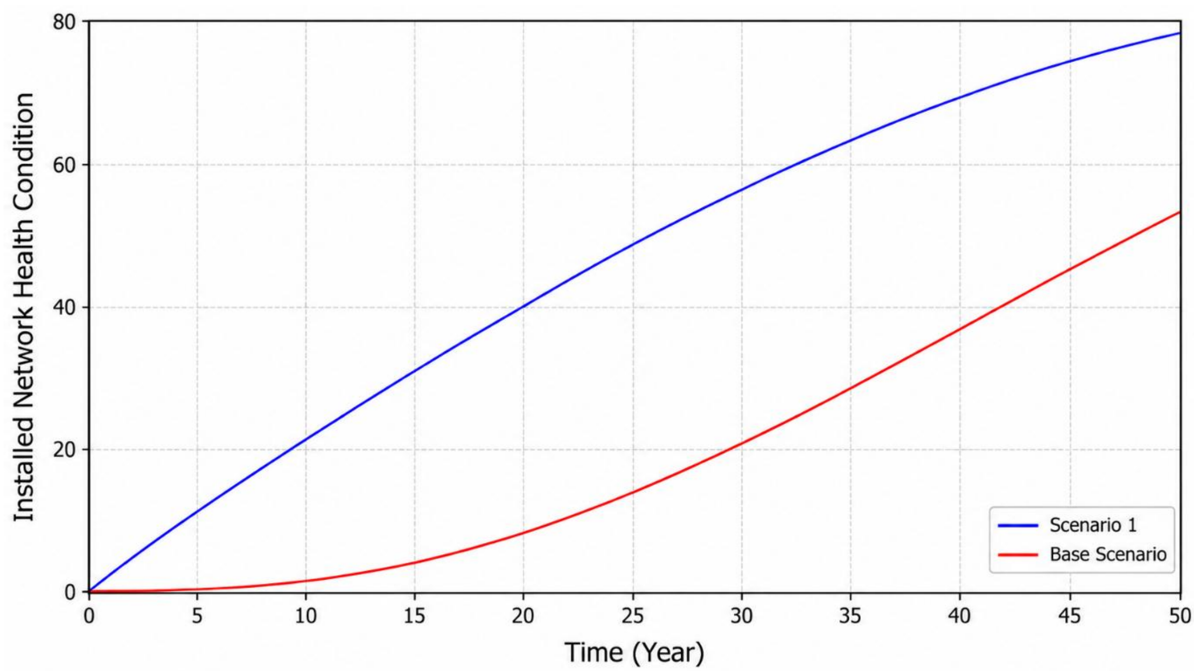

Fig. 8. Installed Network Health Condition (over-aged network fraction) over the 50-year simulation period.

4.4 Natural Aging of the Base Scenario

Figure 9 shows the dynamic aging of the 1,000-km Base Scenario over 50 years. At Year 0, the entire network is concentrated in the youngest 0–12-year cohort. Without replacement or new commissioning, this stock transfers progressively into older cohorts. By Year 50, the youngest cohort declines to approximately 20 km. The intermediate cohorts exhibit a sequential aging-wave pattern: the 12.5–25-year cohort peaks at approximately 390 km around Year 13, the 25–37.5-year cohort peaks at approximately 280 km around Year 27, and the 37.5–50-year cohort peaks at approximately 240 km around Year 41. The successive peaks are separated by roughly 14 years, illustrating the propagation of the initial stock through the defined age classes. The terminal >50-year cohort reaches approximately 540 km by Year 50, meaning that more than half of the network exceeds the assumed 50-year threshold.

4.5 Natural Aging of Scenario 1

Figure 10 illustrates the aging trajectory of Scenario 1, which begins with an already developed network distributed across four active age cohorts. Each cohort initially contains 250 km, with no stock in the >50-year category. In the absence of replacement or rehabilitation, the youngest cohort declines rapidly while the older cohorts transfer progressively toward the terminal >50-year category. By Year 50, the >50-year cohort reaches approximately 780 km, equivalent to 78% of the total 1,000-km network. The result demonstrates how a pre-aged asset base compresses the time available for renewal before a large proportion of the network becomes over-aged

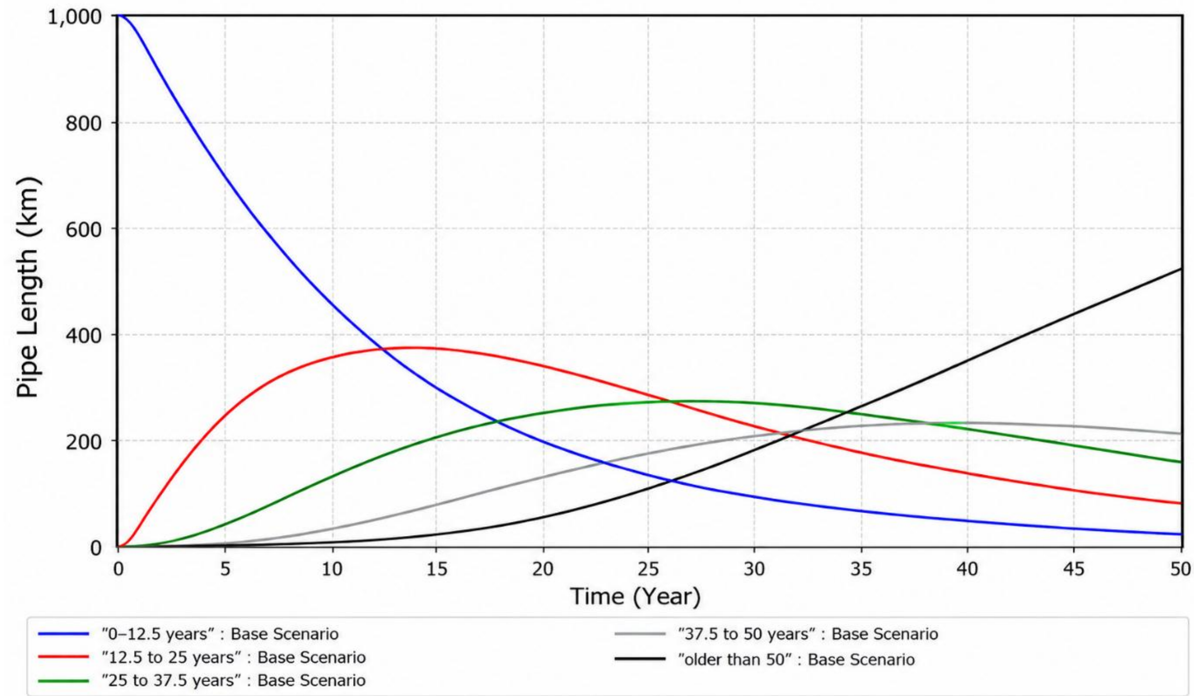

Fig. 9. Natural aging of newly developed installed infrastructure over the 50-year simulation period.

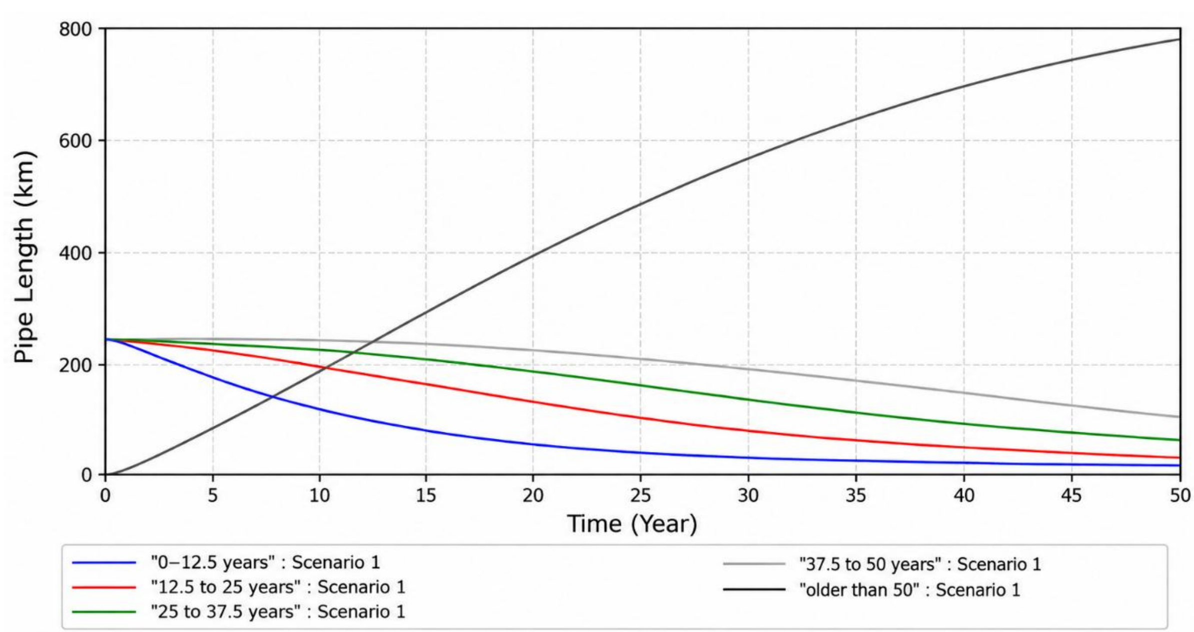

Fig. 10. Natural aging of already developed installed infrastructure over the 50-year simulation period.

4.6 Comparative Discussion

Comparison of the three indicators reveals an important system-level paradox. At Year 50, Scenario 1 has a higher aggregate serviceable-life indicator (46.5 years) than the Base Scenario (42 years); it also has a higher leakage fraction (0.81 versus 0.70) and a substantially larger over-aged network fraction (78% versus 54%). Thus, the 4.5-year serviceable-life advantage coexists with 0.11 higher leakage and 24 percentage points more over-aged infrastructure. The result shows that an aggregate longevity measure can mask the accumulation of vulnerable assets; infrastructure planning should therefore combine serviceable life with leakage and age-threshold indicators.

4.7 Engineering and Asset-Management Implications

The simulations provide a quantitative basis for prioritizing renewal and monitoring. The Base Scenario develops a substantial late-life backlog, reaching approximately 540 km of over-aged network by Year 50, while Scenario 1 reaches approximately 780 km. Because the model does not include active replacement, rehabilitation, economic optimization, or groundwater-recharge interventions, these results do not define an optimal investment schedule. Instead, they indicate the scale and timing of the aging problem that should be addressed through condition assessment, targeted rehabilitation, and planned capital renewal. Table 3 summarizes the principal quantitative differences between the scenarios.

Table 3: Quantitative comparison of reported simulation outputs for the two scenarios.

Indicator	**Base**	**Scenario 1**
Initial leakage fraction	0.10	0.35
Year-50 leakage fraction	0.70	0.81
Leakage increase	+0.60 (600%)	+0.46 (131.4%)
Initial serviceable life	6 years	25 years
Year-50 serviceable life	42 years	46.5 years
Year-50 over-aged network	54% (540 km)	78% (780 km)

5. Conclusions

The following conclusions are drawn from this study:

1. The developed Natural Infrastructure Aging System Dynamics model translates the physical/technical component of the qualitative Causal Loop Diagram into a quantitative framework for evaluating long-term infrastructure deterioration. The model explicitly represents pipe-age cohorts and their interactions with leakage, serviceable life, and over-aged network accumulation, providing a basis for scenario comparison and infrastructure planning.
2. The 50-year simulations demonstrate that initial network-age structure materially changes deterioration trajectories. The Base Scenario increases from a leakage fraction of 0.10 to 0.70 and reaches 54% over-aged infrastructure, whereas Scenario 1 increases from 0.35 to 0.81 and reaches 78% over-aged infrastructure. The latter corresponds to approximately 780 km of the 1,000-km network exceeding the 50-year threshold by Year 50.
3. A key finding is the divergence between aggregate serviceable life and physical condition. Scenario 1 reaches a Year-50 serviceable-life indicator of 46.5 years compared with 42 years in the Base Scenario. Its leakage fraction is 0.11 higher, and its over-aged network fraction is 24 percentage points higher. This demonstrates that serviceable life alone may not adequately represent the accumulation of infrastructure deterioration and should be complemented by leakage and age-threshold indicators.
4. The aging-wave analysis further shows that the Base Scenario develops a substantial late-life backlog, with approximately 540 km exceeding 50 years by

Year 50, while Scenario 1 reaches approximately 780 km. These results provide quantitative support for proactive asset replacement and condition-based rehabilitation. The model does not, however, quantify the economic benefits of specific replacement schedules or the effects of groundwater-recharge interventions; such claims require additional scenario runs and corresponding data. The present results therefore support evidence-based prioritization of renewal and monitoring rather than a specific optimal investment schedule.

5. The findings support proactive asset-replacement strategies and improved monitoring of groundwater and water-loss conditions. However, the present model does not quantify the effects of specific replacement schedules or groundwater-recharge interventions; these should be evaluated through additional scenario runs supported by project-specific data.

6. Policy Recommendations

The findings provide a basis for the following practical policy recommendations:

1. Demand-side management via launching water conservation programs. Enforcement of stringent pricing models and water metering targeting a quantifiable reduction in diurnal consumption.
2. Enforcement of building codes, including installation of Rainwater Harvesting Systems in all new and existing urban hubs for groundwater replenishment.
3. All urban and industrial expansion projects accompanied by water supply facilities projects need to be strictly aligned with the District Land Use Plan. To avoid over-exploitation in designated zoning and controlled extraction operations.
4. Allocating dedicated funds to immediately replace aging pipelines. To reduce leakage losses, improve network health conditions, and lower groundwater extraction.
5. Maintaining authentic and real-time datasets to understand future policy levers and infrastructure investment strategies based on evidence.

Authors' Contribution

Zohaib Hassan conceived the study, developed the system dynamics model, collected and analyzed the data, performed the simulations, interpreted the results, and prepared the original manuscript draft. Rashid Rehan supervised the research, provided overall guidance on the study design and methodology, and critically reviewed and revised the manuscript. Fayaz Ahmad Khan co-supervised the research, contributed to methodological refinement, and provided technical and academic input throughout the study. Mujahid Khan and Arshad Ali, as members of the evaluation committee, provided valuable expert feedback, reviewed the research framework, and contributed to improving the study through constructive recommendations. Salman Saeed assisted in interpreting the simulation results and contributed to the discussion of the findings. All authors reviewed, edited, and approved the final version of the manuscript.

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Data availability

The data supporting the findings of this study were obtained from multiple sources, including published literature, expert consultations, and parameters derived from established engineering practices and standards. The datasets generated and/or analyzed during the current study are available from the corresponding author upon request.

Conflict of Interest

The authors declare that they have no known competing financial interests, personal relationships, or other conflicts of interest that could have appeared to influence the work reported in this paper.

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