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Original Article

A Framework of Minimizing Life Cycle Impact Towards Sustainable Asset Management of Water Supply Systems in Smart Cities

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Abstract *- Systematic Asset management is an important and essential attribute to ensuring sustainable water supply for the well-being of smart cities. There is a need for technological innovation and implementation of an affordable asset management system, taking into consideration the Life Cycle Impact (LCI) of all integrated components to achieve a robust water supply system in smart cities. Health risks due to possible intrusion through leakages, associated loss of energy, monetary involvement, and consequent loss of water, as well as the use of pumps, have made asset management a vital aspect of contemporary research and the practical world. Therefore, a decision-framing system is required to be developed through a life cycle assessment related to various integrated water supply components under smart cities. Studies suggested that water treatment and water abstraction were found to be the main consequences for most of the categories, considering their huge electricity consumption. The detailed inventory list, data requirement, and LCI parameters are assessed based on literature, essential for the holistic assessment of water supply assets. This paper attempts to provide a brief review of available literature and provide an impetus for preparing a conceptual framework for a proper trade-off concerning asset management systems, highlighting possible advantages and drawbacks considering its real-world application in the water supply system. A brief detail of the life cycle analysis system and its applications in water supply systems based on available literature are captured in this paper so that a simple, easy-to-operate, cost-effective, user-friendly and efficient method can be adopted for efficient asset management of water supply components under smart cities. Impacts are conventionally assessed for environmental, economic, and social consequences for analyzing sustainability. Advancement pertaining to the arena of life cycle assessment is discussed and the requirement of decision framing to detect possible detrimental effects on the assets and how it can be pro-actively assessed/ avoided are also emphasized. The role of life cycle analysis in water supply asset management is evaluated through literature-based case studies. An overview of the work carried out through Life cycle tools/ approach is examined to give motivation for future research work. Critical parameters are carefully reviewed, considering their importance in benchmarking asset management systems. A conceptual framework has been proposed based on how water supply assets under smart cities can be efficiently managed to achieve a sustainable water supply system. The issues and challenges associated with Asset management, along with a brief outline of future research scope, are also highlighted.*

Keywords - *Asset management, Decision making, Life cycle, Loss management, Sustainability, Water supply.*

1. Introduction

Water is the heart of life and essentially the most indispensable contributor to human civilization. World Health Organization (WHO) reported worldwide drinking water coverage in 2011 as 89% [52]. Access to good quality water and sanitation services has the prospect of preventing 9.1% of the world's health issues and 6.3% of all deaths [39, 23]. It is one of the least expensive and most triumphant ways of improving global public health status [35, 23].

This study provides a structured approach to addressing the multifaceted challenges of urban water supply management in smart cities. The development of a comprehensive framework is objective pertaining this paper that minimizes life cycle environmental impacts of urban water supply systems while ensuring sustainable asset management in the context of smart cities. The study aims to integrate sustainability principles, life cycle thinking, and smart technologies to address critical challenges such as ageing infrastructure, resource inefficiencies, and environmental degradation. By focusing on optimizing water resource management, enhancing operational resilience, and incorporating advanced technologies like IoT and data analytics, the framework seeks to balance competing demands, reduce environmental footprints, and support the long-term sustainability goals of smart cities. This research also aims to bridge governance and policy gaps, providing actionable strategies for equitable and efficient water management in rapidly urbanizing environments.

An adequate and sustainable supply of safe water [20] essentially requires proper asset management and improvement of looming infrastructure to serve the communities belonging to the urban fraction, including slum areas [41]. Urban water supply systems face challenges like leakage, energy loss, and health risks that compromise efficiency and sustainability. These issues lead to resource wastage, increased costs, and potential health hazards. Addressing them requires advanced technologies and proactive management strategies, with a Life Cycle Assessment (LCA) approach offering a holistic solution. Key strategies to enhance water supply efficiency include advanced leak detection through sensors and real-time monitoring to reduce water loss and repair costs, improved energy efficiency by upgrading pumping systems and integrating renewable energy to cut consumption and operational expenses, proactive maintenance through routine inspections and predictive maintenance to extend infrastructure life and prevent costly failures, and leveraging data analytics from smart meters and sensors to optimize decision-making, prioritize repairs, and allocate resources effectively. These strategies, supported by LCA, enhance system sustainability, reduce risks, and improve long-term water supply resilience.

The increasing trend of financial and environmental costs associated with water asset management has evolved as a major area of concern for water supply utilities. The complex water system is essentially comprised of the extraction of raw water, production and distribution of potable water, water consumption, and collection of wastewater and treatment, which are often managed independently. However, environmental considerations associated with all these processes need to be incorporated into a variety of decisions made by concerned individuals, corporations, as well as policymakers and public administrations. For benchmarking the impact, many tools and indicators are reported in the literature assessment methods such as Environmental Impact Assessment (EIA), Life Cycle Assessment (LCA), Strategic Environmental Assessment (SEA), Material Flow Analysis (MFA), Environmental Risk Assessment (ERA), Ecological Footprint, and Cost Benefit Analysis (CBA) among others. [10].

Among the available techniques, the comprehensive features of LCA include focusing on products or processes from a lifecycle perspective; moreover, its usefulness for assessing environmental consequences has made it unique in the contemporary research world. LCA, with its multipurpose features, can determine and assess the environmental effects associated with a product or system in a rigorous manner throughout its lifespan. The popularity of LCA has increased enormously in recent years as a unique assessment tool, which is well supported by the enhanced publication status [19].

The inbuilt protocol of LCA can act as a suitable assistance tool for recognizing and evaluating the environmental effects of concerned assets and water facilities and predicting different situations to act as a framing system for possible improvement of water supply assets [3]. Various features of water systems are reported in the literature, which is taken care of through life cycle analysis; however, the importance of cost recovery in maintaining the system is not emphasized in most literature [51]. Environmental impacts arising from groundwater and surface water acting as a source (used either in isolation or in combination) are also not adequately compared and documented in the literature. Achieving the consistency of the water supply system year in and year out requires an enormous effort, flawless mechanism, and good governance from the authorities concerned.

The problem lies in the lack of an integrated framework that addresses the effects of life cycles related to water supply systems pertaining to smart cities while aligning with the principles of sustainable asset management. Current approaches often focus on isolated aspects, such as technological advancements or stakeholder engagement, without considering the broader environmental and social implications. This fragmented approach limits the ability of cities to achieve long-term sustainability goals. In this paper, an attempt will be made to develop a noble framework using the life cycle analysis tool that could be employed to Indian conditions for managing water supply assets in order to make the water system self-sustainable in smart cities. Such a framework has been integrated with life cycle thinking, smart technologies, and sustainability principles to address the interconnected challenges of resource efficiency, environmental impacts, and operational resilience. This study presents a pioneering novel framework that combines life cycle impact minimization with sustainable asset management tailored to the unique demands of smart cities.

2. Motivation of the Study

Life cycle analysis presents a great challenge with its interdisciplinary research provision, such as water, wastewater, structure, transportation, water resources, architectures, etc., with different parameters and target perspectives. The water supply system is facing challenges not only to display superior performance but also to have lower environmental impact and cost. Integrated multidisciplinary tools/ framework in the form of proper pumping operation, water loss control, energy efficient electrical motor use, application of public, private partnership model (PPP) and strategy of proportionate use of drinking water source between surface water and groundwater are few of the areas where not much work has been reported.

Average 44 % water loss [53], ageing water network, significant loss of energy, inadequate pricing mechanism, and poor recovery of operation cost in the Indian domestic water sector have made the condition of the water distribution network very susceptible. In developing countries, water supply sectors are mostly controlled by the public sector, and it only recovers approximately 22 to 25 % lower than operation and maintenance costs [4]. In addition, rampant discharge of untreated industrial and domestic discharge and unprecedented groundwater exploration have made both water sources very vulnerable under the Indian scenario.

Asset management is crucial for the sustainability and efficiency of water supply systems, as it directly impacts infrastructure performance and long-term costs. A life cycle approach, covering design, operation, maintenance, and decommissioning-helps reduce costs, extend infrastructure life, and minimize environmental impacts. Without systematic management, utilities risk deteriorating assets, inefficiencies, and rising costs. The Manila Water case study exemplifies this: in the 1990s, high non-revenue water (NRW) levels of 63%, through asset management improvements, Manila reduced NRW to 12.69% by 2022 [1].

The water utility attributes its success in reducing NRW to a comprehensive method that integrates solutions through technical means, innovations, and public involvement. This strategy included network reconfiguration, precise assessment of supply volumes, proactive leakage management, repairs, supply and pressure regulation, and meter management initiatives. Investing in infrastructure upgrades, advanced monitoring, and proactive maintenance can significantly reduce water loss and enhance system sustainability.

There is a dearth of practical guidelines in the overall consolidated assessment of water asset management, and smart city projects require special attention to ensure sustainable water asset management. There is a need to develop a simple, easy-to-operate, cost-effective, user-friendly, and efficient method for assessing assets to create sustainable water systems in smart cities. Impacts are conventionally assessed for environmental, economic and social consequences for analyzing the eco-friendliness of any system or product [10]. To analyze the effects associated with all these phases, LCA has emerged as a proven technology to quantify the consequence of a facility and product or process from inception to disposal [7]. This calls for developing a holistic framework to identify the appropriate tools, methodology, and means of implementing the same. This paper aims to provide a conceptual framework in accordance with the idea that water supply assets in smart cities can be efficiently managed to achieve a sustainable water supply system. The novelty of this research lies in its holistic and integrated approach to minimizing life cycle impacts while ensuring sustainable asset management of water supply systems in smart cities. By addressing gaps in existing research-such as the lack of life cycle focus, limited integration of smart technologies, and insufficient stakeholder alignment-this work provides a comprehensive, innovative, and practical framework for advancing sustainability in urban water management.

3. Literature Review

3.1. Background

LCA has been established as a proven technology for assessment pertaining to the sustainability of the environment related to water systems in a few decades by showing quantitative and on-the-whole information on source utilization and environmental discharge of the scheme examined. Life Cycle Engineering (LCE) is an analytical tool. It can be utilized efficiently as a decision-support tool that essentially integrates the data about fiscal and environmental characteristics with technical factors in the decision-making process**.** [6]. It is a standardized process applied to evaluate the environmental impact of a product, service, or activity from a life cycle viewpoint [24, 25], which in turn will ensure proper management of water supply assets. This diversified tool evolves around the complete, from the withdrawal of raw material to development, allocation, utilization, accomplishment of required treatment, recycling and eventually, disposal [2]. It has been acknowledged as a strong analytical framework for selecting environmental sustainability indicators [33], which is of paramount importance considering the agenda of post-2015 MDG [49]. Among the different explored areas, LCA, as an evaluation and assessment instrument, has proven its worth in the water sector in recognizing, illustrating, and assessing all water-related environmental impacts, aiding water professionals and decision-makers. It has been recognized as an effective tool for pinpointing environmental hot spots within systems for eco-design purposes. It offers guidance for preventing pollution shifts across impact categories or life cycle stages [10]. It was studied and reported that in Ghana, present asset management [28] methods are governed by people and fiscal availability, and to improve the same need, detailed results/ data and its robust analysis system to judicious planning and strategic call for effective asset management. Developing a framework to minimize life cycle impacts for sustainable asset management of water supply systems in smart cities is a critical and timely topic.

Environmental impact through LCA, encompassing different aspects of water systems like drinking water collection and treatment [40, 50], wastewater treatment [14], and sewage sludge treatment [42], are documented in the literature. It may be customized for diverse applications in the water industry, ranging from choice of chemicals to finalization of any processes and asset management. LCA works on various parts of water, such as domestic WTP [21], water reuse effect [36], and treatment of sludge related to wastewater [46], which were reported in the literature. LCA work has further suggested planning for sustainable water systems [32, 48] or pumping station effects in wastewater treatment plants [29], which are prerequisites for asset management. A framework based on the concept of LCA was first reported [33] for analyzing and assessing the environmental impact of the water supply system. The methodology of LCA has shown immense potential in its strategic task for recognizing the significant processes, the probable ways for development, and asset management facilitating the computation of the environmental load scientifically and methodically concerning inputs and outputs of a water supply system [5]. However, most studies carried out and reported are case-specific, and overall analyses that consider processes and distribution systems are missing. That apart, LCA, as per recent trends, has been used for assessing the impact consequential from water production, conveyance of water and wastewater treatment, but a small number of works have analyzed the overall asset management of the water supply system.

A water supply system has environmental, economic, and social impacts throughout its lifecycle-from material sourcing to decommissioning. Life Cycle Assessment (LCA) helps evaluate these impacts and guide sustainable practices. The lifecycle of a water supply system involves key stages-material sourcing, construction, operation, and decommissioning-each with significant environmental impacts. Raw material extraction and construction can lead to resource depletion, pollution, and waste, but LCA helps identify sustainable materials and optimized techniques to reduce these effects. The operation phase is energy-intensive, involving high energy use, chemicals, and inefficiencies like leaks; LCA evaluates energy consumption and operational efficiency, promoting resource reduction and the integration of renewable energy. At decommissioning, infrastructure generates waste, including hazardous materials, and LCA aids in assessing waste management and recycling opportunities, supporting circular economy practices to minimize environmental harm. LCA also supports climate resilience by identifying design and operational improvements to withstand climate impacts, such as energy-efficient technologies or increased water storage. Developing a framework to minimize life cycle impacts for sustainable asset management of water supply systems in smart cities is essential to address the growing challenges of urbanization, resource scarcity, and climate change. By integrating life cycle thinking, smart technologies, and sustainability principles, such a framework can provide a comprehensive solution to enhance the resilience and efficiency of urban water systems. This approach will support the sustainability goals of smart cities and contribute to global efforts to ensure access to safe water and sanitation for all.

Integrating LCA into water system planning and operation ensures sustainability, reduces long-term environmental harm, and enhances resilience to climate change, safeguarding reliable water access for future generations.

3.2. Overview of LCA Methods

LCA study comprises four stages: goal and specification, inventory analysis, impact assessment and interpretation, which can be utilized in product development and corresponding improvement, marketing, strategic approach, and public policy planning [25]. Goal and specification are major steps that clearly define the envisioned uses, ensuring overall detail pertaining to research from where one research perspective differs from others. The extent typically includes the product or system to be examined, and most importantly system boundary, functional units and data requirements are finalized as per the need of the research. The inventory analysis usually quantifies the use of energy and raw material input and corresponding environmental emissions from a defined system, which is included in the inventory list. The potential impacts on human health and the environment are analyzed in this phase, which includes developing a characterization model and impact categories. Normalization and weighing are considered optional steps in the basic methods; however, different existing models and research works have been reported regarding this step.

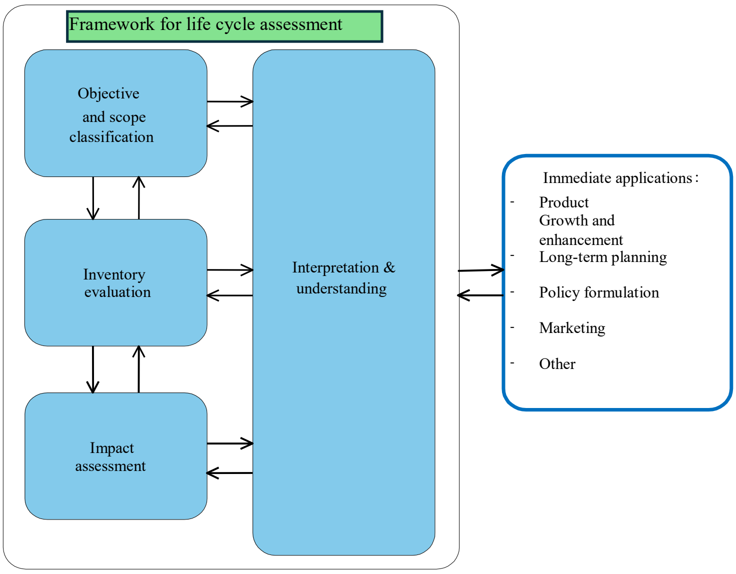


Fig. 1 Basic outline for LCA methodology

Finally, the interpretation corresponds to the choice of making process depending on inventory and impact assessment of the system [24, 25].

Important features of various steps of LCA are presented in Table 1**Error! Reference source not found.** and schematic of the methodology is presented in Figure 1.

The Table 1 represents some of the brief features of LCA methodology included on ISO 14040, 2006 and ISO 14044, 2006 [24, 25]. However, there are different aspects present within LCA, which require further detailing to understand the process. Aspects like characterizations model, impact assessment methods, normalization, weighing etc. are still a dynamic field of study where a lot of work can be carried out.

3.3. Life Cycle Impact Assessment Methods

The methods discussed provide assessment of the significance of the possible environmental consequences with the help of the outcome of the inventory investigation and asset management. The procedure followed for these methods are provided by ISO 14040, 2006; however, researchers must finalize their own methodology for finalizing the impact methods to be used for the assessment of the target objectives towards achieving water supply asset management.

Table 1. LCA methodology at a glance

Sr. No	LCA Step	Salient Features	Typical Quantitative Measure
1	Objective and scope classification	• Finalization pertaining to research steps. Identification system boundary. • Quality of data requirement. Methodology of impact assessment.	• Operational unit considerations. Inhabitant's data. • Number or Km of pipe considerations. • Components like Intake, WTP, Rising Main, OHR, Pumping stations, house connections
2	Inventory Evaluation	• Data collection and identification of procedure. • Data base considerations.	• Data collection usually includes energy inputs, raw material inputs, product, co product and waste related data. • Water flow and consumption. • Electrical consumptions etc.
3	Assessment of Life cycle impact	• Identification of categories of impact. • Category indicators. • Characterization model. • Assignments of LCI results. • Category indicator result calculations. • Assessment of the scale of category indicator outcomes and normalization of the same (Optional). • Grouping (optional). • Weighing (optional).	• Climate change impacts data. • Acidification potential, • Eutrophication impacts etc. • Water consumption impacts estimation. • Status of pipelines • electro-mechanical items and its impact • Civil components • Water loss • Loss in energy • Converting all data to single score data.
4	Life cycle interpretation and understanding	• Impact assessment and inventory analysis assessment considered together. • LCIA results is not reflection of actual impact prediction of category endpoints, but they are based on relative approach.	• Interpretation can suggest conclusion and recommendation to decision makers, corresponding to the goal of study.

3.3.1. Conceptual Methods

The probable impact from every inventory emission, flow from processes, water loss, higher energy consumption, pressure drop are conceptualized in mathematical form, corresponding to environmental process with the help of characterization model. Material corresponding characterization factors of characterization model, articulate possible consequence of individual basic consideration with respect to the general unit of the group indicator. Potency of every elementary flow through relative expression with the help of characterization factor is estimated, which can compare the impact of the category indicator. Inventory data are multiplied by characterization factor to derive result of category indicator. It is presented in a unit general to every consequence corresponding to the impact domain.

Conventionally, existing characterization models or developed characterization models addressing corresponding impact category are used for life cycle impact assessment (LCIA) method. Research groups across globe are working on the development of standardized internationally recognized collection of characterization models and parameters. Attempts have been reported in water impact index and industrial water use (31).

Literature has reported the creation and implementation of diverse methods for assessing life cycle impacts in LCA studies, like ReCiPe [17], Eco-indicator 99 (16), CML 2002 [18], EPS [47] IMPACT 2002+ [26]. Research work has evolved from early application of midpoint concept (CML 2002) and endpoint methods (EPS, Ecoindicator 99) to methods encompassing both concepts with consequent effect incorporating together endpoint and midpoint levels (ReCiPe, IMPACT2002+). However, most existing models are very case specific and still under research phase. Practitioners are in dearth of characterizations models and factors, which may affect different results regarding the impact categories employed [38].

A typical representation of midpoint and end point category are schematically presented in Figure 2.

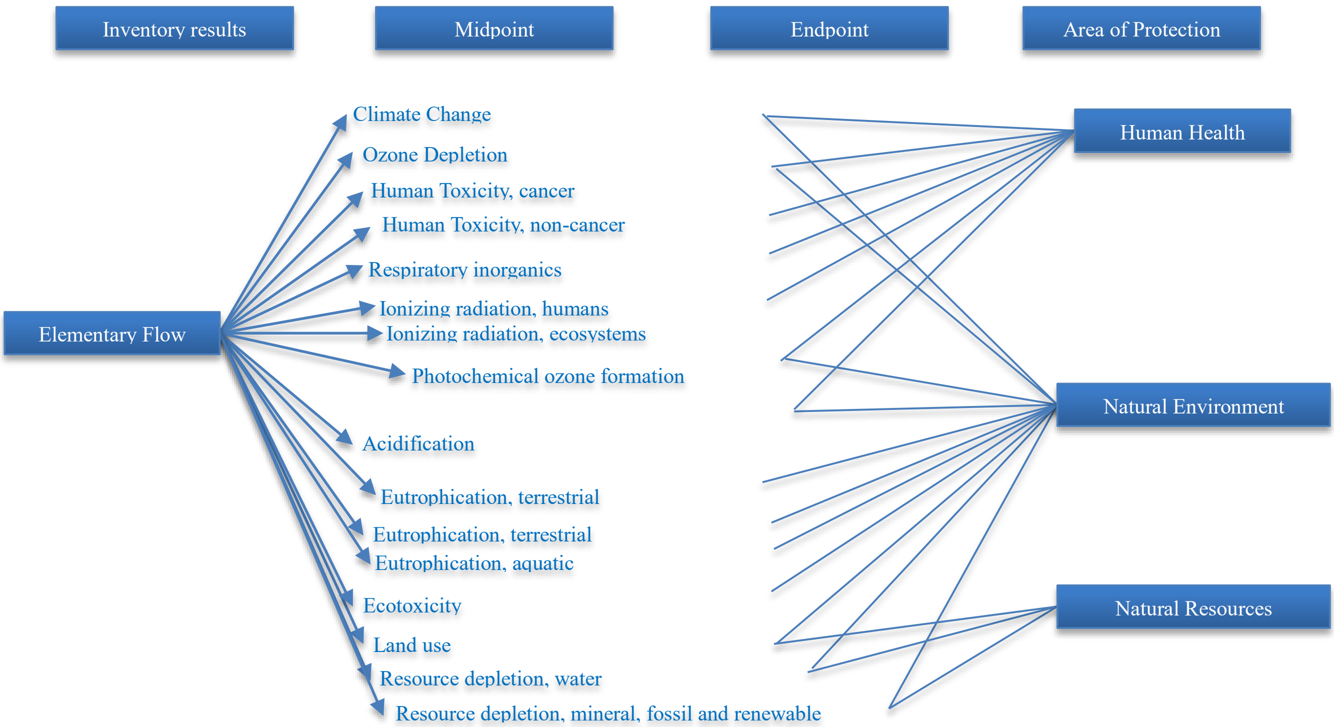


Fig. 2 Schematic representation of impact category [22]

Midpoint level is preferably designated by an indicator positioned inside impact trail, till which a general mechanism persists in line with key attributing elements inside that corresponding category of impact. However, the endpoint modeling basically incorporates the characterization of the extent of the harm represented by the midpoint indicator. Best available characterization models for mid-point level & midpoint to end point level are well documented in literature [22]. Commonly used impact categories usually practiced for life cycle impact analysis are represented in Table 2.

Table 1. Commonly practiced impact classifications

Impact category	Scale	Typical Inventory data	Characterization factor
Global warming	Global	Carbon Dioxide (CO_2), Nitrogen Dioxide (NO_2), Methane (CH_4), CFC, HCFCs, Methyl Bromide (CH_3Br)	Global warming potential [11]
Stratospheric Ozone Depletion	Global	Chlorofluorocarbons (CFCs) Hydrochlorofluorocarbons (HCFCs), Halons Methyl Bromide (CH3Br)	Ozone Depleting Potential
Eutrophication	Local	Phosphate (PO4) Nitrogen Oxide (NO) Nitrogen Dioxide (NO2) Nitrates Ammonia (NH4)	Eutrophication Potential
Acidification	Regional Local	Sulfur Oxides (SOx) Nitrogen Oxides (NOx) Hydrochloric Acid (HCL) Hydroflouric Acid (HF) Ammonia (NH4)	Acidification Potential
Health of human	Global Regional Local	Total releases to air, water, and soil.	LC50 Converts LC50 data to equivalents; uses multi-media modeling exposure pathways.

Impact category	Scale	Typical Inventory data	Characterization factor
Depletion of resource	Global Regional Local	Quantity of minerals used Quantity of fossil fuels used	Resource Depletion Potential Converts LCI data to a ratio of the quantity of resources used versus the quantity of resources left in reserve.
Use of water	Regional Local	Water used or consumed	Converts LCI data to a ratio of the quantity of water used versus the quantity of resources left in reserve.

Source: Adopted from [24, 19]

Some of the equations used for calculating characterization factors for a few impact categories are elaborated in Table 3.

Table 3. A typical formulation of characterization factor for impact for a few categories

Impact category considered	Characterization of equivalence factors	Descriptions	Reference
Global warming potential	$GWP_{f,i} = \frac{\int_0^T a_i c_i(t)dt}{\int_0^T a_{CO_2} c_{CO_2}(t)dt}$	a_i and a_{CO2} = radiative forcing per unit conc increase of greenhouse gas i and that of CO_2. C_i (t) and C_{CO2} = concentration of greenhouse gas i and that of CO_2 at time t after release. T= number of years.	[18]
Acidification potential	$\frac{n_i}{n_{SO_2}}$	Number of H+ ions (mole/kg) that can be produced per kg of substance i and that of SO_2	[18]
Ozone depletion potential	$\frac{\partial(O_3)_i}{\partial(O_3)_{CFC-11}}$	Ozone breakdown in equilibrium state due to annual emissions (kg per year) of substance, I that of CFC-11 released into the atmosphere	[18]
Water use impact	$\left[{}^{WU}/_{(WR-EWR)}\right]^{\{({}^{WR}/_{2})\times EWR}$	WU= water use, WR- renewable water resources, EWR- environmental water requirement	[31]. (Amount of water multiplied with CF, which will result in local or regional sensitivity towards freshwater extraction)
	$WTA = {}^{W_w}/_{W_a}$	Ww= water withdrawal, Wa= water availability.	[2] $FEI = \sum_{i=1}^{n} CWU_i$ FEI= freshwater ecosystem impact,

			CWUi = consumptive water use of a unit process in cum
Potential human health impacts of water deprivation of user i (agriculture, domestic user or fisheries)	$CF_i\left(\frac{DAILY}{m^3}\right) = SI \times DAU_i \times \underbrace{SEP \times EF_i}_{\substack{SEE_i \\ factor}}$	SI= Scarcity or availability index, depending on the inclusion (availability) or exclusion (scarcity) of quality in the index. DAUi = distribution of affected users i (i.e. fraction of water use that affects users i) SEP= Socio-economic parameter EFi= Effect factor for water deprivation of user i SEEi factor= Socio-economic and effect factor	[12]

3.4. Summary of LCA Application in the Water Industry

LCA for the water industry has been broadly encompassed in the following aspects, as marked in Table 4.

Table 4. The broad area of LCA works reported in the water system

Sr. No	Major area for research	Salient features covered
1	Water technology (both plants and network)	Drinking water production plant. Water supply assets Distribution of water for drinking Network for collection of wastewater Wastewater treatment plant.
2	Water system	Work includes several water technologies, including drinking water distribution, assets, and wastewater collection. LCA techniques include partial or full LCA incorporating one impact category or multi-criteria impact assessments.
3	Unit processes	LCA of unit processes.

Since late 1990, LCA has been reported to be successfully used in water technology assessment with application in part of the water system, along with drinking water production and life cycle approach to improving water supply system [27]. However, major emphasis was placed on LCA application in wastewater treatment systems [8].

Studies on the environmental impact of water supply systems in South Africa, Australia, Spain, Belgium and Egypt, respectively, are well documented in literatures considering the different perspectives of water systems [32, 29, 13, 34]. The impact associated with the drinking water system is summarized in Table 5.

Majorities of the case studies were reported for European cities, where as balance studies were reported from North America, Australia, South Africa, China and Southeast Asia. An overview of some of the latest studies incorporating water supply status is captured below in Table 6.

Table 5. Probable impact category related to drinking water works

Impact category	Influence on the water system
Climate change	The emission from water treatment due to chemical use, transport, construction power, etc., generates green house gas, such as CO_2, use of pumps etc.
Ecotoxicity	Sludge generated from water treatment.
Minerals	Use of chemicals.
Respiratory organics	The use of ozone may be associated.
Fossil fuel	Energy used in pumping, treatment
Ozone layer	Chlorine-containing substance used in water treatment for pre and post chlorination.
Land use	Infrastructure used for land use.
Water use impact	Effect on source as water abstraction, water scarcity.

Source: adopted from [34, 25, 43]

Table 6. Summary of recent important LCA papers on the water supply system

Study location	Functional unit	Inhabitants covered	Broad area	Key findings	Reference
Trondheim, Norway	A city/year	1,71,000	DWP, DWD, WWC, WWT	• Energy consumption and use of chemicals resulted in freshwater eutrophication, which contributed to maximum environmental impact. • A proper trade-off is needed between consumption of chemicals, energy use, and pollutant discharge.	[45]
Tarragona, Spain	1cum	1,45,000	DWP, DWD, WWC, WWT	• High energy consumption resulted in the main environmental impacts due to global warming potential, resulting in more than 35 % due to water network, more than 20 % due to collection pumping and around 14 % resulting from wastewater treatment plants.	[2]
Aveiro, Portugal	1cum	78,450	DWP,DWD, WWC,WWT, ADM	• Water treatment and water abstraction were found to be the main consequences for the majority of the categories, considering their huge electricity consumption. The result can be taken as a decision-making process considering environmental sustainability and corresponding future investment.	[30]
Copenhagen, Denmark	1cum	5,20,000	DWP, DWD, WWC, WWT, Users	• Among the scenarios assessed, the rain and stormwater harvesting case is responsible for minimum overall consequences, followed by the cases dependent on groundwater	[15]

Study location	Functional unit	Inhabitants covered	Broad area	Key findings	Reference
				abstraction, whereas desalination was responsible for comparatively little but still significant enhancement resulted.	
Iasi City, Romani	1cum	2,61,384	DWP, WWC, WWT	• High water loss and energy required for the distribution systems envisaged a higher impact occurring before the tap system than the impact taking place subsequent to the tap system, even considering the treated water discharge taking place after the tap.	[3]
Manatee County, USA	1cum	323 833	DWP, DWD, WWC, WWT	• Analysis of an integrated carbon footprint and cost was carried out, which enumerates the CO2 equivalent emissions in the life cycle phase of 20 alternatives. • The result suggested that considering GHG emission as a new characteristic has affected the priority ranking of the 20 alternatives and may guide a completely diverse choice in water expansion strategy.	[40]
Berlin (part), Germany	1capita/year	-	DWP, WWT	• Analysis of the impact assessment suggested that 13 to 26 % of cumulative energy demand can be decreased through energy extraction of resources from the organic content of toilet wastewater and household biowaste through anaerobic digestion.	[42]
Oslo, Norway	1capita/year	5,29,800	DWP, DWD, WWC, WWT	• The energy consumed at the downstream side was 0.8 kWh / cum of wastewater treated, and at the upstream, it was around 0.4 kWh per unit volume on average.	[50]
Aurora, Australia	NA	8500 houses	DWP, DWD, WWC, WWT, Users	• Results suggested that depending on the type of water heater installed, GHG emissions due to water-related issues from water users from residences are analogous with or	[9]

Study location	Functional unit	Inhabitants covered	Broad area	Key findings	Reference
				surpassing consequences from combined emissions from various sources for the system studied. • Higher GHG emission was observed with the recycling system on each house for selected domestic grey water installation in contrast to the centralized or decentralized water system options.	
Alexandria, Egypt	1 cum	37,00, 000	DWP, DWD, WWC, WWT	• Results suggested that the disposal of primary treated wastewater is responsible for the highest impact, encompassing 68% of the total impact, followed by 18 % of the total impact for energy-intensive water treatment facilities. • Analysis of different scenarios further suggested decentralization and source separation of different kinds of household wastewater will be preferred in long-term scenarios.	[34]
Mediterranean Region, Spain	1 cum	2,00,00,000	DWP, DWD, WWC,WWT	• Analysis suggested that with respect to the ecotoxicity perspective, the reuse of wastewater by virtue of including tertiary treatments was found to be as the best choice.	[37]
Australia	10 MLD for over 20 years.	-	WWT, ST, T, D, FP	• Enhancement of increasing nitrogen removal is associated with increase of Energy usage, direct greenhouse gas (GHG) emissions, and chemical usage. A significant rise in infrastructure demands and chemical usage was noted alongside enhanced phosphorus removal.	[14]
California, USA	123 million liters	200,000	WWT, ST, T, D, FP, H, C	• The result suggested desalination required 2-5 times larger energy demand and was found to be responsible for 2–18 times more emissions than importation or recycling arising due to the energy-	[48]

Study location	Functional unit	Inhabitants covered	Broad area	Key findings	Reference
				intensive treatment process.	
Walloonregion,Belgium	1 cum	35,00,000	DWP, DWD, WWC, WWT	• Significant contributions to global environmental Anticipated loads are associated with water discharge, wastewater treatment operations, and, to a lesser extent, the sewer system. Small discharges without any treatment may result from significant environmental impact.	[29]
Toronto, Canada	-	26,00,000	DWP, DWD, WWC, WWT	• Key relations and feedback tools between infrastructure and surrounding environmental, economic, and social systems are emphasized by developing a framework for the sustainability assessment of water infrastructure.	[44]
Sydney, Australia	1 city/year	45,00,000	DWP, DWD, WWC, WWT, Adm	• The small increase in water supply in the case of desalination produced a considerable enhancement in greenhouse gas emissions due to coal-fired electricity generation. Proper incorporation of water demand management, on-site treatment, and local irrigation may provide an improved environmental scenario.	[32]

DWP- Drinking water production, DWD- Drinking water distribution, WWC- Wastewater collection, WWT- Wastewater treatment, Adm- water administration, T- transport of water, D- disposal, FP- fertilizer production, ST- sludge treatment.

Although LCA tools are already established for analyzing the overall impacts of systems or products on various counts, there is ample scope to improve the estimates by improvising parameter selection and LCA methodologies. From the chronicles of literature, the major gap is the preparation of a decision framework with holistic parametric correlations through LCA based approach for providing the decision makers a sustainable asset management platform.

3.4.1. Proposed Enhancements to Analytical Techniques Statistical Methods

- Descriptive Statistics: Clearly outline how Summary statistics, such as means, standard deviations, and ranges, were employed to encapsulate the data and identify trends in water supply system performance metrics (e.g., water loss, energy consumption, carbon emissions).
- Inferential Statistics: If applicable, include inferential methods such as regression analysis, hypothesis testing, or ANOVA to determine relationships between variables (e.g., water demand vs. energy use) or to compare system performance under different scenarios.
- Uncertainty Analysis: Provide a description of uncertainty quantification techniques, such as Monte Carlo simulations, to evaluate the reliability of life cycle impact assessments given variations in input data.

3.4.2. Software and Tools

- Life Cycle Assessment Tools: Specify the software or tools used for life cycle impact assessment, such as:
    - SimaPro or GaBi: For conducting the life cycle inventory and impact analysis.
    - Ecoinvent Database: This is used to access standardized life cycle inventory datasets.

- Data Management and Statistical Software:
    - Use of Excel or Python for data preprocessing and visualization.
    - Application of R or SPSS for advanced statistical analysis.
    - GIS Tools: If geospatial analysis was part of the framework, mention GIS software (e.g., ArcGIS) used to map water supply networks and identify spatial patterns of resource use or environmental impact.

4. Objective and Scope of the Present Study

The primary objective of this research is to evaluate the life cycle impact analysis of the water supply system with due consideration of minimization of life cycle impact. The framework will include the following important parameters.

- Identification of all the parameters that are pertinent/ critical for asset management of water supply systems under smart cities.
- Compilation of data inventory in accordance with the requirement laid in ISO 14040, 2006 and ISO 14044, 2006.
- Framing interactive relations between identified parameters and their associated impacts.
- Work out independent and interactive cause-effect relationships for the input parameters in the LCA of water utilities asset management.
- Development of a conceptual framework for minimizing life cycle impact for achieving sustainable management of water supply assets for smart cities.

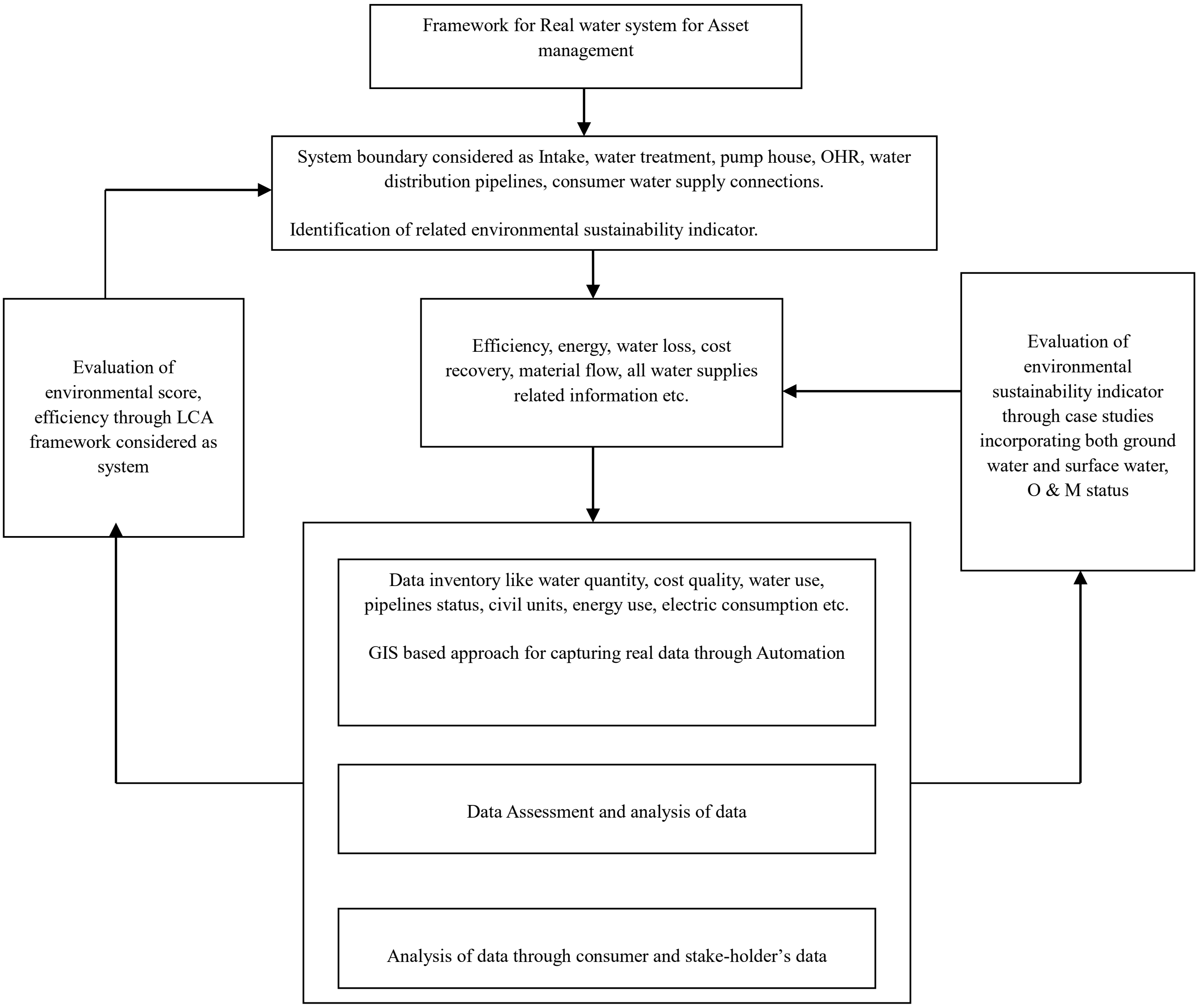


Fig. 3 Framework concept for the analysis of environmental sustainability (source- modified from [33]) for sustainable asset management

5. Methodology Framework

The basic LCA framework for the proposed study is adopted from [33]. It is depicted in Figure 3**Error! Reference source not found.**. Environmental sustainability of the water supply system will be depicted based on the proposed framework for providing a decision-framing system for ensuring sustainable water management. For our study, system boundary has been considered starting from the source of water, treatment of water, and water distribution and consumer water supply as shown in Figure 4. All data related to water supply, like all assets like Intake, WTP, Pump houses, OHR, pipelines; energy and electricity consumed at various steps, water consumption, pump operation related data, water loss, cost recovery, material flow, chemical use, maintenance related information will be collected and assessed. Various stages of water use within our target system boundary, along with the probable life cycle and expected data types, are provided in Table 7. The water supply system within the study boundary, parameters to include, and salient features of pertinent impact categories for both surface water sources and groundwater sources are shown in Figure 5 and 6, respectively.

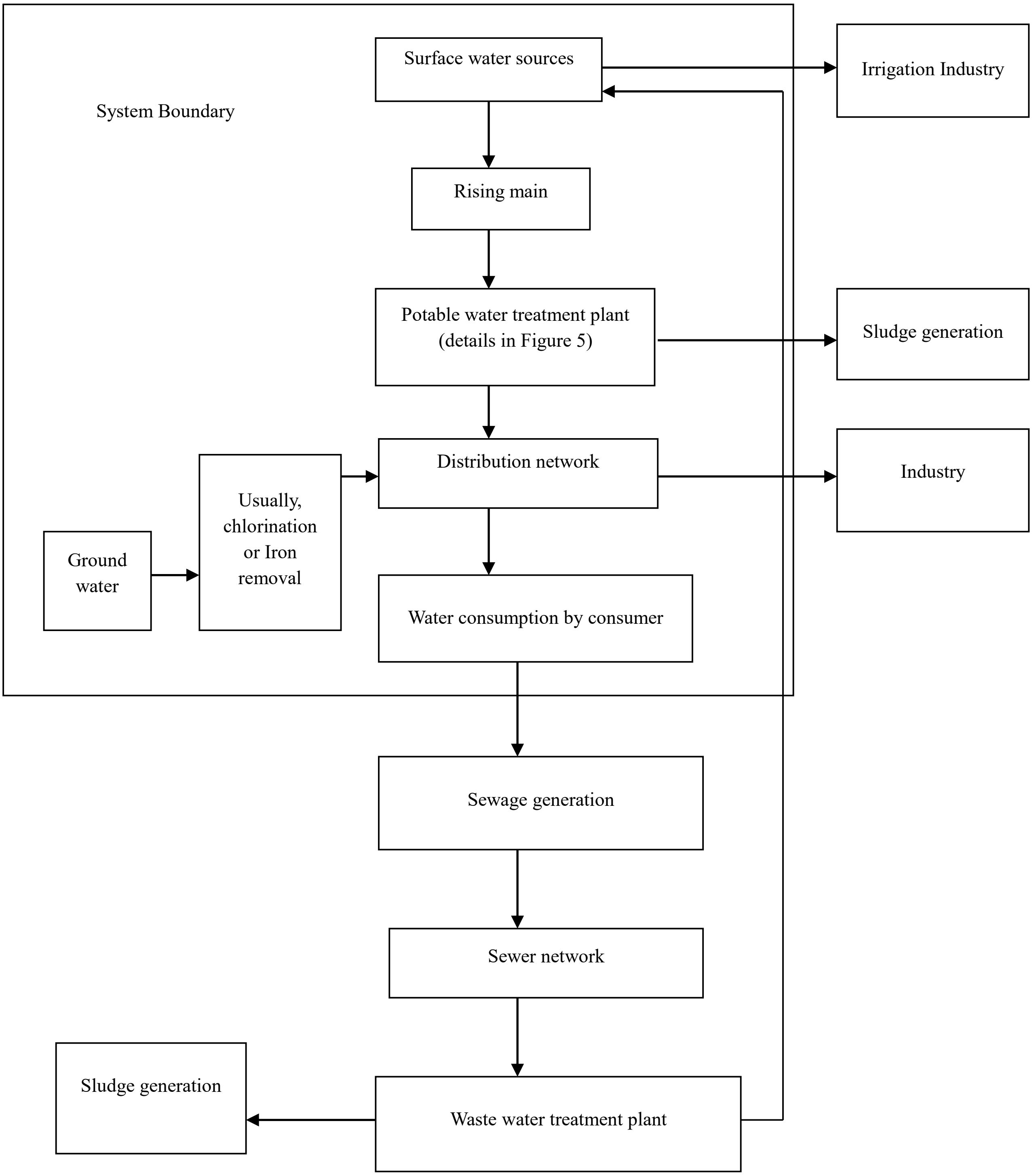
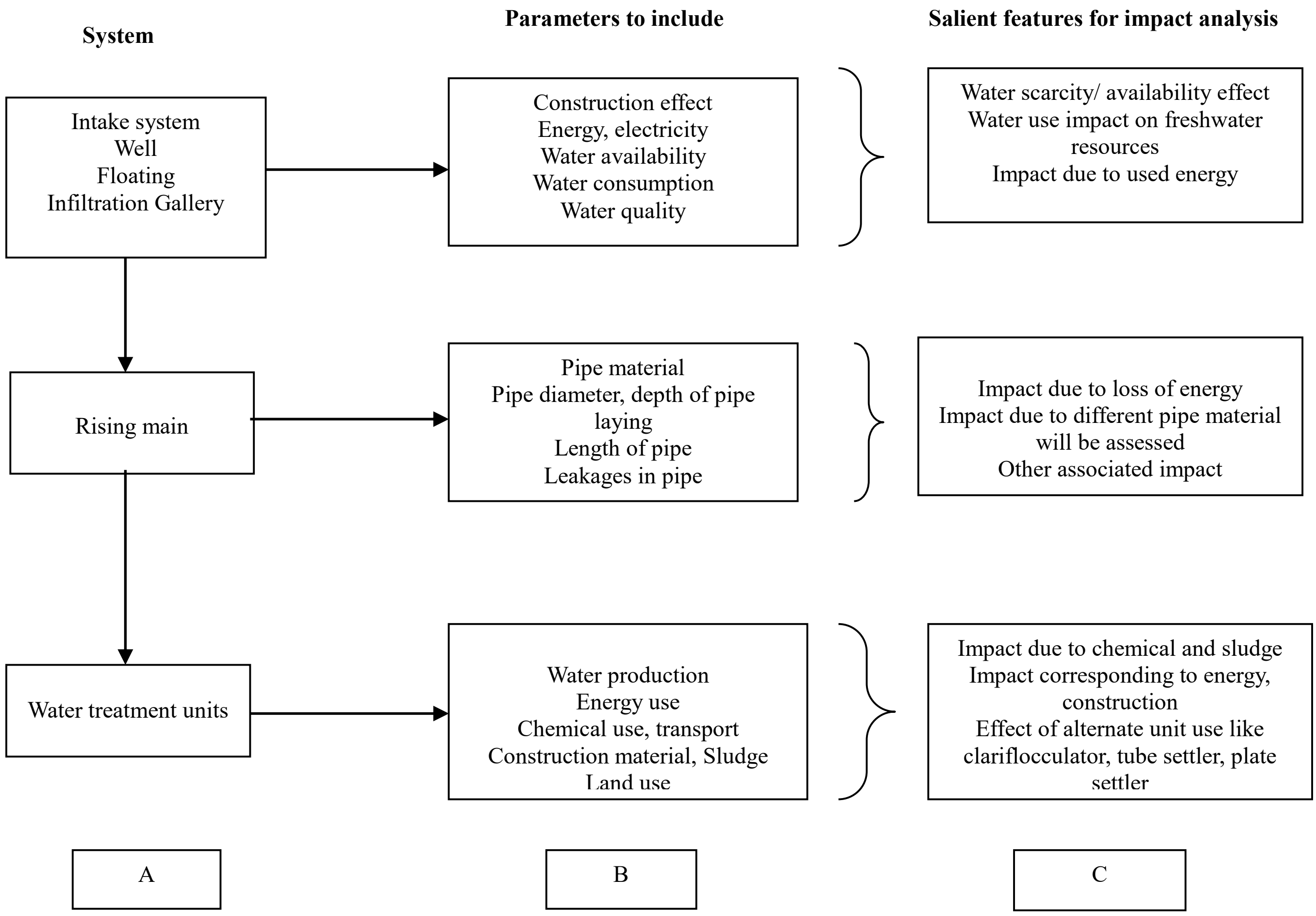


Fig. 4 Broad system boundary considered for life cycle inventory analysis

Table 7. Brief summary inventory data for asset management framework

Stages of water use	LCI parameters	Data type	Remarks
Water abstraction	Volume of water abstraction, energy, infrastructure, and water quality.	Electricity consumption, pump energy, operating data, and infrastructure materials (concrete, steel).	Water use impact, water availability.
Rising main	Pipes detail, leakages, infrastructure	Pipe length, depth of pipe laying, pipe breaks, leakages, fuel used, pipe loss.	Transportation effect to be considered with GIS implementation.
Potable water treatment plant	Water produced, chemical use, energy, infrastructure, operation and maintenance.	Electricity consumption, pump energy, operating data, infrastructure materials (concrete, steel), chemical use and transport, leakages, sludge details, and sludge management.	Transportation effect to be considered, SCADA and Automation.
Drinking water distribution	Pipes detail, leakages, infrastructure, operating data, chemicals, operation and maintenance.	Pipe length, depth of pipe laying, pipe breaks, leakages, non-revenue water, fuel used.	The transportation effect is to be considered using the GIS-based SCADA integrated approach.
Consumer end	Volume of water, cost of water, quality of water, health.	Water use, quality check, water access, coverage.	% of the population having access to safe water adequately, automation.

Source: [2, 3, 30]



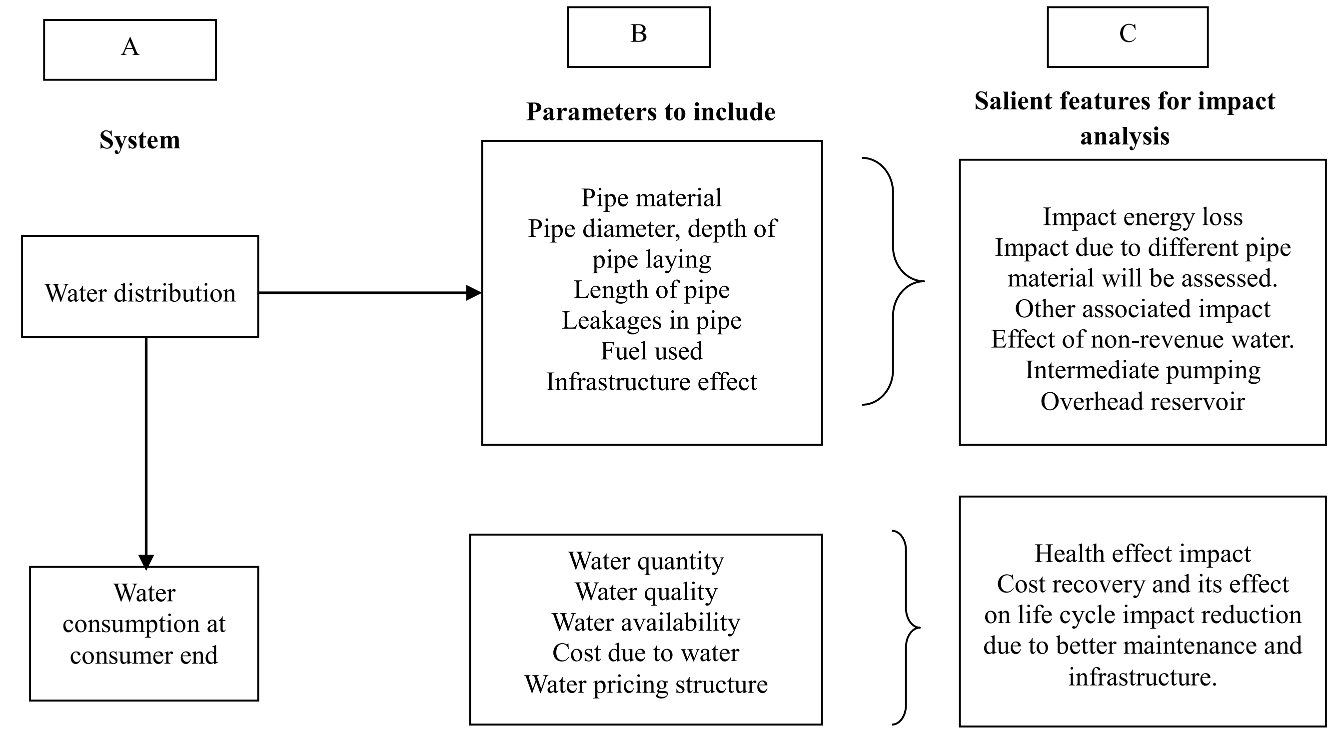


Fig. 5 Characteristics feature of water supply system with surface water source

The total impact will be a cumulative result of all the impacts from different water supply components. The overall analysis will provide guidelines for the life cycle impact minimization scenario for water supply in smart cities.

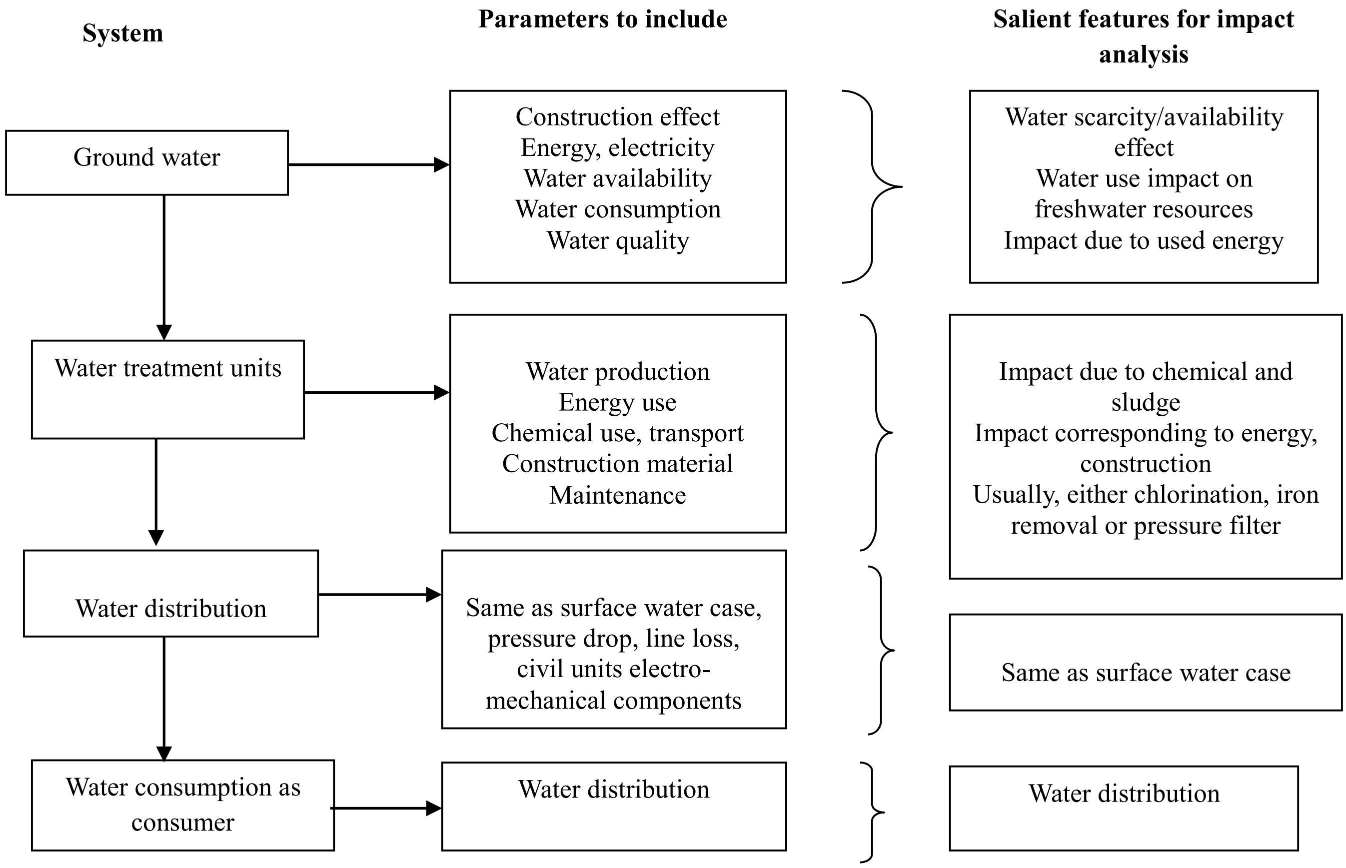


Fig. 6 Frame-work for decision support for water system with ground water source

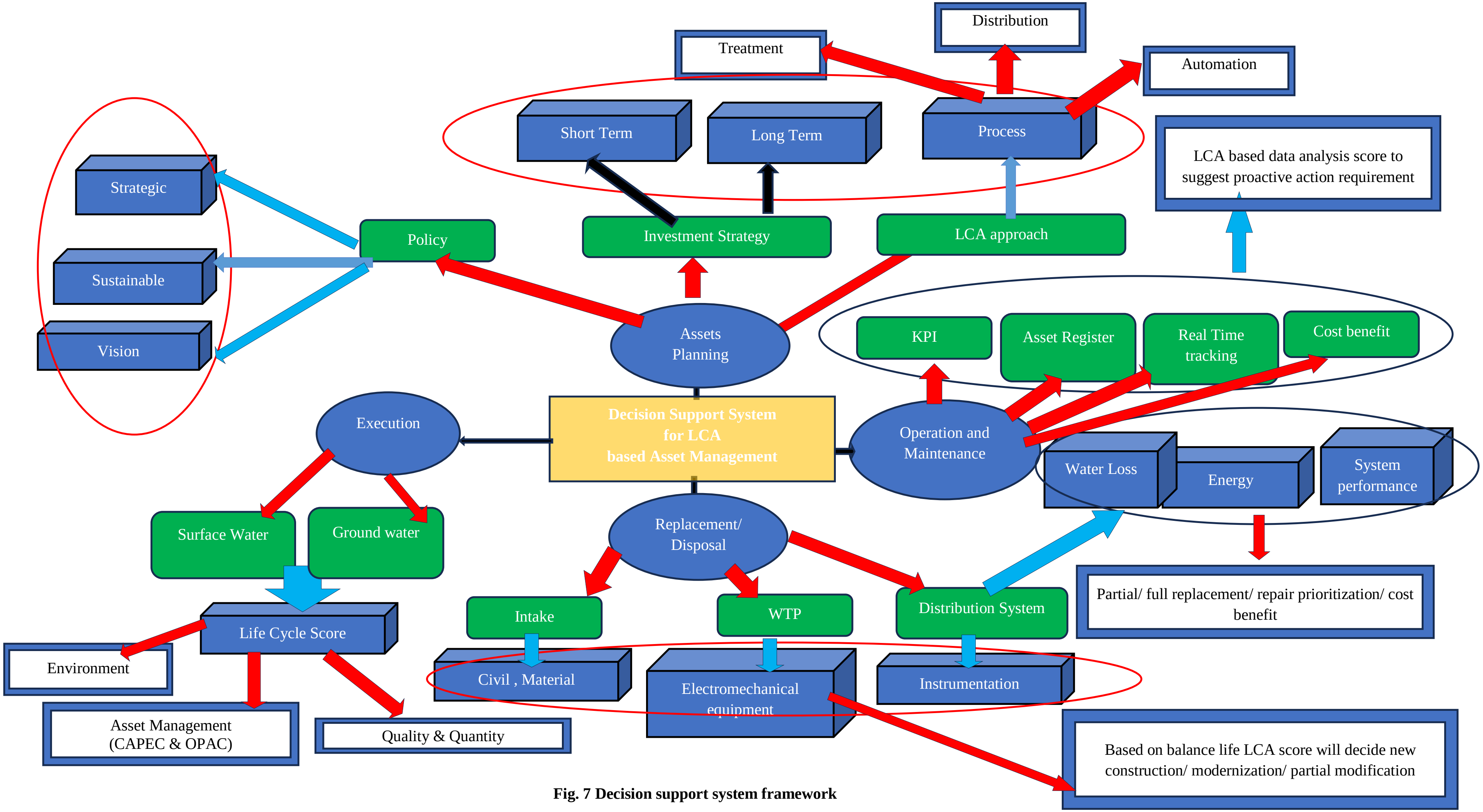


Fig. 7 Decision support system framework

The proposed framework and its proper application will provide suitable impetus for the authority to make informed decisions and prioritise the work as needed.

The key findings through this framework have been highlighted below.

- Sustainable Resource Management**:** Implement practices that ensure the sustainable use of water resources, including rainwater harvesting and groundwater recharge.
- Infrastructure Resilience**:** Design and upgrade water supply infrastructure to withstand climate change impacts and natural disasters, ensuring long-term reliability for smart city water supply assets.
- Integrated Water Resource Management (IWRM)**:** Adopt a holistic approach that considers all aspects of the water supply, promoting collaboration among stakeholders in line Key performance index (KPI) targeted.
- Smart Technology Integration**:** Utilize IoT and data analytics for real-time monitoring and management of water supply systems to enhance efficiency and reduce waste and energy optimization.
- Community Engagement**:** Foster community involvement in decision-making processes to ensure that water supply strategies meet local needs and preferences.
- Immediate Infrastructure Repairs**:** Prioritize repairing and maintaining existing water supply systems to prevent service disruptions.
- Public Awareness Campaigns**:** Educate the community about water conservation practices and the importance of sustainable water use in case any discrepancy is observed.
- Emergency Response Planning**:** Develop and implement contingency plans for water supply disruptions due to emergencies or natural disasters.
- Data Collection and Analysis**:** Based on the framework, collect and analyze data on water usage patterns, residual pressure, and water losses to inform short-term operational decisions.

5.1. Detailed Explanation of Data Collection Methods

- Primary Data Collection: Specify how real-world data was gathered (e.g., field surveys, monitoring systems, stakeholder interviews). For instance, if IoT devices were used to monitor water flow, pressure, and quality, describe the type of sensors, frequency of data collection, and geographic coverage.
- Secondary Data Sources: Identify the datasets or reports used for analysis, such as government water usage statistics, smart city infrastructure reports, or environmental impact assessments. Include details on data sources, time frames, and any preprocessing steps (e.g., cleaning or validation).
- Case Study Approach: If applicable, describe why a particular city or region was selected as a case study, including its relevance to smart city initiatives and water management challenges.
- The same can be included in the Contractor's scope of work so that data can be collected systematically and so that it can be assessed.

This framework aims to create a balanced approach that addresses both immediate needs and long-term sustainability goals for water supply systems in smart cities.

The following Flowchart for Conceptual Framework on Managing Water Supply Assets has been presented, providing a deep insight into how the overall LCA concept will help effectively manage water supply systems in smart cities.

Start: Water Supply System Management

- Focus on efficient, sustainable, and resilient systems.

Life Cycle Assessment (LCA)

- Collect data on all stages of the system (Material Sourcing, Construction, Operation, Decommissioning).
- Evaluate environmental, economic, and social impacts.

→ Inform Decision-Making
Decision-Making Processes

- Use LCA data to guide strategic decisions.
- Prioritize sustainable materials, operational practices, and technologies.
- Incorporate energy efficiency, water loss reduction, and waste management.

→ Identify Key Areas for Technology Integration
Technology Integration

- IoT (Internet of Things): Enable real-time monitoring (sensors, smart meters, leak detection). → Inform operational efficiency and predictive maintenance.
- AI (Artificial Intelligence): Analyse data for predictive analytics. → Optimize asset management, forecast asset life cycles, and identify risks.

→ Feedback on Decision-Making
Outcome:

- Optimized Asset Management
- Reduced Resource Consumption
- Enhanced Climate Resilience

End: Continuous Improvement Cycle

- Use real-time data, AI, and LCA to iterate and improve the system over time.

- By incorporating sensitivity analysis, a more comprehensive and reliable assessment of the system's performance ensures that the data corresponds directly to the outlined parameters and addresses uncertainties effectively.

5.2. Framework Implementation through Local Government and Stakeholder

During the proposal stage of the project, the framework needs to be integrated. Proper due diligence, stakeholder engagement, and workshops are to be done to ensure the benchmarking and implementation of the framework. Data collection, implementation, and brainstorming are to be done to make proper decisions using the proposed framework. Moreover, during the finalization of the tender and Contractor's scope, all the scope is to be properly captured so that the framework can be effectively implemented for the water supply system of the smart city.

5.3. Ethical Considerations Regarding Data Use or Any Potential Conflicts of Interest

Ethical considerations in the framework for minimizing life cycle impact towards sustainable asset management of water supply systems revolve around the responsible use of data and addressing potential conflicts of interest. The growing reliance on data in water systems management necessitates adherence to data ethics principles, including transparency, privacy, and fairness, to ensure that data collection, sharing, and usage do not infringe on individual rights or disproportionately impact vulnerable communities.

To mitigate these risks, it is essential to establish clear ethical guidelines, involve diverse stakeholders in decision-making, and ensure accountability in both data practices and broader management strategies.

6. Conclusion and Future Scope of Work

It is an immense challenge for the water supply authority to develop a comprehensive database for asset management to ascertain a finer assessment of the level of maintenance required and timely replacement/update of important assets. Tools available for asset management are either labour intensive or costly and difficult to carry out for a long time frame. The available techniques require a paradigm shift, particularly in developing countries, to make it more pragmatic towards effective implementation. The use of state-of-the-art asset management techniques in conjunction with proper inventory management and having a proper decision-making system needs to be encouraged for smart cities. Utility-wise management techniques, like pipe leak management and the implementation of early pinpointing techniques, are necessary to prevent inadequate/ or higher pressure in the distribution network, and they are an active area of research that is an integral part of asset management. A cost-effective solution integrated with the LCA approach with GIS and suitable automation in complex real-world networks is still a major research challenge for asset management.

A proper decision-making framework is necessary for proper asset management in smart cities to reach the goal of maintaining the required protocol for all important assets in a systematic way.

In this paper, a framework has been proposed through a lifecycle-based approach that will help the stakeholders prioritize the maintenance, replacement, and modification based on data analysis, performance benchmarking analysis, and early awareness of asset management for smart cities. The framework and its implementation will help the decision makers to have enough logical evidence, which will provide them with enough impetus for managing the assets and avoid its part or overall damage else/ otherwise, it will defeat the essence of sustainable water management in smart cities. This framework provides a much-needed bridge between technical solutions and governance frameworks, ensuring that the proposed strategies are both practical and adaptable to diverse urban contexts. This innovative novel framework sets a new benchmark for sustainable water management in smart cities, contributing to the global transition toward more sustainable and resilient urban environments. The following is a very important and summarized aspect towards sustainable water management under smart cities.

- Root Cause Analysis: The framework will conduct data inventory analysis to identify the root causes of issues and propose mitigation measures for effectively managing water supply assets.
- Automation Integration: While automation in India's water sector is limited, structured and cost-effective integration with a decision-making framework can enhance the management of electro-mechanical assets.
- Real-Time Monitoring: Utilizing real-time GIS applications and SCADA systems will provide key indicators, aiding decision-makers in managing civil assets and long-term investment planning.
- Current Limitations: Despite advancements in asset management and hydraulic analysis via GIS, real-world application remains limited, especially in developing countries.
- Performance Benchmarking: There is a need for extensive research on performance benchmarking through DMA integration with LCA frameworks to establish effective asset management control measures.
- Holistic Approach: Emphasizing a holistic benchmarking approach tailored to different geographical contexts will improve asset management strategies.
- Good Governance: Effective asset management requires skilled manpower, stakeholder engagement, and a focus on state-of-the-art operation and maintenance through an LCA-based approach.

- Public-Private Partnerships (PPP): Implementing PPPs with thorough research and field feedback can be vital for sustainable water distribution asset management.
- Pricing Mechanisms: Establishing a pricing mechanism based on metered consumption is essential for maintaining the network and ensuring overall asset management.
- Research Gaps: Investigating the impacts of asset management on intermittent versus continuous systems through LCA is critical for transitioning systems to continuous operation.

The distinctiveness of this framework lies in its ability to combine life cycle impact minimization, cutting-edge technologies, and sustainable asset management into a cohesive approach. Unlike existing models, it offers a comprehensive, adaptable, and future-ready solution to the challenges of urban water supply in smart cities. By addressing both environmental and technological dimensions, the framework ensures that water systems are not only efficient and resilient but also aligned with the broader goals of sustainability and resource conservation. This multi-dimensional approach sets it apart as a pioneering, sustainable urban water management model.

Future research in water supply systems should focus on integrating emerging technologies like IoT and AI to enhance Life Cycle Assessment (LCA) and asset management. IoT offers the potential for real-time infrastructure monitoring, enabling more accurate data collection that can improve LCA analysis and inform predictive maintenance strategies. This will allow utilities to proactively address issues such as leaks or inefficiencies, reducing downtime and costs. Additionally, AI can play a key role in optimizing asset management by analyzing large datasets, forecasting asset life cycles, and identifying potential failures before they occur. Leveraging these technologies could enable future research to lead to more intelligent and efficient solutions for sustainable water systems, particularly within the framework of smart cities, where data-driven insights can drive more effective decision-making and resource management. Furthermore, the challenges posed by climate change and rapid urbanization are prompting water utilities worldwide to pursue water security. Digital technologies have proven effective in improving the operations of these utilities and their water supply systems.

6.1. Summary of Future Research

- Sensitivity Analysis and Uncertainty Quantification
- Integration of Smart Technologies and Digitalization
- Socioeconomic and Cultural Considerations
- Circular Economy and Resource Recovery
- Comprehensive Validation and Benchmarking

6.2. Practical Implications

- Informed Decision-Making for Asset Management
- Optimization of Water Supply Systems
- Stakeholder Engagement and Capacity Building
- Scalability and Transferability

A proper framework and cost-benefit analysis are required for developing decision-making tools to conclude the economic level of asset management strategy through LCA based approach. Extensive research needs to be carried out with close coordination between the water sector industry and research organization considering all the mentioned aspects. Research needs to be focused on the direction of real-life problems to compensate for the gap between theory and practical scenarios.

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