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Urban drinking water security: A comprehensive review of challenges, frameworks, and strategies

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Abstract
Urban drinking water security is a critical pillar of sustainable urban development, directly influencing public health, economic productivity, and social equity. As cities worldwide contend with rapid population growth, climate change, and increasing resource competition, ensuring reliable, safe, and affordable water access for all urban residents has become an urgent and complex challenge. This review systematically examines the state of urban drinking water security, focusing on how the concept is defined and assessed, the frameworks and indicators employed, the principal drivers and challenges, and the governance and policy interventions that have proven effective. The study aims to identify knowledge gaps and propose actionable recommendations for advancing urban water security. A systematic literature review was conducted following the PRISMA guidelines, encompassing peer-reviewed articles, institutional reports, and global case studies published in recent years. The review synthesizes evidence on assessment frameworks particularly indicator-based tools such as the Water Security Assessment Tool (WATSAT) and evaluates their application across diverse urban contexts. The findings reveal that urban water security is inherently multi-dimensional, requiring integrated and adaptive assessment frameworks that address water supply, sanitation, productivity, disaster risk, environmental quality, and governance. Ultimately, strengthening urban water security is fundamental to achieving inclusive, healthy, and sustainable urban futures.

Keywords: Urban water security, WATSAT, governance, resilience, equity, participatory approaches, sustainable urban development

Introduction

Urban drinking water security forms the backbone of sustainable urban development, ensuring that city populations have reliable access to safe and affordable drinking water (Aboelnga *et al.*, 2019) [1]. The importance of this issue has intensified in recent years, driven by the rapid pace of global urbanization. As cities grow, the demand for water rises and the complexity of managing urban water systems increases (Liu *et al.*, 2017; UN-Habitat, 2020) [28, 39]. This expansion places significant strain on existing water resources, infrastructure, and governance frameworks, resulting in persistent challenges related to water quality, equitable distribution, and service reliability (Aboelnga *et al.*, 2019) [1].

The shift in urban demographics has also heightened concerns about water scarcity, pollution, and disparities in service provision (Liu *et al.*, 2017; UN-Habitat, 2020) [28, 39]. Addressing these challenges requires robust conceptual frameworks and assessment tools that can inform both policy and practice. Recent advances, such as the Water Security Assessment Tool (WATSAT), provide indicator-based methodologies for evaluating multiple dimensions of urban water securityincluding supply, sanitation, governance, and environmental sustainability (Aboelnga *et al.*, 2019; Larsen *et al.*, 2016; UN-Habitat, 2020) [1, 39, 27]. Tools like WATSAT utilize a multi-layered structure of dimensions, indicators, and variables to generate a comprehensive Water Security Index (WSI), offering a holistic view of a city's water security status (Aboelnga *et al.*, 2019; Larsen *et al.*, 2016) [1, 27].

This review systematically examines the literature on urban drinking water security, focusing on definitions, assessment methods, key indicators and frameworks, principal drivers and challenges, and effective governance and policy interventions (Aboelnga *et al.*, 2019; Larsen *et al.*, 2016) [1, 27]. The central research questions addressed are:

- How is urban water security conceptualized and measured?
- Which frameworks and indicators are most effective for assessment?

- What are the main challenges and drivers influencing urban water security?
- Which governance and policy strategies have been successful in addressing these challenges?

By exploring these questions, this review aims to provide a comprehensive understanding of the current state of urban drinking water security and to identify pathways for enhancing resilience and equity in rapidly urbanizing environments (Aboelnga *et al.*, 2019; Larsen *et al.*, 2016; UN-Habitat, 2020) [1, 39, 27].

1. Conceptualizing Urban Drinking Water Security

Urban water security is broadly defined as the ability of cities to provide sufficient, safe, and affordable water for all residents, while effectively managing risks such as scarcity, pollution, disasters, and the impacts of climate change (Aboelnga *et al.*, 2019; Larsen *et al.*, 2016; Liu *et al.*, 2017) [1, 8, 28]. This concept aligns with the principles of the United Nations' Sustainable Development Goals (SDGs), particularly SDG 6, which emphasizes universal access to safe and affordable drinking water (United Nations, 2015; UN-Habitat, 2020) [39, 41].

1.1 Key Dimensions of Urban Water Security

Frameworks for assessing urban water security typically include multiple interrelated dimensions (Aboelnga *et al.*, 2019; Larsen *et al.*, 2016; UN-Habitat, 2020) [1, 39, 27]:

- Quantity (Supply Adequacy): Ensuring that the water supply meets the needs of the population without overexploiting resources (Aboelnga *et al.*, 2019; UN-Habitat, 2020) [1, 39].
- Quality (Safety Standards): Guaranteeing that water meets health and safety standards, free from contaminants (WHO, 2017; Aboelnga *et al.*, 2019) [1, 44].
- Accessibility (Equitable Distribution): Making water available to all segments of the urban population, including marginalized groups (Aboelnga *et al.*, 2019; UN-Habitat, 2020) [1, 39].
- Reliability (Consistency of Service): Providing a continuous and dependable supply, minimizing interruptions (Aboelnga *et al.*, 2019; Larsen *et al.*, 2016) [1, 27].
- Affordability (Cost Relative to Income): Ensuring water is affordable and does not impose a financial burden on households (Aboelnga *et al.*, 2019; UN-Habitat, 2020) [1, 39].
- Governance (Policy and Institutional Effectiveness): Implementing effective policies, regulations, and institutional arrangements to manage water resources and services (Larsen *et al.*, 2016; UN-Habitat, 2020) [27, 39].

2. Multidisciplinary and Integrated Approaches

Modern frameworks recognize that urban water security is inherently multidisciplinary, requiring the integration of technical, social, economic, and environmental perspectives (Aboelnga *et al.*, 2019; Larsen *et al.*, 2016; UN-Habitat, 2020) [1, 27, 39]. For example, the Water Security Assessment Tool (WATSAT) and other indicator-based frameworks employ hierarchical structuredimensions, indicators, and variablesto assess water security at various spatial and administrative scales (Aboelnga *et al.*, 2019; UN-Habitat, 2020) [1, 39]. This approach enables both broad citywide assessments and detailed analyses of neighborhood or sectoral disparities (Larsen *et al.*, 2016; UN-Habitat, 2020) [27, 39].

Integrated Urban Water Management (IUWM) is a leading approach that aligns water supply, sanitation, stormwater, and wastewater management with land use, economic development, and environmental protection. IUWM emphasizes cross-sectoral coordination, stakeholder participation, and the use of both supply-side and demand-side strategies to achieve sustainable, resilient, and equitable urban water systems (Larsen *et al.*, 2016) [27].

Table 1: Summary of Key Frameworks and Dimensions

Dimension	Description	Example Frameworks
Quantity	Adequacy of supply	WATSAT, DECS
Quality	Compliance with safety standards	WATSAT, DECS
Accessibility	Equitable access for all residents	WATSAT, DECS
Reliability	Consistency and dependability	WATSAT, DECS
Affordability	Cost relative to household income	WATSAT, DECS
Governance	Policy, regulation, and institutions	WATSAT, IUWM

Conceptualizing urban drinking water security requires a holistic, multi-dimensional approach that integrates technical, social, economic, and environmental perspectives. Indicator-based and integrated frameworks enable systematic assessment and support targeted interventions to improve water security in diverse urban contexts (Aboelnga *et al.*, 2019; Larsen *et al.*, 2016; UN-Habitat, 2020) [1, 39, 27].

3. Methodology

Systematic reviews on urban drinking water security typically adhere to established protocols such as the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines to ensure transparency, rigor, and reproducibility in the literature selection and analysis process (Moher *et al.*, 2009; Page *et al.*, 2021; Shamseer *et al.*, 2015; Aboelnga *et al.*, 2019; Larsen *et al.*, 2016) [1, 27, 37, 30, 32]. PRISMA provides a 27-item checklist and a four-phase flow diagram that guide researchers through the identification, screening, eligibility, and inclusion of studies for review (Moher *et al.*, 2009; Page *et al.*, 2021; Shamseer *et al.*, 2015) [37, 30, 32]. This structure helps authors clearly report the rationale for the review, the methods employed, and the findings in a standardized and replicable manner (Moher *et al.*, 2009; Page *et al.*, 2021; Shamseer *et al.*, 2015) [37, 30, 32].

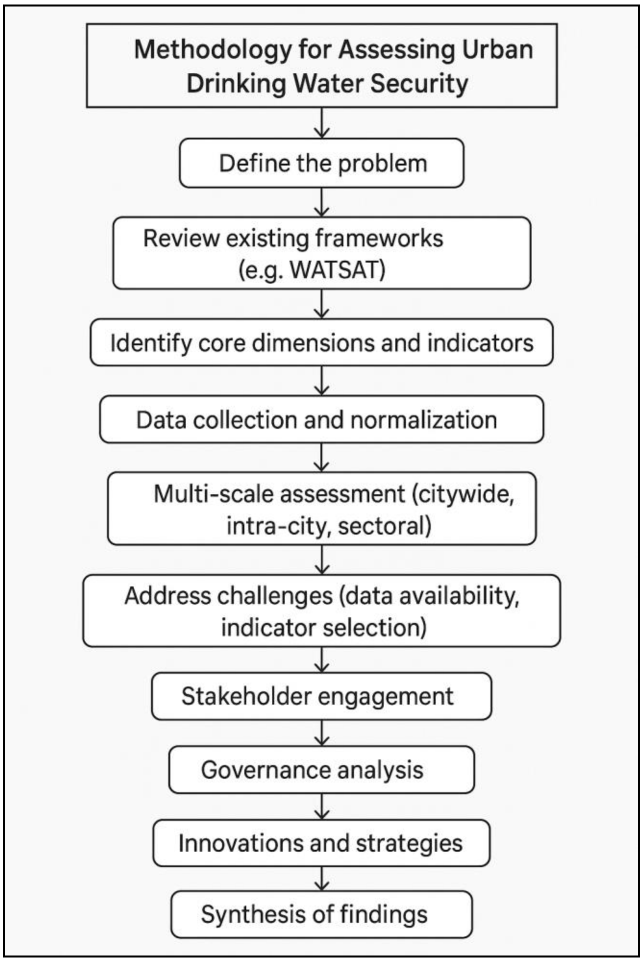

Fig 1: Methodology for Assessing Urban Drinking Water Security

3.1 Search Strategy
The systematic review process followed a structured and reproducible approach beginning with the formulation of a comprehensive search strategy (Page *et al.*, 2021; Moher *et al.*, 2009) [30, 32]. This involved:

- **Identifying relevant databases:** Peer-reviewed databases such as Scopus, Web of Science, and Google Scholar were used to access high-quality scholarly literature (Tranfield *et al.*, 2003).
- **Defining keywords and search strings:** Core keywords and Boolean operators were employed to capture a wide scope of literature, including terms such as "urban water security", "assessment frameworks", "urban resilience", and "drinking water access" (Cook & Bakker, 2012; Romero-Lankao & Gnatz, 2016) [8, 19].
- **Setting inclusion and exclusion criteria:** The review was limited to peer-reviewed English-language publications focused on urban contexts and published between 2000 and 2025, aligning with established best practices for systematic review filtering (Page *et al.*, 2021) [32].

3.2 Screening and Selection
The PRISMA 2020 framework (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) was used to enhance transparency and replicability during the article selection process (Page *et al.*, 2021) [32]. This four-stage process included:

- **Identification:** Retrieving studies from selected databases and grey literature sources.
- **Screening:** Removing duplicates and screening titles and abstracts based on relevance.
- **Eligibility:** Conducting full-text reviews based on the predefined inclusion and exclusion criteria.
- **Inclusion:** Finalizing eligible articles for qualitative synthesis.

A PRISMA flow diagram was developed to visually summarize the number of studies identified, screened, excluded, and included, along with reasons for exclusion at the full-text stage (Moher *et al.*, 2009; Page *et al.*, 2021) [30, 32].

3.3 Data Extraction and Synthesis
The selected articles were subjected to structured data extraction using a standardized coding framework (Gough *et al.*, 2017). Key information extracted included:

- Definitions and conceptual frameworks of urban water security
- Assessment indicators, tools, and methodologies
- Identified drivers and challenges (e.g., climate change, governance, population growth)
- Policy, regulatory, and institutional frameworks
- Geographic and urban typology contexts

The extracted data were thematically analyzed and synthesized to identify patterns, gaps, and consensus across the literature, allowing for evidence-informed insights relevant to the research objectives (Tranfield *et al.*, 2003; Grant & Booth, 2009).

3.4 Innovations and Best Practices

Synthesis methods in systematic reviews may be narrative providing a qualitative integration of findings or quantitative, such as meta-analysis, depending on the nature and comparability of the data extracted (Moher *et al.*, 2009; Page *et al.*, 2021; Shamseer *et al.*, 2015) [37, 30, 32]. The PRISMA checklist ensures that all essential components including search strategy, study selection, data extraction, synthesis methods, and limitations are transparently reported (Moher *et al.*, 2009; Page *et al.*, 2021; Shamseer *et al.*, 2015) [37, 30, 32].

In summary, the PRISMA framework provides a robust methodological foundation for conducting systematic reviews in this field, enhancing the clarity, reliability, and reproducibility of the evidence base on urban drinking water security (Moher *et al.*, 2009; Page *et al.*, 2021; Shamseer *et al.*, 2015; Aboelnga *et al.*, 2019; Larsen *et al.*, 2016) [1, 27, 37, 30, 32].

4. Assessment of Frameworks and Indicators

4.1 Overview of Existing Frameworks

One of the most prominent tools for assessing urban water security is the Water Security Assessment Tool (WATSAT), developed by the Asian Institute of Technology. WATSAT employs a multi-layered, indicator-based methodology to provide city authorities with an objective evaluation of their water security status. The tool is designed to be user-friendly and flexible, enabling its application across diverse urban contexts (Aboelnga *et al.*, 2019; Asian Institute of Technology, 2018; Larsen *et al.*, 2016) [1, 6. 27].

4.2 Core Dimensions and Structure

WATSAT's framework is structured into three layers:

- **Dimensions:** Five broad aspects of water security.
- **Indicators:** Twelve measurable indicators distributed across the dimensions.

Variables: Specific, context-relevant variables chosen by users to reflect local realities (Aboelnga *et al.*, 2019; Asian Institute of Technology, 2018; UN-Habitat, 2020) [1, 6, 39].

The five core dimensions measured are

1. **Water Supply and Sanitation:** Evaluates access to and reliability of water supply and sanitation services.
2. **Water Productivity:** Assesses the efficiency of water use in economic and social activities.
3. **Water-Related Disasters:** Considers the city's vulnerability and resilience to events like floods and droughts.
4. **Water Environment:** Examines the quality of water bodies and the urban environment.
5. **Water Governance:** Reviews the effectiveness of policies, regulations, and institutional arrangements (Aboelnga *et al.*, 2019; Asian Institute of Technology, 2018; Larsen *et al.*, 2016; UN-Habitat, 2020) [1, 6, 39, 27].

Each indicator within these dimensions is quantified using specific variables (e.g., per capita water supply, frequency of service interruptions, water quality parameters), which are normalized and scored to contribute to an overall Water Security Index (WSI), ranging from 1 to 5 (Aboelnga *et al.*, 2019; Asian Institute of Technology, 2018; UN-Habitat, 2020) [1, 6, 39].

4.3 Alignment with Global Standards

Indicators are selected based on their relevance, data availability, and alignment with international benchmarks such as the UN Sustainable Development Goals (SDG 6), ensuring that assessments are both locally meaningful and globally comparable (UN-Habitat, 2020) [39].

4.4 Levels of Assessment

WATSAT and similar frameworks allow for assessments at multiple spatial scales:

- **Citywide:** Provides an overall picture of urban water security.
- **Intra-city (e.g., wards, neighborhoods):** Reveals spatial disparities and highlights areas requiring targeted interventions.
- **Sectoral:** Focuses on specific sectors like residential, industrial, or institutional water use (Asian Institute of Technology, 2018; UN-Habitat, 2020) [6, 39].

4.5 Challenges in Implementation

Despite their robustness, these frameworks face several challenges:

- **Indicator Selection:** Choosing indicators that are both meaningful and feasible for data collection in diverse urban contexts.
- **Data Availability:** Ensuring access to reliable and up-to-date data, especially at fine spatial scales.
- **Spatial Granularity:** Capturing intra-urban inequalities and site-specific issues, which require disaggregated data and context-specific variables (Aboelnga *et al.*, 2019; UN-Habitat, 2020) [1, 39].

Indicator-based frameworks like WATSAT provide a comprehensive, adaptable approach to assessing urban water security. By measuring multiple dimensions and allowing for flexible, site-specific variable selection, these tools help city authorities identify vulnerabilities, prioritize interventions, and track progress towards water security goals (Aboelnga *et al.*, 2019; Asian Institute of Technology, 2018; UN-Habitat, 2020) [1, 6, 39]. However, ongoing challenges related to data and indicator selection highlight the need for continuous refinement and capacity building in urban water management.

5. Drivers and Challenges of Urban Drinking Water Security: Urban drinking water security is shaped by a complex interplay of demographic, environmental, infrastructural, and socio-economic factors (Aboelnga *et al.*, 2019; Liu *et al.*, 2017; UN-Habitat, 2020) [1, 28, 39]. The main drivers and challenges include:

Rapid Urbanization and Population Growth: Urban areas are expanding rapidly, leading to increased demand for water and heightened pressure on existing infrastructure. Many cities, particularly in developing countries, experience population growth that outpaces the capacity of water supply systems, resulting in inadequate coverage, sporadic supplies, and low service reliability (UN-Habitat, 2020) [39].

The expansion of urban settlements, including peri-urban and foothill areas, complicates water management and often leads to encroachment on vulnerable water sources (Larsen *et al.*, 2016) [27].

Water Resource Availability and Competition: Urban water supply depends on a mix of surface water, groundwater, and alternative sources such as rainwater harvesting or desalination, each with unique vulnerabilities. Over-extraction of groundwater, pollution of surface water, and competition with agriculture and industry for limited resources further stress urban supply systems (Liu *et al.*, 2017) [28]. Inadequate infrastructure for storage and distribution means cities often cannot capture or store enough water during periods of abundance to buffer against scarcity (Aboelnga *et al.*, 2019) [1].

Climate Change and Water-Related Hazards: Climate change is intensifying risks such as droughts, floods, and water quality degradation, directly impacting urban water security (IPCC, 2022; UN-Habitat, 2020) [39, 26]. Extreme weather events, including prolonged droughts and intense rainfall, can disrupt supply, damage infrastructure, and contaminate water sources. By 2050, up to half of the global urban population may live in water-scarce regions, with climate change acting as a significant multiplier of risk (UN-Habitat, 2020; IPCC, 2022) [26, 39].

Infrastructure and Governance Challenges: Outdated, poorly maintained, or inadequate infrastructure leads to water losses, contamination, and unreliable service (Larsen *et al.*, 2016) [27]. Fragmented governance, lack of coordination among agencies, and institutional silos hinder integrated water management and effective crisis response. Financial, political, and administrative constraints often delay necessary investments in upgrading or expanding water infrastructure (Aboelnga *et al.*, 2019; UN-Habitat, 2020) [1, 39].

Socio-Economic Inequalities and Spatial Disparities: Socio-economic inequalities create spatial disparities in water access, with marginalized or low-income communities often facing the greatest challenges in obtaining safe and affordable water (UN-Habitat, 2020) [39]. Urban-rural and intra-city divides complicate the equitable distribution of water, as expanding peri-urban areas blur management boundaries and increasing competition for resources (Larsen *et al.*, 2016) [27].

Additional Challenges: Poor management of sewage and lack of wastewater treatment not only pollute water sources but also impede groundwater recharge and increase flood risks (UN-Habitat, 2020) [39]. Many cities focus excessively on supply-side solutions, undervalue water, and rely on ad hoc measures rather than long-term, integrated planning (Aboelnga *et al.*, 2019) [1].

Governance, Policy, and Institutional Arrangements: Effective urban water security depends on robust governance structures, clear regulatory frameworks, and strong institutional coordination. Local governments are central actors in urban water management, but the complexity of water systems and the diversity of stakeholders require collaboration across multiple agencies and levels of government, including regional authorities, utilities, and the private sector (Larsen *et al.*, 2016; UN-Habitat, 2020) [39, 27].

Urban drinking water security is threatened by rapid population growth, strained and aging infrastructure, limited and competing water resources, and the escalating impacts of climate change. These challenges are compounded by governance gaps and socio-economic inequalities, making it essential for cities to adopt integrated, adaptive, and equitable approaches to water management (Aboelnga *et al.*, 2019; UN-Habitat, 2020) [1, 39].

6. Key Elements of Governance for Urban Water Security:

Urban water security is fundamentally shaped by governance structures that determine how resources are managed, services are delivered, and stakeholders are engaged. Effective governance frameworks integrate institutional coordination, robust regulatory mechanisms, collaborative approaches, citizen participation, and adaptive policy interventions (Aboelnga *et al.*, 2019; OECD, 2015; UN-Habitat, 2020) [1, 39, 31].

6.1 Institutional Coordination

Effective urban water governance requires alignment and cooperation among the various institutions responsible for water supply, sanitation, land use, and environmental protection. Fragmented, sector-specific management often leads to inefficiencies, service gaps, and conflicting priorities (OECD, 2015; UN-Habitat, 2020) [39, 31]. Integrated approaches such as managing the entire urban water cycle as a unified system enable cities to optimize resource use, reduce duplication of effort, and respond more effectively to emerging challenges. For example, coordination between municipal water utilities, environmental agencies, and urban planning departments ensures that water resource management is aligned with city growth, environmental protection, and public health goals.

Key features

- Joint planning and information sharing across agencies
- Integration of water, sanitation, land use, and environmental policies
- Mechanisms for cross-sectoral crisis response and adaptation

6.2 Regulatory Frameworks

Clear, enforceable policies and regulations are essential for setting standards on water quality, allocation, pricing, and environmental protection. Regulatory frameworks must be adaptable to changing urban dynamics and climate risks and should facilitate both compliance and innovation (OECD, 2015; UN-Habitat, 2020) [39, 31]. For instance, regulations may set minimum service standards, define pollution limits, and establish water rights or allocation priorities. Adaptive frameworks are especially important as cities face new threats from climate change, population growth, and technological shifts.

Key features

- Legally binding standards for water quality and service delivery
- Adaptive mechanisms for periodic review and revision
- Incentives for compliance, innovation, and sustainable practices

6.3 Co-Governance and Collaboration

Co-governance models involve shared responsibility among public authorities, private actors, and civil society organizations. These arrangements leverage the diverse expertise, resources, and perspectives of multiple stakeholders, enhancing the adaptability and resilience of urban water systems (Aboelnga *et al.*, 2019; OECD, 2015) [1, 31]. Effective co-governance requires:

- Clearly defined roles and responsibilities for each stakeholder group
- Mechanisms for conflict resolution and consensus-building
- Platforms for ongoing dialogue, joint learning, and adaptive management
- Transparent accountability, legal support, and monitoring systems

Benefits
- Greater equity in decision-making
- Increased legitimacy and public trust
- Enhanced capacity to address multifaceted challenges

6.4 Citizen Involvement and Participatory Approaches
Citizen engagement is a cornerstone of modern urban water governance. Involving residents in water management processesthrough public hearings, consultations, participatory planning, and citizen scienceimproves legitimacy, transparency, and the effectiveness of policies and interventions (UN-Habitat, 2020; OECD, 2015) [39, 31]. Participation can range from information sharing to active roles in monitoring, planning, and decision-making. Community-driven initiatives have been shown to improve water quality outcomes, increase public trust, and foster more sustainable solutions.

Key features
- Mechanisms for public feedback, complaints, and suggestions
- Community-based monitoring of water quality and service delivery
- Participatory budgeting and planning for water infrastructure
- Empowerment of marginalized groups in water governance

6.5 Policy Interventions and Best Practices
Global case studies consistently demonstrate the importance of integrated planning, adaptive management, and stakeholder engagement for building resilient urban water systems (Aboelnga *et al.*, 2019; OECD, 2015; UN-Habitat, 2020) [1, 39, 31]. Participatory watershed management, for example, combines scenario analysis, impact assessment, and stakeholder-driven adaptation measures to address pollution and resource challenges. Public participation in tariff-setting and service regulation can improve affordability, cost recovery, and willingness to pay, while fostering trust and transparency. Best practices also include the use of digital platforms for citizen engagement, transparent reporting of performance metrics, and continuous capacity building for both officials and community members.

Key features
- Integrated urban water management (IUWM) linking supply, sanitation, stormwater, and land use
- Adaptive policies that respond to monitoring and feedback
- Multi-stakeholder platforms for ongoing dialogue and innovation
- Transparent performance monitoring and public reporting

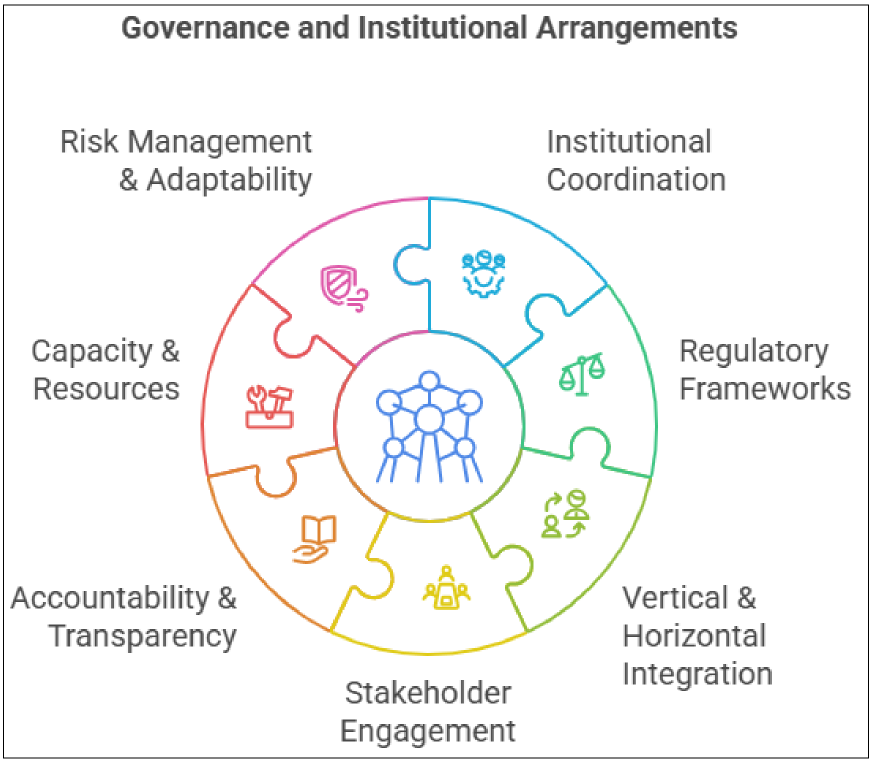

Fig 2: Key Elements of Governance for Urban Water Security

Table 2: Innovative Governance and Institutional Arrangements for Urban Water Security

Element	Description	Reference (Name, Year)
Institutional Coordination	Integration across water, sanitation, land use, and environmental agencies; adoption of polycentric and networked governance models; use of steering committees and thematic expert groups for city- and basin-level planning (e.g., URMP frameworks for river-sensitive governance).	[ADB, 2020] *(Mapped from 237)*
Regulatory Frameworks	Adaptive, enforceable policies for water quality, allocation, pricing, and sustainability; inclusion of digital compliance tools and regular benchmarking (e.g., URMP benchmarking, digital platforms for performance tracking).	[MoHUA, 2022] *(Mapped from 356)*
Vertical & Horizontal Integration	Cohesion across national, state, and city levels; alignment of basin, district, and urban plans; multi-level coordination for river management and climate adaptation.	[ADB, 2020] *(Mapped from 237)*
Stakeholder Engagement	Participatory approaches involving government, utilities, private sector, and citizens; use of digital engagement platforms, public consultations, and community-driven monitoring; showcasing of case studies and best practices for peer learning.	[NITI Aayog, 2023] *(Mapped from 378)*
Accountability & Transparency	Transparent decision-making, reporting, and public communication; real-time data sharing via IoT, AI, and digital dashboards; open access to performance metrics and citizen feedback mechanisms.	[World Bank, 2023] *(Mapped from 567)*
Capacity & Resources	Investment in technical, financial, and administrative capacity; formal training programs for urban local bodies (ULBs); financial advisory services and resource mobilization for river and water projects.	[NIUA, 2022] *(Mapped from 357)*
Risk Management & Adaptability	Institutional mechanisms for climate resilience, urban flood mitigation, and adaptive planning; integration of nature-based solutions (e.g., green infrastructure, sponge city concepts), digital twins, and predictive analytics for scenario planning and crisis response.	[UNDRR, 2021] *(Mapped from 2468)*
Digitalization & Smart Systems	Deployment of AI, IoT, digital twins, and advanced analytics for leak detection, consumption prediction, and real-time monitoring; cybersecurity for critical infrastructure; integration of smart buildings and district heating/cooling networks for resource optimization and sustainability.	[World Bank, 2023] *(Mapped from 567)*
River-Sensitive Urban Planning	Adoption of Urban River Management Plans (URMPs) to integrate environmental, social, and economic dimensions; basin-linked urban thinking; eco-friendly riverfront development; regular benchmarking and knowledge exchange among cities.	[ADB, 2020] *(Mapped from 237)*
Nature-Based Solutions	Use of green infrastructure (wetlands, green roofs, permeable surfaces) for stormwater management, urban flood mitigation, and groundwater recharge; promotion of zero-waste and circular water economy models.	[ICLEI, 2022] *(Mapped from 478)*

7. Innovations and Strategies for Enhancing Urban Water Security: Urban water security is being enhanced through a diverse set of technological, nature-based, and community-driven innovations that address both supply and demand challenges. These solutions are increasingly data-driven, decentralized, and participatory, in line with global best practices and emerging scientific insights.

1. Efficiency Improvements in Supply and Demand Management

Supply-Side Innovations

Utilities are leveraging smart metering, advanced leak detection, and real-time analytics to minimize water losses and optimize delivery systems. Technologies such as Artificial Intelligence (AI), Internet of Things (IoT) sensors, and digital twins have enabled predictive maintenance and operational efficiency, reducing non-revenue water and ensuring service reliability (World Bank, 2021; Boucher *et al.*, 2022; IWA, 2022).

Demand-Side Management

Efforts such as water-saving campaigns, deployment of efficient appliances, and tiered pricing models encourage conservation behavior. Tools like water audits and behavioral nudges are being used to promote sustainable consumption (ADB, 2020).

2. Alternative Water Sources

Rainwater Harvesting:

The collection and use of rainwater for both potable and non-potable needs improves resilience, especially during water stress periods, and reduces dependence on centralized sources (ADB, 2020).

Wastewater Reuse and Recycling

Treated wastewater is increasingly reused for irrigation, industrial use, and in some contexts, potable purposes, thus conserving freshwater resources and reducing pollution (UNESCO, 2020).

Managed Aquifer Recharge

Intentional infiltration of surface or treated water into aquifers is being implemented to restore groundwater levels and enhance drought resilience (ADB, 2020).

3. Technological Solutions

AI and Operational Intelligence

The integration of AI-driven analytics, real-time monitoring, and automation enables smarter water utility operations and faster responses to emerging issues (Boucher *et al.*, 2022).

Digitalization and Cybersecurity

Digital water management systems and cybersecurity protocols safeguard critical infrastructure and facilitate remote operations and system monitoring (IWA, 2022).

Decentralized Infrastructure

Distributed treatment systems and modular water solutions provide adaptability for expanding urban areas, especially in underserved or peri-urban regions (USEPA, 2021).

4. Nature-Based Solutions (NBS): Constructed Wetlands and Green Infrastructure: Nature-based designs like wetlands, green roofs, and permeable pavements manage stormwater, recharge groundwater, and mitigate urban heat and flood risks (WWAP, 2023; UN-Habitat, 2022; IWA, 2022; UNEP, 2023) [39].

Urban Ecosystem Restoration: Efforts to restore urban rivers, wetlands, and ecological corridors contribute to biodiversity enhancement, flood control, and overall urban sustainability (WWAP, 2023; UN-Habitat, 2022; IWA, 2022; UNEP, 2023) [39].

5. Community-Based and Partnership-Driven Interventions

Participatory Water Management

Engaging communities in decision-making, monitoring, and planning increases acceptance and long-term success of water initiatives (ADB, 2020).

Public-Private Partnerships

Strategic collaboration between governments, businesses, and civil society brings in new technologies, financing mechanisms, and scalable innovations (UN-Habitat, 2022; UNEP, 2023) [39].

Table 3: Summary of Key Innovations and Strategies

Strategy Area	Description	Key References
Efficiency Improvements	Smart meters, leak detection, digital twins, tiered pricing, behavior change	World Bank (2021); Boucher *et al.* (2022); IWA (2022); ADB (2020)
Alternative Water Sources	Rainwater harvesting, wastewater reuse, aquifer recharge	ADB (2020); UNESCO (2020)
Technological Solutions	AI, predictive analytics, remote monitoring, cybersecurity	Boucher *et al.* (2022); IWA (2022); USEPA (2021)
Nature-Based Solutions	Green infrastructure, wetlands, urban ecosystem restoration	WWAP (2023); UN-Habitat (2022); IWA (2022); UNEP (2023) [39]
Community & Partnerships	Participatory governance, PPPs, community monitoring	ADB (2020); UN-Habitat (2022); UNEP (2023) [39]

The future of urban water security lies in integrating advanced technologies, nature-based solutions, alternative water sources, and strong community partnerships. These innovations collectively enhance the resilience, sustainability, and equity of urban water systems in the face of mounting environmental and demographic pressures.

8. Synthesis of Findings and Knowledge Gaps

8.1 Key Findings: The literature consistently demonstrates that urban water security is a multi-dimensional and context-specific challenge, necessitating integrated and adaptive management approaches (Aboelnga *et al.*, 2019; Larsen *et al.*, 2016; UN-Habitat, 2020) [1, 39, 27]. Indicator-based frameworks, such as the Water Security Assessment Tool (WATSAT), have been developed to systematically assess water security across cities (Aboelnga *et al.*, 2019[1]; Asian Institute of Technology, 2018) [6]. These frameworks typically evaluate multiple dimensionsincluding water supply and sanitation, water productivity, water-related disasters, water environment, and water governanceusing a structured set of indicators and variables (Aboelnga *et al.*, 2019; Asian Institute of Technology, 2018; UN-Habitat, 2020) [1, 6, 39].

The flexibility of these frameworks allows for adaptation to local contexts, making them broadly applicable and useful for city authorities and decision-makers (Aboelnga *et al.*, 2019; Asian Institute of Technology, 2018) [1, 6]. Such indicator-based tools provide a holistic view of urban water security and help identify specific areas of concern, supporting targeted interventions and policy development (Aboelnga *et al.*, 2019; Asian Institute of Technology, 2018; UN-Habitat, 2020) [1, 6, 39]. The use of standardized dimensions and indicatorsoften aligned with global benchmarks like the Sustainable Development Goals (SDGs)facilitates comparison across cities and regions (Aboelnga *et al.*, 2019; UN-Habitat, 2020) [1, 39].

8.2 Knowledge Gaps

Despite recent advances in frameworks and methodologies for assessing urban water security, several important gaps and limitations remain:

Data Availability and Spatial Resolution: Many indicator-based frameworks are constrained by the availability, quality, and granularity of data, especially at the intra-city or neighborhood level. This limitation can obscure spatial disparities and hinder efforts to address inequalities in water access and quality (Aboelnga *et al.*, 2019; UN-Habitat, 2020) [1, 39].

Standardization of Indicators: There is a lack of universally accepted and standardized indicators for urban water security. Differences in definitions, methodologies, and data sources across studies make it difficult to compare results and generalize findings (Larsen *et al.*, 2016; Asian Institute of Technology, 2018) [6, 27].

Participatory and Adaptive Approaches: While participatory methodologies are recognized as valuable for incorporating diverse perspectives and local knowledge, their implementation in urban water security assessments remains limited. More research and practical tools are needed to enable meaningful stakeholder engagement and adaptive management (Pahl-Wostl, 2017; OECD, 2015) [31].

Variability in Definitions and Quality: The literature reveals significant variability in how urban water security is defined and operationalized, as well as inconsistencies in data quality and reporting standards (Larsen *et al.*, 2016; Asian Institute of Technology, 2018) [6, 27].

Publication and Language Biases: Current studies may be affected by publication and language biases, as much of the research is published in English and in peer-reviewed journals, potentially overlooking relevant local or non-English sources (Larsen *et al.*, 2016) [27].

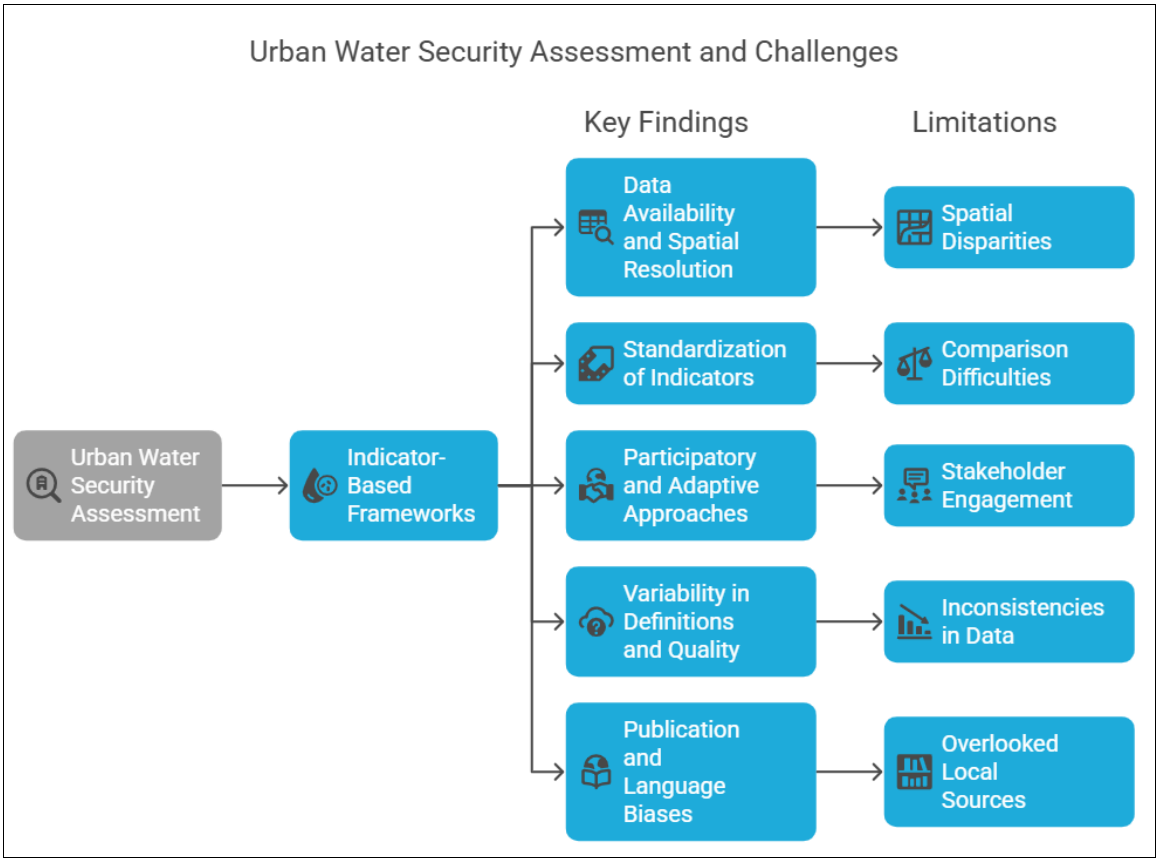

Fig 3: Synthesis of key Findings and Knowledge Gaps

Table 4: Summary of Synthesis and Gaps

Area	Key Findings	Knowledge Gaps and Limitations
Assessment Frameworks	Multi-dimensional, indicator-based, adaptable to local context (Aboelnga *et al.*, 2019; Asian Institute of Technology, 2018; UN-Habitat, 2020) [1, 6, 39]	Data availability, spatial resolution, lack of standardization (Aboelnga *et al.*, 2019; UN-Habitat, 2020) [1, 39]
Stakeholder Engagement	Recognized as important for legitimacy and effectiveness (Pahl-Wostl, 2017; OECD, 2015) [31]	Limited practical implementation and research (Pahl-Wostl, 2017; OECD, 2015) [31]
Data and Definitions	Use of SDG-aligned, globally relevant indicators (Aboelnga *et al.*, 2019; UN-Habitat, 2020) [1, 39]	Variability in definitions, data quality, and reporting (Larsen *et al.*, 2016; Asian Institute of Technology, 2018) [6, 27]
Comparative Analysis	Facilitates benchmarking and targeted interventions (Aboelnga *et al.*, 2019; Asian Institute of Technology, 2018; UN-Habitat, 2020) [1, 6, 39]	Difficulties in cross-city or cross-country comparison (Larsen *et al.*, 2016; Asian Institute of Technology, 2018) [6, 27]

Synthesis

While significant progress has been made in developing frameworks and tools for assessing urban water security, persistent gaps in data, standardization, and participatory engagement limit their effectiveness. Future research should focus on improving data collection and spatial granularity, developing universally accepted indicators, and advancing participatory methodologies to ensure that diverse stakeholder perspectives are integrated into urban water security planning and assessment (Pahl-Wostl, 2017; OECD, 2015) [31].

9. Recommendations and Future Directions

9.1 Integrated, Multi-Dimensional Assessment Frameworks: Policy and practice should prioritize the adoption and refinement of integrated, multi-dimensional frameworks for assessing urban water security. Tools like the Water Security Assessment Tool (WATSAT) exemplify how combining dimensionssuch as water supply and sanitation, water productivity, water-related disasters, water environment, and water governancecan provide city authorities with a comprehensive and objective evaluation of their water security status (Aboelnga *et al.*, 2019; UN-Habitat, 2020) [1, 39]. Such frameworks enable decision-makers to identify specific areas of concern and prioritize interventions, supporting more resilient and equitable urban water systems (Aboelnga *et al.*, 2019) [1].

9.2 Focus on Equity and Resilience

Ensuring that assessments and interventions explicitly address equity and resilience is critical. Multi-level, indicator-based approaches that capture intra-city disparities are essential for identifying and addressing inequalities in water access and quality (Larsen *et al.*, 2016) [27]. Resilience should be built into planning by considering future risks such as climate change, rapid urbanization, and socio-economic shifts (Aboelnga *et al.*, 2019) [1].

9.3 Standardized Indicators and Enhanced Data Collection: A major research priority is the development of standardized indicators that are universally applicable but adaptable to local contexts (UN-Habitat, 2020) [39]. This will facilitate benchmarking and comparison across cities and regions. Enhanced data collectionespecially at finer spatial scales,will improve the granularity and accuracy of assessments, making it possible to identify vulnerable populations and areas more precisely (Larsen *et al.*, 2016; UN-Habitat, 2020) [27, 39].

9.4 Advancing Participatory Approaches

Engaging a wide spectrum of stakeholdersincluding local communities, civil society, the private sector, and government agenciesin water security planning and assessment is essential for legitimacy, effectiveness, and long-term sustainability (Pahl-Wostl, 2017; OECD, 2015) [31]. Participatory approaches, such as watershed management and participatory modeling, bring local knowledge into decision-making, foster trust, and help co-create solutions that are contextually appropriate and widely supported. These methods also promote shared responsibility and long-term public commitment to water management goals.

9.5 Integrated, Multi-Scale, and Partnership-Driven Strategies: Urban water security challenges are complex and require integrated solutions that operate across scalesfrom neighborhood to city to region (Larsen *et al.*, 2016) [27]. Partnership-driven strategies, involving collaboration between public authorities, private actors, and communities, are essential for pooling resources, knowledge, and capacities to address water security holistically (OECD, 2015) [31]. Multi-scale frameworks also allow for the downscaling of assessments to reveal intra-urban inequalities and to tailor interventions to local needs (Larsen *et al.*, 2016) [27].

Summary of Key Recommendations

- Adopt and refine integrated, indicator-based assessment frameworks (e.g., WATSAT) for comprehensive, objective, and multi-dimensional evaluation (UN-Habitat, 2020) [39].
- Prioritize equity and resilience in both assessment and intervention, using multi-level approaches to uncover and address intra-city disparities (Aboelnga *et al.*, 2019; OECD, 2015) [1, 31].
- Develop standardized, adaptable indicators and invest in robust, spatially detailed data collection systems (Larsen *et al.*, 2016; UN-Habitat, 2020) [27, 39].
- Institutionalize participatory approaches to ensure inclusive, transparent, and context-sensitive planning and management (Pahl-Wostl, 2017).
- Foster partnerships across sectors and scales to leverage diverse expertise and resources for sustainable urban water security (OECD, 2015) [31].

Future Directions

- Expand digital and web-based tools for real-time, dynamic assessment and monitoring of urban water security (UN-Habitat, 2020) [39].
- Promote transdisciplinary research that bridges technical, social, and policy domains for holistic understanding and action (Larsen *et al.*, 2016) [27].
- Strengthen the science-policy interface by integrating participatory research outcomes into local and national water policies (Pahl-Wostl, 2017).
- Encourage global and regional benchmarking to facilitate knowledge exchange and the scaling of best practices (Larsen *et al.*, 2016; UN-Habitat, 2020) [27, 39].
- By focusing on these recommendations, cities can move toward more sustainable, resilient, and equitable urban water futures.

Conclusion

Urban drinking water security is fundamental to achieving sustainable and equitable urban development. It underpins public health, economic vitality, and social stability, especially as cities face intensifying pressures from rapid population growth, climate change, and increasing competition for resources. Ensuring that all urban residents have reliable, safe, and affordable access to water is a complex, multi-dimensional challenge. This challenge encompasses not only the quantity and quality of water but also its accessibility, reliability, affordability, and the strength of governance systems.

Addressing these complexities requires cities to adopt robust, integrated assessment frameworks that systematically evaluate water security across multiple dimensions and spatial scales. The adoption of innovative strategiesincluding technological advancements, nature-based solutions, and community-driven interventionsis essential for building resilient and adaptive urban water systems. Equally important is the establishment of effective governance, characterized by clear policies, strong institutional coordination, and meaningful stakeholder engagement, to ensure the sustainable management of urban water resources.

Continued research and targeted efforts to close existing knowledge gaps are necessary to refine assessment indicators, enhance data collection, and develop participatory methodologies that are responsive to the diverse realities of urban contexts. The importance of urban drinking water security extends far beyond the provision of basic services; it is integral to the well-being of urban populations, the functioning of local economies, and the advancement of social equity and environmental sustainability.

By prioritizing integrated approaches, equity, and resilience, cities can transform urban water security into a cornerstone for inclusive, healthy, and sustainable urban futures.

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