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Complexities of the urban drinking water systems in Ethiopia and possible interventions for sustainability

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Abstract

Rapid urbanization in developing countries has imposed threats and challenges to basic urban infrastructures like drinking water, transportation, and energy systems. The existing urban drinking water systems (UDWS) are highly stressed and unsustainable, particularly under changing hydroclimatic conditions, population growth, changing socioeconomic conditions, government decisions, and various policies. This study focuses on the complexities of UDWS in Sub-Saharan African countries, especially in Ethiopia. The objective of this study is to investigate the issues and challenges of urban drinking water systems (UDWS) in Ethiopia, specifically, to assess the gap between water supply and demand, water loss/non-revenue water, environmental, technical, institutional, and governance, etc. and propose sustainable interventions to deal with such issues so as to improve. For this purpose, a mix of methods involving primary data (including key informant interviews, field observations, and field measured data) and secondary data (including published articles, books, various reports, and design documents), as well as various computer-aided applications (mainly, ArcGIS and WaterGEMS) are used to collect data. The issues are deliberated through the UDWSs of Addis Ababa, Adama, Mekelle, and Dire Dawa cities in Ethiopia. Complexities like water shortage, high and low pressure in the water distribution network (WDN), non-revenue water (NRW)/water loss, source pollution, ineffective policies and governance, and weak institutions are the main challenges to Ethiopian cities' water utilities. Further, the case study noticed that in Addis Ababa alone, potable water is only accessible to 66% of the city population. A significant water supply deficit was observed in Mekelle city, where only half of the city population has access to potable water from the system. Additionally, in Addis Ababa, Adama, Mekelle, and Dire Dawa, above 35% of the freshwater produced is either NRW, unaccounted for, or lost, which is significantly higher than the upper 25% limit suggested by the World Bank. Therefore, it is recommended to adopt certain sustainable interventions, such as integrated water resource management, installing appurtenances like pressure-reducing valves, check valves in the WDN, controlling and monitoring of WDN through supervisory control and data acquisition and Internet of Things, effective and long-term planning and policy, etc. It is felt that the study will help the decision-makers and the operators of the UDWS utilities to run the water supply schemes in a sustainable manner.

Extended author information available on the last page of the article

Keywords Ethiopian urban drinking water system · Integrated water management · Sub-Saharan Africa · Sustainable water supply · Urban water distribution network

1 Introduction

Next to air, potable water and food are the basic requirements for every human being. Water is vital for development in many aspects, including social and economic. The availability of sanitation and adequate and safe water is inextricably related to public health and better living standards for any society. Lack of sufficient drinking water and poor sanitation services causes the spread of diseases responsible for the deaths of millions of people worldwide, particularly in developing countries like Ethiopia (Toubkiss, 2006). According to WHO and UNICEF (2015) report, almost one-third of all deaths in developing nations and about 80 percent of the diseases are water-related, and each person spends nearly one-tenth of their productive time tending to water-related illnesses. Further, the data indicates that close to two billion people globally lack water services that are well managed, including 1.2 billion people who cannot access basic water services; 282 million with limited services, 367 million who use unimproved sources, and 122 million who drink surface water in 2020 (WHO, 2021). The coverage of well-managed safe drinking water services was higher in urban areas (86%) than in rural areas (60%) per the data of 2020. WHO (2021) estimates that 90% of the world's population has been using essential drinking water services, but only 65% of Sub-Saharan Africans have access to these services. In Sub-Saharan Africa (SSA), the national average of a basic drinking water service ranged from a low of 38% in the Central African Republic (CAR) to a high of 99% and above in Réunion. Countries in SSA had significant disparities in the percentage of essential drinking water services, as shown in Fig. S1 in the supplementary material.

Despite Ethiopia being touted as one of the fastest-developing countries in the world and endowed with twelve major river basins with an annual renewable water volume of 122 billion cubic meters (Getachew et al., 2021), regarding the availability of clean water to its citizens, Ethiopia is among the least developing nations in SSA and the entire world. The main challenges of UDWS in Ethiopian cities include rapid urbanization, high water demand, shrinkage of water supply sources, mismanagement of water, water quality deterioration, low functionality of the existing water supply system components (technical problems), limitation in institutional capacity, and lack of efficient and proper planning (MoWIE, 2017). The fast urban growth rate in Ethiopia, emerging climate change issues, rapid population growth, and substantial agricultural practices continue to exert pressure on the availability/quantity and quality of water, which already pose a health threat. Drinking water delivery must be provided safely in urban and rural Ethiopia to safeguard public health and ensure livelihoods. Despite being the water tower of East Africa, Ethiopia faces water quality and quantity problems. These problems are observed in the entire country, and the water quality and distribution system activities are not advancing at the required pace. One of the good examples of this is that water-related diseases are common in the country. Water supply stresses are bound to affect Addis Ababa, Ethiopia's capital city, to the complex interactive nature of the rapid urbanization and climate change causes (Arsiso et al., 2017). The WDN performance in Ethiopian cities like Dire Dawa (DD) is low in aggregated performance index (Beker & Kansal, 2022; Kansal et al., 2022). Moreover, the study carried out by Beker and Kansal (2021) indicated that the hydraulic performance of the DD network is low, and it could not deliver sufficient water for the consumers at all places and at the required time.

A few researchers have attempted to assess the issues and challenges of UDWS in specific cities in Ethiopia (i.e., not at the Ethiopian level but in the selected city), but all were focused on specific topics and cities. For instance (Alemu & Dioha, 2020; Kitessa et al., 2021a, 2021b) on water supply and demand in Addis Ababa city; (Getachew et al., 2021; Gizachew et al., 2020; Yimer & Geberkidan, 2020) on water quality/environmental issues; (Bhagat et al., 2019; Berhane & Aregaw, 2020; Venkata and Sudheer 2018) on technical issues related to WDS and non-revenue water, whereas (Debela, 2021; Kayaga et al., 2018) on institution and governance issues. It may be noticed that only a few studies were carried out to focus on the challenges of UDWS in very few Ethiopian cities (not at the Ethiopian level). Also, there are several gaps/missing information as elaborated here: (1) The past studies have focused on the capital city of Ethiopia (Addis Ababa) only, which is not representative of other Ethiopian cities. This study tries to cover more Ethiopian cities. (2) Previous studies had several limitations on UDWS challenges assessment methods, but the current study is more elaborative as it considers a mix of methods involving key informant interviews, field observations, and various advanced computer-aided applications for water distribution network analysis, scenario prediction, and analysis for supply and demand. (3) Previous studies have investigated specific challenges/complexities, but none has incorporated sustainable intervention for each challenge. This study addresses the complexities of the UDWS with possible interventions for sustainability.

The main objectives of this study are to investigate/highlight the issues and challenges of UDWS in Ethiopia. Specifically, it focuses (1) on assessing the water supply and demand gaps, (2) on determining the water loss/unaccountable water, (3) on identifying the low and high pressure as well as water deficit nodes in the WDN, (3) to investigate the water quality problem in WDN, (4) to study the environmental, institutional and governance problem in Ethiopia and (5) proposes sustainable interventions to improve the same through the case studies of four major cities such as Addis Ababa, Adama, Mekelle, and Dire Dawa. Further, the presented study suggests interventions for sustainable and reliable urban water supply systems in Ethiopia. It is hoped that the assessment of UDWS complexities and proposed interventions will help decision-makers and water utilities to understand and improve the overall performance of the UDWS.

2 Status of UDWS in the Sub-Sahara African countries

Attaining clean water and sanitation is the 6th Sustainable Development Goal (SDG) of the UN in 2030. It seeks to achieve universal access to safe/potable drinking water for all, which is fundamentally a human right. In addition, to reduce poverty, it is desired to maintain co-existence within the environmental ecosystem with low adverse impact development (Banerjee et al., 2019; Bayu et al., 2020). However, several SSA countries, such as Ethiopia, may not be able to achieve the water accessibility objective under SDG 6 by 2030 (Bo et al., 2021). It is a developing country, and despite being endowed with natural water resources, it is among the least countries in terms of providing safe drinking water and sanitation for its people. Worldwide, from 2000 to 2020, there is a reduction from 1123 to 771 million people who lack access to basic drinking water services. However, in the same period, the population of SSA without essential water services increased from 350 to 387 million (WHO, 2021; WHO & UNICEF, 2015).

The reports of WHO indicate that the SSA countries accounted for half of the global population without essential drinking water services in 2020, eighty percent (614 million) of those in SSA in 2020 lived in rural areas, and nearly half (351 million) of them came from the least developed countries (WHO, 2021). According to this report, Ethiopia and other SSA countries require a significant acceleration in potable water management to achieve universal coverage of potable waters in 2030 of the UN Sustainable Development Goals (SDGs). The current rates of progress need to be enhanced fourfold. In SSA, two out of five people have no access to potable water; from 35 countries globally below the UN Millennium Development Goal (MDG) of access to water for all, 26 are located in SSA, including Ethiopia (WHO, 2017). Figure 1a, b indicates the status of the urban population using piped water services and the percentage of the urban population accessing basic drinking water services in SSA countries, respectively. The urban population coverage through the piped water supply varies among SSA countries. Countries like South Africa, Egypt, Tunisia, Boston, Lusito, and Swaziland range from 96 to 100%; SSA countries such as Nigeria, Central African Republic (CAR), Chad, Benin, Liberia, and Republic of South Sudan have poor coverage of the ranges from below 40%(Fig. 1a). Rapid urbanization, climatic changes, political instability, etc., were the main reasons for drinking water scarcity in urban SSA countries, including Ethiopia (Dos Santos et al., 2017).

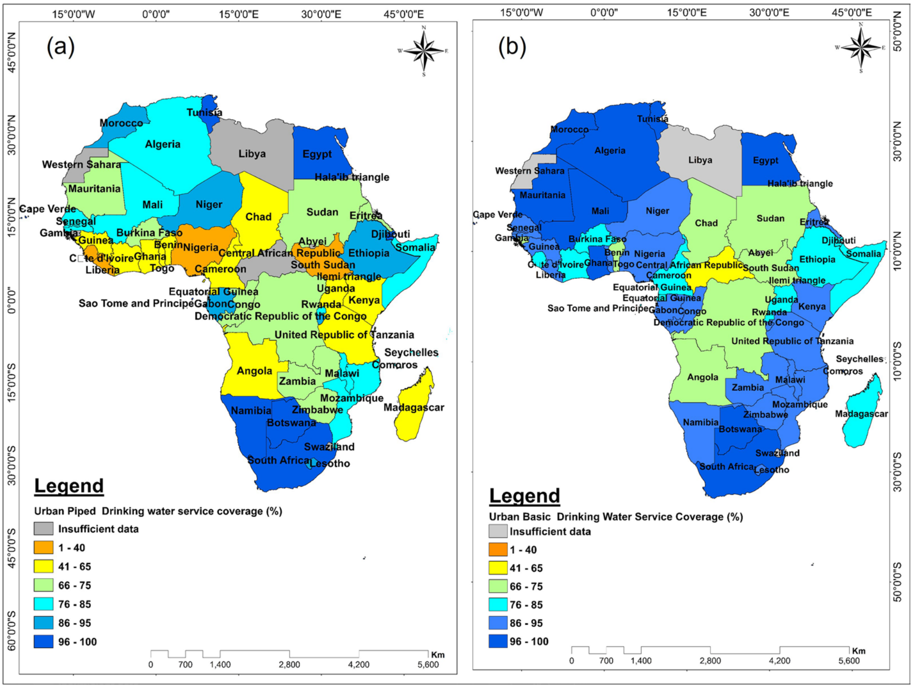

Fig. 1 **a** Percentage of the urban population used water from piped water services, **b** a percentage of the urban population accessed basic drinking water services in SSA countries. Note that the authors have drawn the figures based on the data extracted from WHO (2021)

2.1 Urban drinking water system in Ethiopia

The population's access to potable water in Ethiopia has been growing compared to the previous years between 1990 and 2020, though still many people have no access to clean water in their homes. In 1990, only 17 percent of Ethiopia's population had access to clean water (MoWIE, 2017). According to WHO (2021), the national, rural, and urban coverage reached 50 percent (19.2 million), 41 percent (52.5 million), and 84 percent (71.7 million) of water provided from basic water services in 2020, respectively. Ethiopia is categorized under countries with a high scarcity of drinking water among SSA countries, especially at the rural and national levels (Fig. S1 in supplementary material). Figure 2b indicates that only 45% of the urban Ethiopian population has been using water from safely managed water services in 2020 (WHO, 2021). Safely managed water services are the improved source accessible from the premises or the point of collection within the dwelling area, compound, yard, estate, or safe, clean water is delivered to the household. Although there has been a little increase in all service leaders from 2015 to 2020, more than 55% of urban Ethiopians have not been receiving water from safely managed water services, which is lower than the average for SSA countries and the world by 9% and 41%, respectively, in 2020 (Fig. 2b). Further, more than 0.25 million of the urban population had been using water from unimproved and surface water, which is unsafe for health. In 2020, almost 1.75 million people in urban Ethiopia were using water from limited water services (Fig. 2b). Here, limited water services mean that drinking water is provided from an improved source, for which collection time exceeds/more than 30 min for a round trip (including queuing).

However, in Ethiopia, the water accessibility from safely managed water services is slightly higher than the other SSA countries, such as CAR, Chad, and Nigeria, but very low compared to Morocco and South Africa (Table 1). Furthermore, Table S1 and Fig. S1 in supplementary material indicate the population's percentage using various water supply services and a comparison of Ethiopia with SSA countries and the selected world countries in 2020.

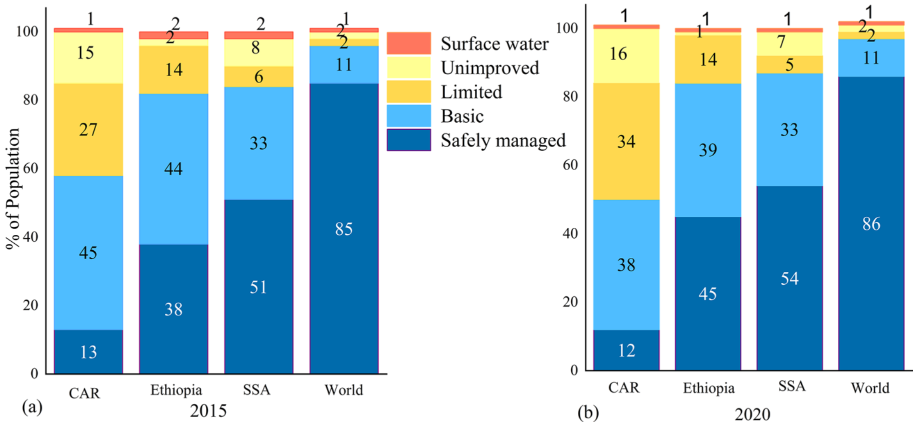

Fig. 2 Comparison of urban drinking water coverage (%) among Ethiopia, CAR, SSA, and world average in **a** 2015 and **b** 2020 (WHO & UNICEF, 2015; WHO, 2021)

Table 1 Comparison of urban safely drinking water coverage (%) among Ethiopia and other selected SSA in 2020 (WHO, 2021)

Country	The proportion of the population using water supplies in %					
	Safely managed	Accessible on-premises	Available when needed	Free from contamination	Piped	Non-piped
CAR	12	12	43	40	32	52
Chad	17	31	69	17	52	38
Ethiopia	39	75	67	39	88	11
Kenya	58	58	78	77	60	31
Nigeria	25	40	81	25	12	83
Morocco	91	97	>99	91	93	7
South Africa	81	91	81	>99	98	2

3 Methodology

3.1 Case study description

Ethiopia, a landlocked country in the Horn of Africa, has a landmass spanning an area of 1.13 million km^2 and is the second-most populated country in Africa after Nigeria, with a total population of 120.8 million, of which 77.8% live in rural areas, and 22.2% of the people live in urban centers in 2021 and ranks twelfth globally (UN-DASE, 2018). For this study, four major Ethiopian cities have been selected based on population, rate of urbanization, water supply scarcity, and complexity of the water distribution network. According to these criteria, Addis Ababa (AA), Adama, Mekelle, and Dire Dawa (DD) cities are selected to investigate UDWS issues and challenges (complexities) with possible remedies. Also, more than 25% of the urban population in Ethiopia lives in these four cities; hence, they may represent Ethiopian cities.

Addis Ababa (38.73° E and 9.17° N) is the capital city of Ethiopia and home to more than 20% (5,060,000) of the urban population of Ethiopia and one of the fastest-growing cities in Africa (UN-DASA, 2018). The city's total area covers 540 km^2, as shown in Fig. 3a, and has an elevation ranging from 2000 to 3000 m above mean sea level (amsl). AA contributes half of the total national gross domestic product (GDP), the GDP of Ethiopia was estimated at 14% in 2015 (World Bank, 2015), but in 2021, it reduced to 5.6% (World Bank, 2021); this is due to various reasons such as civil unrest in the country and Covid-19 pandemic conditions, etc. The high rate of urbanization in Addis Ababa and increased individual water demands have made the city face an increasing rate of water scarcity issues. The total water from surface and groundwater is about 460 million litter per day (MLD) and is distributed to the consumer through pumping and gravity methods (Kitessa et al., 2021a).

Adama city is the other study area, located at 8.39° to 8.43° North latitude and 39.31° to 39.34° East longitude, and 96 km from AA in the eastern direction (Fig. 3b). The city has an elevation between 1600 and 1700 m amsl and covers an area of 130 km^2. Further, the city's total population was estimated to be 394,000 in 2021 (UN-DASA, 2018). The water supply of Adama city is from the Awash River, 17 km far to the southwest direction of the city, with a production capacity of 34.21MLD, and the water is delivered

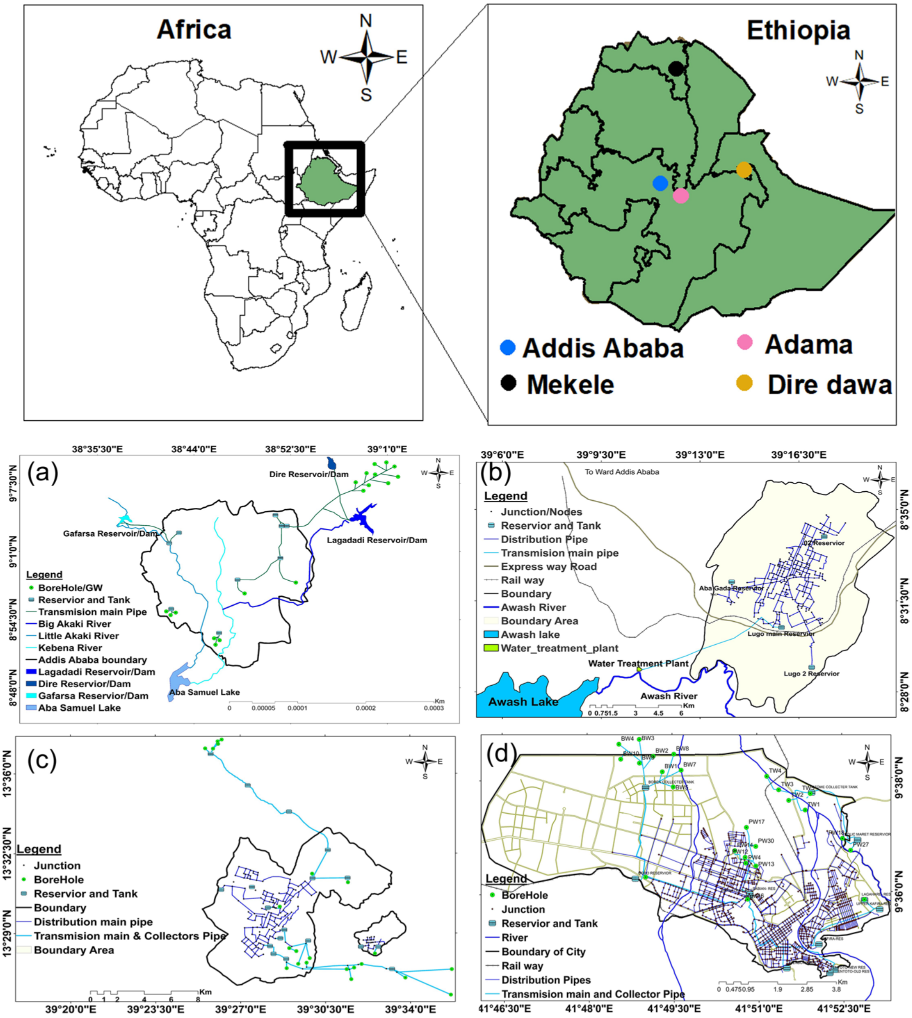

Fig. 3 Details of the urban water supply systems of a case study

from the treatment plant (Fig. 3b) to the end-user through pumping and gravity methods (ATWSSE, 2021).

Mekelle (13.52° E and 39.49° N) is the regional capital city of the Tigray state and hinterlands at approximately 778 km from AA in the northern tip of Ethiopia. The total area of Mekelle city is 92 km^2 and has an elevation ranging from 1700 to 2685 m amsl. However, the city is in rapid economic development and has a high rate of urbanization; the significant water scarcity has hindered the city's growth. The UN-DASA (2018) is estimated to have a total population of 544,000 in 2021 in Mekelle. The groundwater from 17 boreholes serves as the water source with a full capacity of 27.5 MLD (MWSSA, 2019).

Dire Dawa city is another urban center in Ethiopia selected for the presented study. It has nine districts (*kebeles*) that cover an area of 85 km^2. The city is located between 41.768°

and 41.891° latitude and 9.571° to 9.643° longitudinal direction (Fig. 3d) and 458 km far from Addis Ababa in the eastern direction. Its elevation ranges from 1130 to 1335 m amsl. The city's population in 2021 was estimated to be 4,26,000 (UN-DASA, 2018). The current water source of this city is the groundwater from the three wellfields (Sabian, Boren, and Tome) and deep well found in different locations near the city's 3 km radius, which has a total production capacity of 39.42 MLD (Beker & Kansal, 2022).

In this study, primary and secondary data sources were utilized. The primary data include key informant interviews, and field observations were employed in case study cities. The other primary data has been collected for this study, including measured field data (i.e., mainly nodal pressure and residual chlorine concentration for a selected junction in the AA and DD network). The secondary data sources included published articles, books from the internet and journals, various reports and design documents from water utilities that are published or unpublished, and government publications. For this study latest version of WaterGEMS for ArcMap 2021, ArcGIS 10.8, EdrawMax 11.5, and OriginPro 2021 are utilized for simulation, modeling, drawing graph, and data analysis, respectively.

3.2 Population and demand projection

Prediction of population and water demand is essential to investigate the water supply problems due to the city's high urbanization rates and population growth. The Central Static Agency (CSA) of Ethiopia has carried out only three censuses (1984,1994, and 2007). The CSA predicted the growth rate for each city and was used to predict the future population. Several population forecasting methods are available to forecast future populations. For this study, the geometric increase method is adopted for population projection, as shown in Eq. 1.

$$P_{\mathrm{n}} = P_o\left(1 + \frac{\mathrm{Gr}}{100}\right)^{\mathrm{n}} \tag{1}$$

where P_{n} is the future population, P_o is the current population, Gr is the population growth rate, and n represents the number of years.

The geometric increase method has been frequently used for highly developing cities and has been applied by recent studies in Ethiopia (Bhagat et al., 2019; Kitessa et al., 2021a). The past water demand for all cities was determined based on per capita per day (PCD) estimated by the Ministry of Water, Irrigation, and Electricity (MoWIE) in Ethiopia and population data. Further, each city's total PCD (i.e., residential, commercial, industrial, and other) is forecasted based on future living standards and industrial and commercial demand until 2050.

3.3 Water loss/non-revenue water (NRW) estimation

Water loss/ NRW is one of the main indicators used to analyze the technical challenges of the urban water supply systems. The total water loss in cities has been estimated per day based on the amount of water supplied to the WDS compared with the actual water consumption per day using Eq. 2. The average daily water consumption was derived from the annual consumption data for each city in the case study. After the NRW was determined, the comparison carried out was among the case study cities and with the national level of water loss/NRW.

$$\mathrm{NRW} = \left(\frac{\text{Water Production} - \text{Water Consumption}}{\text{Water Production}}\right) \tag{2}$$

3.4 Modeling and simulation of WDN

A hydraulic and water quality (WQ) modeling is a tool for determining how the system responds to the whole system. Water distribution modeling and simulation are essential for designing and operating WDN to serve communities reliably, efficiently, and safely. Modeling and simulation of WDN are crucial to assess the technical problems in the WDN. Both extended period simulation (EPS) and pressure-dependent analysis (PDA) are conducted to characterize the hydraulic and water quality parameters. The hydraulic simulation analysis was performed within 24 h, whereas the WQ simulation was carried out for three days (72 h). Addis Ababa and Dire Dawa city have a complex network and face many problems compared to the other cities and might represent the complexities of Ethiopia's WDN of urban cities; thus, they are being selected to investigate the difficulties of WDN. WaterGEMS for ArcMap (i.e., the latest version of WaterGEMS Connecter) was utilized to model and simulate the WDN that incorporates ArcGIS and WaterGEMS in the same platform. The existing water distribution map (PDF) of the networks was obtained from the water utility of cities and was validated through field visits to the study areas. After validating the network map, it was scanned and imported to ArcMap for georeferencing and digitalization. ArcMap was used to create layers for water distribution components (reservoirs, pumps, pipes, junctions, tanks, and valves). The pipe diameter, material, and other input parameters were added to the attribute table and documented in the ArcMap database.

The other parameters of hydraulic elements such as pumps, tanks, and valves were also transferred to the attribute table. Only pipes more than 90 mm were considered for the modeling and simulation to reduce the network's complexity. The water demand with other necessary data was assigned for further analysis. Water consumption of the node determines the baseline demand allocation, and the flow distribution method involving lump-sum water demand distributed among the service area gives the baseline demands (Giustolisi & Todini, 2009). Based on population density data, Thiessen polygons are generated for each node to estimate the population under each service polygon. After incorporating the necessary data into the hydraulic model, the simulation was performed to predict the hydraulic and WQ parameters of the WDN. Finally, simulated results are calibrated using the field measured values of selected nodal pressure and chlorine residual, which intends to improve the accuracy of the models. Furthermore, the flow chart for modeling and simulation of WDN is indicated in Fig. 4.

3.5 Future scenarios prediction for supply and demand interventions

Once the issues and complexities of UDWS are identified, the next step is to propose the possible intervention/solution for each challenge. Hence, one of this study's primary purposes is to identify potential strategies for water management that could help attain SDG 6-Clean water and sanitation. The intervention/measures taken currently will aid in mitigating the challenges of UDWS and help in achieving the present and future water demands. Integrating different water management options to intervene in the problems aims to

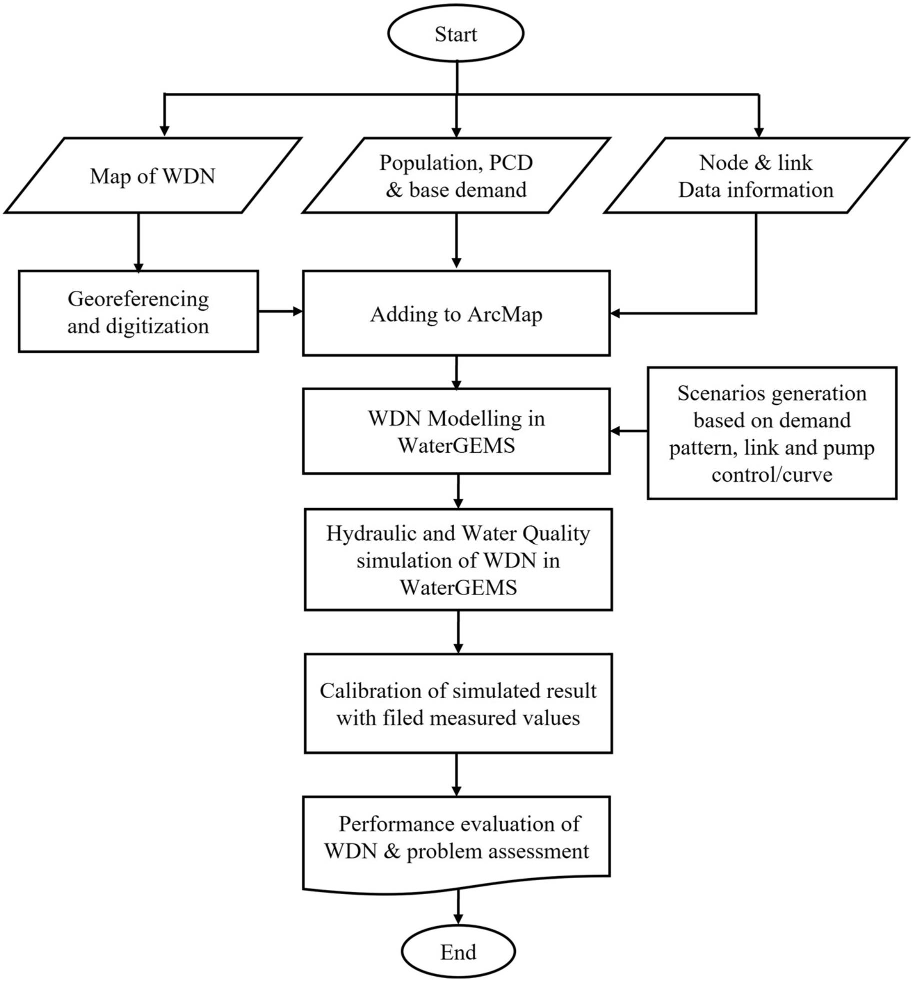

Fig. 4 The methodology for the modeling and simulation of WDNs

discover the solution for achieving water security in Ethiopia. This study proposes various water management interventions such as water conservation, supply and demand management, and integrated urban water management relevant to the Ethiopian cities.

3.5.1 Water demand-side management scenario

The present and future unmet water demands in the cities are significantly important. Thus, the interventions related to demand-side management are critical. Recycling, reusing, and raising consumer awareness of using less water in daily activities are the main proposed interventions for water demand-side management. The other water demand-side management includes (1) increasing end-use efficiency of water using regulators for low-flow showerheads, and dual flush toilets in new residential and commercial developments; (2) enhancing the principle of minimum performance standards on new appliances (laundry washing machines); (3) offering financial incentives for water-efficient purchase and installation; (4) promoting programs to retrofit efficient equipment into existing buildings. Further, growing technology for efficient water supply should be applied mainly; by replacing older inefficient toilets fixtures, installing low-flow showerheads and faucet aerators for residential users, installing low-flow toilets and urinals in government and business buildings, using cloth washer rebates, etc. The percentage growth of water-saving by water conservation and demand management option is shown in Table S2 in the supplementary material.

3.5.2 Water supply-side management scenario

Rainwater-runoff harvesting (RWH) is the best-proposed measure that enhances the water supply with meager investment (even applied at the household level). Three essential variables, such as mean annual rainfall, catchment area, and rainfall runoff coefficient, are used to investigate the stormwater potential. For instance, the average annual minimum and maximum rainfalls are 800 and 1300 mm in Addis Ababa, based on the rainfall measured by National Metrological Agency (NMA) at five meteorological stations (Entoto, Akaki, Bole, Kotobe, and Ayertena). The average minimum standard requirement of average yearly rainfall for the rainwater harvesting system is 300 mm (Seyoum, 2003). The data indicate that all cities in the case study have average annual precipitation greater than the standard rainfall rates (300 mm). Further, the total areas of cities are calculated using ArcGIS, and average runoff coefficients are adopted from the literature. The potential of rainwater runoff can be estimated using Eq. 3 for cities.

$$Q = C_{\text{Ave.}} * A * R \tag{3}$$

where Q = runoff rainwater in m^3, R = average annual rainfall (mm), A = catchment area (m^2), and C_{ave} = average runoff coefficient.

4 Results and discussion

The presented study has two parts: (1) investigating challenges (complexities) of UDWS and technical problems of WDN, and (2) proposing possible sustainable intervention/remedies/. A sustainable and reliable water supply in a city requires careful consideration of all factors that affect the entire system from the point of water sources up to the consumer's delivery end. The challenges may be complex, technical, institutional, environmental, social, and economic. This study categorized the challenges and complexities under water supply and demand, technical issues (related to water loss and hydraulic of WDN), water quality in WDN, environmental and water source, and institutional and governance.

Table 2 Water supply, water demand, and deficit in major Ethiopia cities

City	Water supply (MLD)	Water demand (MLD)	Water deficit (MLD)	% of Pop. accessed to water supply
Addis Ababa	460.00	695.13	235.83	66.11
Adama	34.21	43.34	9.13	78.94
Mekelle	27.50	53.31	25.81	51.58
Dire Dawa	39.42	41.75	2.32	94.43

4.1 Complexities of urban drinking water systems

4.1.1 Urban water supply and demand

In the urban cities of Ethiopia, water shortage is a significant problem for the people, and water demand is rising due to population growth and economic developments. On the other hand, the volume of water produced has been decreasing due to hydroclimatic changes (Kitessa et al., 2022). The current water supply is too low to meet the demand, and the coverage is low (i.e., it does not sufficiently supply some parts of the cities). Thus, no cities in Ethiopia have got piped water on a 24/7 basis. It means that water does not deliver continuously to the service consumer 24 h a day, or water is distributed from the system for a few hours in days and a few days in the weeks, or the water supply system (WSS) is intermittent. Table 2 indicates the water supply, demand, and deficit results in selected cities of Ethiopia (Addis Ababa, Adama, Mekelle, and Dire Dawa) in 2021. The case study results

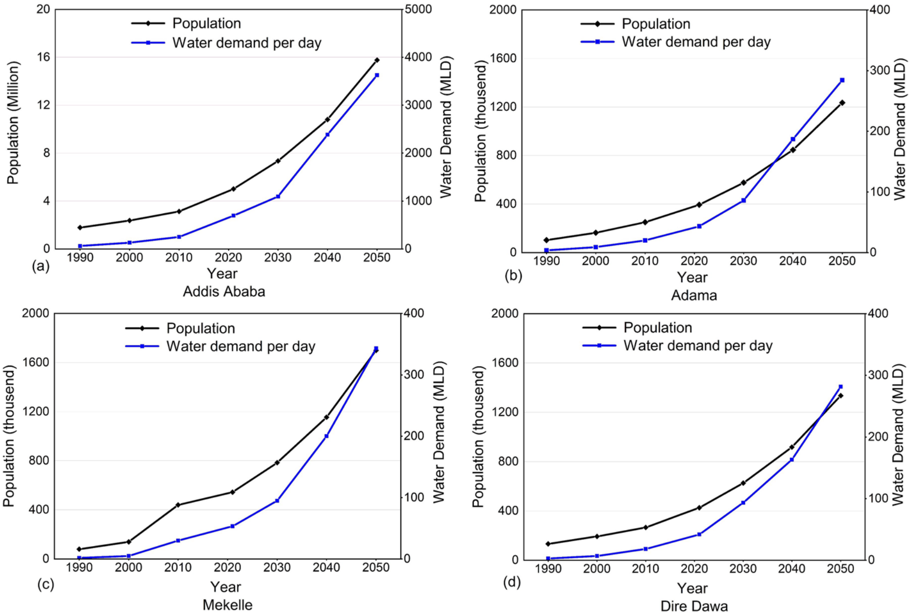

Fig. 5 Trends of population growth and water demand increase in **a** Addis Ababa, **b** Adama, **c** Mekelle, and **d** Dire Dawa city

revealed that in Addis Ababa city, the water supply accessibility to people is nearly 66% or more than 1.7 million (34%) of city residents are provided water from other options, which might be used from unprotected sources that are unsafe for health. The major causes of Addis Ababa's water shortage are rapid urbanization, a high population growth rate, economic development, and hydroclimatic change (Kitessa et al., 2021b). The case study analysis also confirmed significant population growth and high water demand increment in Addis Ababa in the past year, as shown in Fig. 5a. Additionally, the results indicated that the AA population had increased three times, and water demand had grown nearly 11 times (63 to 695 MLD) between 1990 and 2021 and will be expected to increase in the future (Fig. 5a). In scenarios of no intervention/measure/on water demand management, the predicted water demand in 2030 and 2050 will reach 1096 and 3629 MLD, respectively (Fig. 5a), which is a small gap compared to 1181 and 3285 MLD for the respective year as estimated by (Kitessa et al., 2021a).

Like the AA water system, the WSS of Adama could not deliver sufficient water for the residents. Nearly 21% of Adama people lacked access to water (Table 2), which may provide water from the unprotected source (hand-dug and rivers) that might be unsafe for health. This is due to the city's high population growth, urbanization, and industrial expansion. The analysis indicates that Adama city's population increased three times from 1990 to 2021, and the water demand increased from 3.6 to 43.3 MLD (Fig. 5b). Other studies estimate that 73.5% of the population had access to water supply in Adama in 2018 (Fekrudi and Demeku, 2019), which is slightly low compared to the presented study result.

Furthermore, a significant water supply deficit was observed in Mekelle city, which is very high compared to other cities. Nearly 48.4% of city residents in Mekelle do not have access to drinking water from the WSS (Table 2); this is due to the extremely high population growth and industrial expansion of the city in the past, in which the population increased sevenfold between 1990 and 2021, as indicated in Fig. 5c. Also, another study estimated that only 40% of residents had access to water in Mekelle (Asgedom, 2014). However, the federal government of Ethiopia, in cooperation with the World Bank, has launched a new water supply project (under construction) to improve the water accessibility of Mekelle city. Still, water scarcity is significantly high in the city (MWSSA, 2019).

More ever, the results of the case study indicate that the population's access to drinking water supply in Dire Dawa city reached more than 94% in 2021 (Table 2), which is better than in the other cities (i.e., more water supply expansion was undertaken in the DD in the past). The result indicates that from 1990 to 2021, the city's population increased by three times, and the total water demand increased from 2.6 to 42 MLD (Fig. 5d). In Dire Dawa city, 96.5 percent of the population has access to drinking water (DWSSA, 2021). If there is no intervention taken to enhance the water supply in the future, the water demand will reach 284, 243, and 282 MLD in Adama, Mekelle, and Dire Dawa, respectively, in 2050 (Fig. 5b–d).

The accessibility of water to the residents of those cities is significantly less than the national urban water average (84%) of Ethiopia, except for DD city, and very low compared with the average of Sub-Saharan Africa (87%) and world urban water average (97%) (WHO, 2021). The analysis showed that if no intervention is taken, the problem will increase in the future. Therefore, short- and long-term interventions for sustainable water supply should be engaged to enhance the water accessibility of cities (discussed under Sect. 4.2.1), which will help Ethiopia attain SDG-6 by 2030.

Table 3 Water losses of case study cities

City	Water production (MLD)	Water consumption (MLD)	Water loss (MLD)	Water loss (%)
Addis Ababa	460.00	282.95	177.05	38.49
Adama	34.21	20.48	13.73	36.01
Mekelle	27.50	17.82	9.68	35.19
Dire Dawa	39.42	22.55	16.87	42.79

4.1.2 Technical issues

4.1.3 The water loss/ non-revenue water

Globally, more than 30 percent of drinking water is lost from pipelines, and high pressure in the WDN is the leading cause of water loss (Duan, 2020). The water loss in the Ethiopian cities is significantly higher than the allowable limit recommended (25%) by World Bank. Table 3 presents the city's daily water production, consumption, and water loss results. In all the case studies, the results indicate that the percentage of water loss is above the limit value of 25% recommended by the World Bank (Singh et al., 2014). This study estimates that the average daily water loss of AA city is 38.5% of the water produced and has an insignificant gap compared to the 38% determined by Kitessa et al. (2021a). The study results range from 34.43 to 39.98%, which was estimated by Consultancy Service, NRWR (1997). Tracked average water tariff of AA city is 13.25 ETB/M^3 (1USD = 50.88 ETB), and the water loss (177MLD) is estimated to be 16.84 million USD per year.

Similarly, this study estimated that the water loss from input volume in Adama WSS per day to be 36% (Table 3) and which has a slight variation with 34.67% determined by Fekrudin and Demeku (2019), and comparatively, exists a small gap with another city of Mwanza (37%) of Tanzania in East Africa (Shushu et al., 2021). Furthermore, the case study results showed comparatively low and high water loss percentages in Mekelle and Dire Dawa cities, with nearly 35% and 43%, respectively, as presented in Table 3. Even though the estimated water loss in the cities is significantly high, the value is less than the average NRW of the national level of 43% estimated by Macharia et al. (2020). However, the estimated percentage of NRW in cities (case study) is in the range of 30 to 60% of SSA countries (Macharia et al., 2020), and the reported water loss was significantly high compared to a developed country, which ranges from 15 to 30% (Bridges and MacDonal, 1994). Water loss in those cities may result from unauthorized consumption, customer metering inaccuracies, data handling errors, unbilled authorized consumption, and actual losses/leakages.

Furthermore, WDS leaks in the WDS produced by high pressure, improper pipe fitting and installation, water hammer, etc., account for 87 percent of NRW (Annus et al., 2020). This study also proves that high NRW may occur in AA and DD cities due to high pressure, which is observed in the WDN shown in Fig. 7 and discussed in the next section. Additionally, as demonstrated during field observation of case studies city, the water supply in taps has high water losses, and there is no ownership, as the resulting water keeps flowing very high. Further, in these cities, pipe failures are high due to aging pipes, weak fitting installations, and high pressure at midnight, and repair of broken pipes takes more time. As shown in Fig. 6, the average NRW of Ethiopia is significantly greater than that of

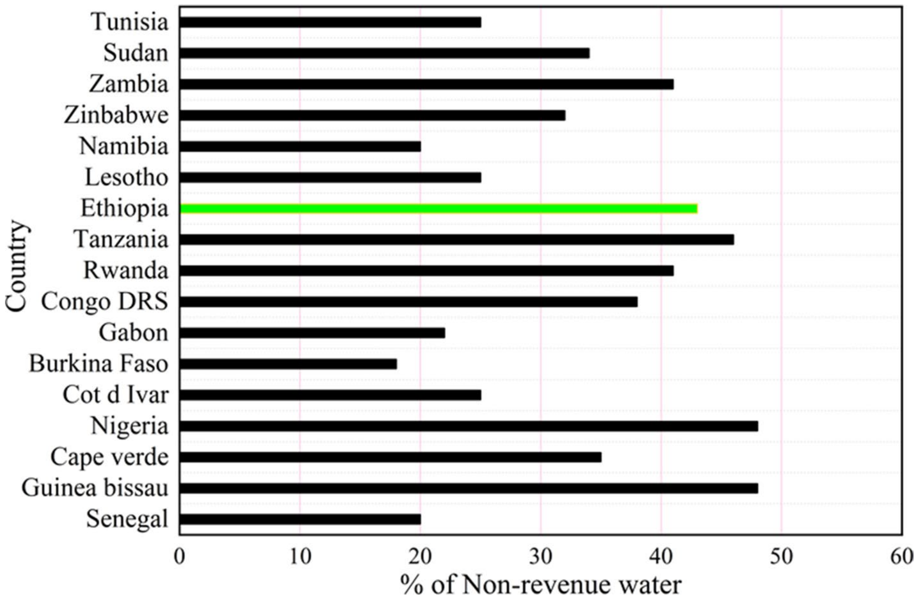

Fig. 6 Percentage NRW for selected countries in SSA. Note, data obtained from (Macharia et al., 2020)

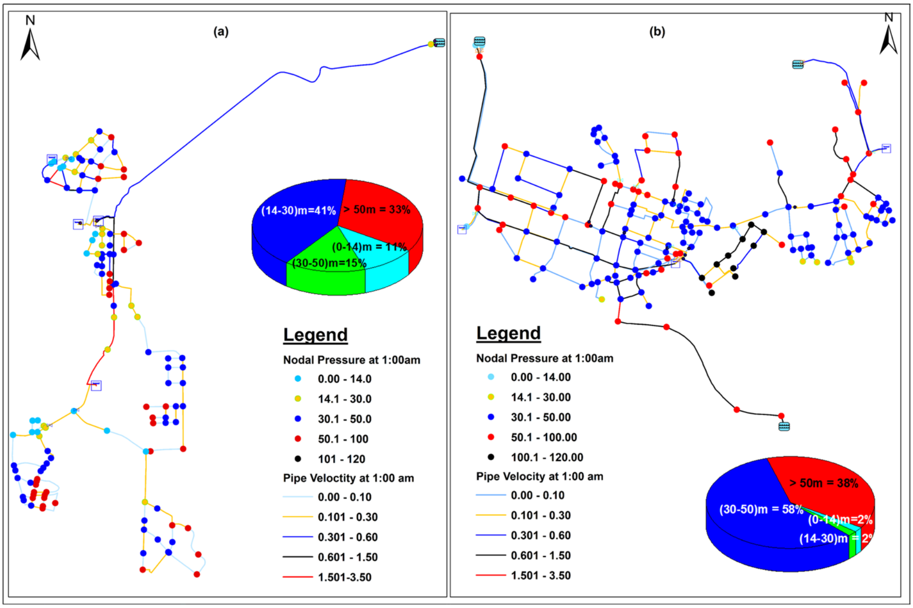

Fig. 7 WDN simulation results of **a** Addis Ababa WDN (Yaka and bole sub-city) and **b** Dire Dawa WDN (Sabian Sub-city or Zone 2) at minimum hour demand (1:00 am) before intervention

other SSA cities, except for Tanzania, Nigeria, and Guinea Bissau. In general, water loss-related issues can account for more than this for all urban WSS in Ethiopia. Efforts should be made to minimize the water loss through leak management and other measures, as discussed under Sect. 4.2.2.

4.1.4 High pressure and flow velocity

The hydraulic parameter (pressure, flow velocity, head loss, and water flow) and WQ (chlorine residual) output of the model simulation indirectly indicate the problematic nodes and pipes of the WDN by comparing its value with the standard. The results show that the WDN of AA and DD has two significant problems: (1) high pressure at several nodes and low velocity, and (2) inadequate available water due to low pressure at various nodes. High pressure in WDN is one of the main causes of pipe failure and water leakage/water loss (Ghieses et al., 2016; Kansal & Kumar, 2000). Figure 7 indicates the result of nodal pressure and pipe velocity at minimum hourly demand (1:00 am) for Addis Ababa WDN (Yeka and bole sub-city) and Dire Dawa WDN (Zone 2). The result revealed that more than 33% and 38% of nodes have high pressures above the 50 m for the AA and DD networks, respectively, which is responsible for the high NRW of these systems at minimum hourly demand occurring at midnight. According to the results, several pipelines have velocities below the recommended minimum velocities (0.3 m/sec) at the time of 1:00 am (Fig. 7). Low flow velocity in a pipe can cause silt accumulation and water quality to deteriorate in the pipelines, which could reduce the WDN's network performance (Walski, 2003; Kansal et al., 2004).

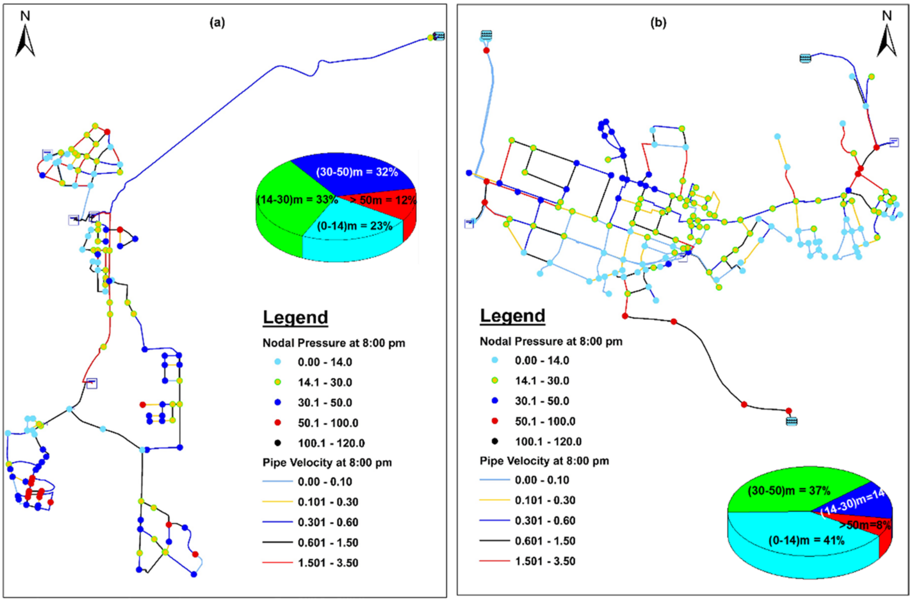

Fig. 8 WDN simulation results of **a** Addis Ababa WSN (Yaka and bole sub-city) and **b** Dire Dawa WDN (Sabiyan sub-city or Zone 2) at Peak hour demand (8:00 pm) before intervention

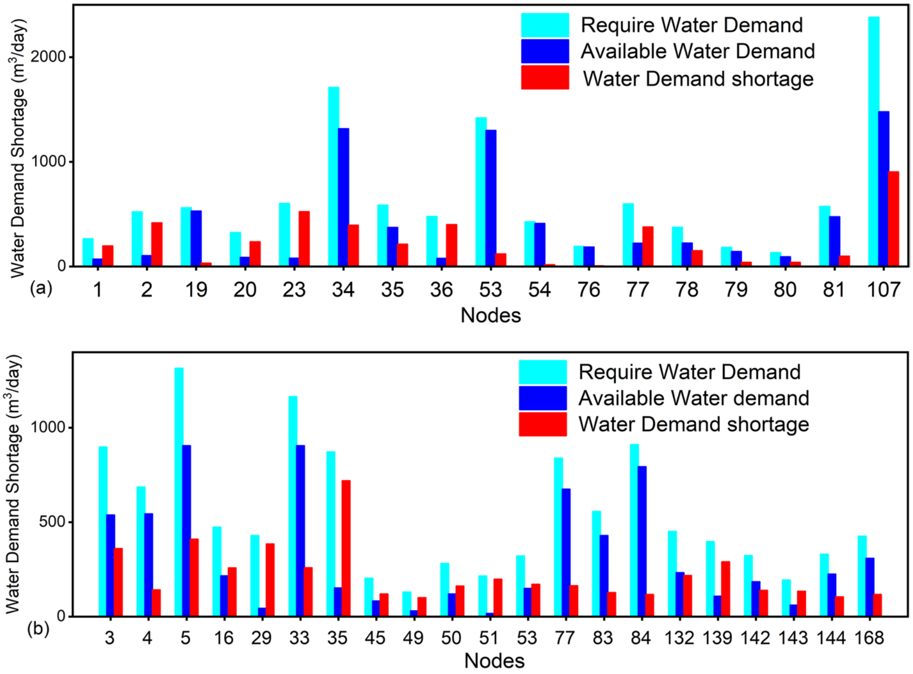

Fig. 9 Water demand shortage at a node for **a** AA WDN and **b** DD WDN of nodes at peak hour demand (8:00 pm)

4.1.5 Low pressure (Insufficient water)

The other problem related to the WDN was that the available flow (delivered demand) at the various node is less than the required demand due to low nodal pressure. The results indicated that at maximum hourly demand (8:00 pm), a significant number of nodes have a pressure less than 14 m for AA and DD networks, as shown in Fig. 8a, b, respectively, which is the main responsible factors for the inadequacy of water at nodes.

Further, the simulation results of PDA indicated that significant water shortage/inadequacy was observed at peak hourly demand at several nodes of WDNs (Fig. 9). In the PDA, the nodal water demand depends on the pressure at the junction. The available node's demand is lower than the required demand when the pressure is low, less than the minimal value (considered 20 m for this study), resulting in a water deficit at that node, as illustrated in Fig. 9. Several studies indicated that there is a relationship between water demand and pressure. The water demand decreases as pressure is less than the minimum recommendable limit, and other studies have proposed the function that shows the relationship between pressure and water demand (Kansal & Tyagi, 2009; Wagner et al., 1988; Wu & Walski, 2006). Most pumps cannot overcome head losses in the pipes and static head. As a result, the furthest nodes that are located at higher elevation in the WDN do not receive sufficient water due to low pressure, especially at the maximum hourly demand. Also, the results of the case studies prove that those nodes with high water shortages are located far from reservoirs and high elevations, as shown in Fig. 8a, b for the AA and DD network, respectively.

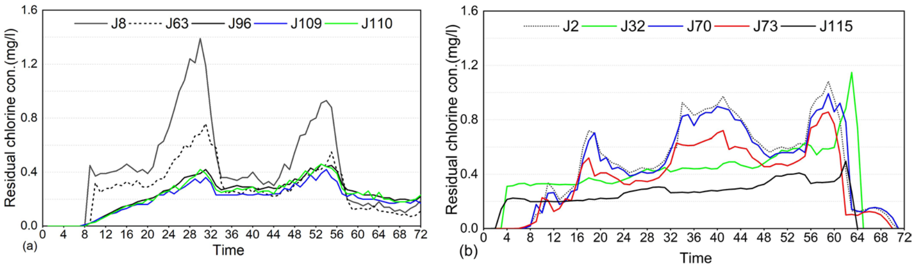

Fig. 10 Residual chlorine concentration variation in 72 h for critical nodes in WDN of **a** Addis Ababa and **b** Dire Dawa

4.1.6 Water quality in WDN

Water quality issues are critical, just like the water supply problem in urban Ethiopia; hence, the supplied water should be safe and potable for consumers. The water quality may deteriorate because of travel in space and time and natural or artificial accidents. Ensuring appropriate water quality for the consumer is one of the primary responsibilities of water utilities. The safety of water supplies can be judged based on the health risk posed to the users. This study investigated the water quality complexities in WDN after distributing the water to the consumer in WDN. For this purpose, two cities' WDN (AA and DD) are selected as case studies. Water quality is a function of various parameters. For this study, the residual chlorine concentration (RCC) is considered to investigate the water quality problems in the WDN; hence, residual chlorine is one of the best indicators of water quality in WDN (Fisher et al., 2011). The results revealed that many nodes had RCC below and above the acceptable limit of (0.2 ml/g–0.5mlg/l) set by WHO for the AA network (Fig. 10a).

Similarly, the analysis of water quality simulation for the DD network indicated that low RCC was observed in several nodes, especially after 58 h as shown in Fig. 10b. Those areas with a low RCC are far from the chlorine boosting station. The pipe failure affected by NRW might cause water quality deterioration in the WDN (Gupta et al., 2012; Kansal et al., 2004).

The application of chlorine in the reservoir was insufficient to satisfy all nodes at a given time (i.e., due to inadequate chlorination). It may be due to poor pipe deterioration because of the dispensation water age. Also, studies prove that Addis Ababa water quality at the tab level has contaminated fecal by 6% from the sample taken (Wolde et al., 2020). The low RCC in the system may be responsible for the regrowth of bacteria in the design, affecting the consumer's health. The results of the RCC of critical and selected nodes for 72 h simulation periods are shown in Fig. 10a, b for AA and DD networks, respectively. In the WDN of Ethiopia, there are many contributing factors to water quality deterioration. Linkage in the sewerage system, old pipe in the distribution systems, lack of regular washing of reservoirs, unsafe water collection and storage by community members, etc. Due to the lack of an advanced monitoring system, the RCC in WDN could not be determined at specific nodes or times. The lack of an advanced monitoring system was noted as the other major problem related to the water quality in AA, and DD networks. Therefore, sustainable interventions should be taken to improve the water quality in the distribution system (discussed in Sect. 4.2.3).

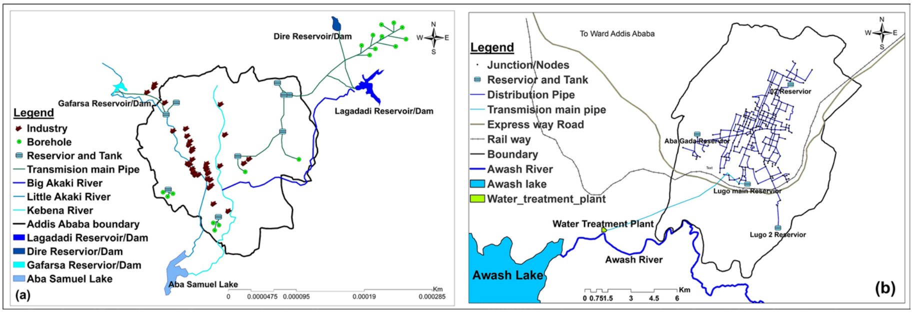

Fig. 11 Vulnerability of water source/water body to pollution from cities in **a** Addis Ababa and **b** Adama

4.1.7 Environmental and water source

The problems related to environmental and water sources in urban Ethiopian cities are investigated in the case studies. The primary water sources in Addis Ababa are mainly surface water (such as the Legedadi, Gefersa, Dire, and Aba Samuel lakes found in the Awash basin, which provides through artificial water reservoirs) and groundwater (Fig. 11a). The field observation indicated that the raw water source was polluted due to anthropogenic activities (e.g., untreated domestic wastewater, industrial discharge, commercial waste, and poor sanitation facilities), increasing pressure on AA water treatment plants. For instance, the Akaki river, Ethiopia's most polluted river, provides water for the Aba Samuel Lake (Acharya et al., 2020). This study proves that several industries are located on the riverbanks/riversides (Fig. 11a). A study indicated that most of the water in Addis Ababa from the reservoirs/dams is polluted with multiple pollutants, making it unfit for human consumption (Colombani et al., 2018). In AA, almost 3 million people lack access to sewage waste collection/treatment services (Colombani et al., 2018; Kumar Singh, 2021). The city's external water sources often receive untreated domestic and municipal effluents (Colombani et al., 2018). Additionally, more than 65% of the country's industries are concentrated in Addis Ababa's urban areas (Kumar Singh, 2021). Studies show that more than 40% of these industries are located near the rivers, but nearly all of the city's industries discharge untreated effluent into the water body without treating the water (Beyene & Banerjee, 2011; Kumar Singh, 2021). Studies estimated that more than 90 percent of all wastewaters are directly discharged into water bodies in developing countries like Ethiopia (Corcoran, 2010).

Like AA, most water sources for Adama city have been surface water (Awash River near the city within a 3 km radius) and groundwater. Based on an investigation conducted through field observation, effluents from domestic and agricultural sources, industrial discharges, and the expansion of Lake Beseka have strongly degraded the water quality sources for Awash River. Studies have revealed that several industries discharge domestic wastewater and solid waste directly or indirectly and dump it into the water sources (Bussi et al., 2021; Degefu et al., 2013; Yimer & Geberkidan, 2020). The releasing waste into the water body significantly increased the pressure on the water treatment plant near the river, as shown in Fig. 11b. In Adama city, no modern and proper solid and liquid waste management system is available (Bussi et al., 2021). Due to the proximity of the trustworthy dumping site to the city and the lack of a proper waste management system, these reliable and liquid waste dumping sites might worthy threaten the water sources of Adama. Recent studies revealed the mean fluoride concentration in groundwater of the Adama source to be 6.03 mg/l, which is above the recommended limit of 0.5 mg/l set by WHO for drinking purposes (Bayu et al., 2022). The pooled prevalence of dental fluorosis among residents in the rift valley area, including Adama city, is 32% (Demelash et al., 2019).

In Mekelle city, low coverage of sewerage systems and a lack of modern solid and liquid waste management systems threaten the quality of the city's water sources. The rapid city expansion toward well fields is also an additional problem; the boundary is not demarcated, and the urban settlements are expanding toward boreholes and wellfields. Household solid and liquid wastes are dumped and discharged into nearby water sources. Additionally, industrial and vehicular wastes are the primary sources of the chemical pollution of water sources in the Mekelle. However, Mekelle is among Ethiopia's most rapidly growing cities though wastewater management is abysmal (Nigusse et al., 2020). According to the study conducted by Alemayehu et al. (2019), the landfill near the water sources, the samples of groundwater, and the stream in the landfill neighborhood are characterized by high concentrations of TDS, sulfate, chloride bicarbonate, and nitrate. Generally, it can be said that the rivers in use are polluted bacteriologically and chemically due to anthropogenic activity in Mekelle.

The water supply for Dire Dawa City (almost 100%) comes from groundwater sources, including boreholes, dug wells, and springs. These waters are highly polluted (UN-Habitat, 2010). As observed during field observation, the pollution was very high in the urban center and advanced from the southeastern part toward the north and north-western part of the study. Analysis of groundwater samples shows that Nitrate (NO_3) concentration exceeds the allowable limits (35.5–109.5 mg/l). Also, bicarbonate ($Ca–HCO_3$ type) concentration with total dissolved solids is high, ranging from 400 to 640 mg/l, and the raw water is hard (DWSSA, 2021). The increase in nitrate concentration is attributed to contamination by organic pollutants from waste generated within the wellfield and the catchment areas, mainly from pit latrines around the wells. The interaction with other factors, such as pH and alkalinity, water with a hardness of more than 200 mg/l can cause scale accumulation in the system and lead to excessive soap consumption and subsequent scum formation, leading to clogging of pipes. Recent studies in WDN of Dire Dawa indicated water quality problems in groundwater cause corrosion and scale problems to WDS due to its content of dissolved ions that can cause public health and economic issues (Gebremikael & Dawod, 2021). Further, studies revealed that groundwater and surface water were polluted with nitrate, which exceeds the natural/normal 9 (nine) mg/l nitrates in the groundwater area (Sahele et al., 2018).

4.1.8 Institutional and governance

The absence of proper monitoring systems coupled with low operation and maintenance capacity is among the main institutional problems in Ethiopia's UDWS. A comprehensive information-sharing system can be better achieved through a regular monitoring process with a continuous reporting system. However, water supply management lacks this; thus, monitoring systems and technical data are unavailable for reliable decision-making. The necessary facilities for the engineer (expertise) and technical workers are not available with sufficient amount and quality. As observed in city field visits, some pumping systems are operated by non-skilled persons in some stations. Such practices are worsening the water utility liability and causing unsustainable service provision.

The lack of legal and institutional security in a case study city like Adama has rendered the decentralized government incapable of delivering reliable water services to the residents. The local government thus heavily relies on the regional state government and hence lacks political independence and goodwill to improve the water services independently. Secondly, the hierarchical political and the upward accountability of the Enterprise's management reinforces political control from above, contrary to the expectations of the logic of the 'Enterprise model' of water supply. Thirdly, the rapid and hugely informal rate of urbanization is overwhelming the decentralized urban water-service delivery in Adama; the city's horizontal physical expansion and demographic changes have already exceeded the pressure zones for the water supply distribution system. Fourthly, even though the water supply enterprise is mandated to supply water to the residents, the authority to determine the structure and technical and financial sources of the city's water supply projects is controlled by the regional water Bureau. Finally, the coordination and partnership among the multilevel water institutions (federal, state, and local governments) are mainly observed during water crises to moderate political and electoral contingencies. Generally, the results obtained from field visits and key informative interviews revealed that the cities in the case studies lacked citizen participation, weak institutional coordination, and lack of awareness.

Additionally, lack of skilled human resources, inadequate customer service and management, inconvenient methods of bill settlement in the office, a low number of branch offices, and over-centralization of activities were the other main challenges observed in all cities of case study observed during the field visits and key informal interviews. So that is crucial to apply sustainable solution for those challenges related to institutional and governance that helps water users (discussed in Sect. 4.2.5).

4.2 Proposed interventions for sustainability of urban drinking water systems

4.2.1 Interventions for water supply and demand management

The urban Ethiopian city water supply capacity (existing and planned) could not meet the present and future water demand described in the case studies. Water utilities will have to dedicate themselves to enhancing their water availability provided the constrained water supply in cities in order to reduce the gap between supply and demand. Depending on supply and demand management intervention, four scenarios, including reference scenarios, were proposed to minimize the water scarcity in the cities: (1) baseline scenarios (BLS) or business as usual, (2) supply-side water management scenarios (SSMS), (3) water

Table 4 Rainfall-runoff harvesting potential of case study cities

City	Annual Ave. RF (mm)	Area (km^2)	C_{ave}	Q_{RWH} (MCM/year)	Q_{RWH} (MLD)	Q_{RWH} 60% of potential (MLD)
Addis Ababa	1115	540	0.50	301	825	495
Adama	784	132	0.54	57	156	94
Mekelle	756	92	0.52	36	99	59
Dire Dawa	615	85	0.45	24	64	39

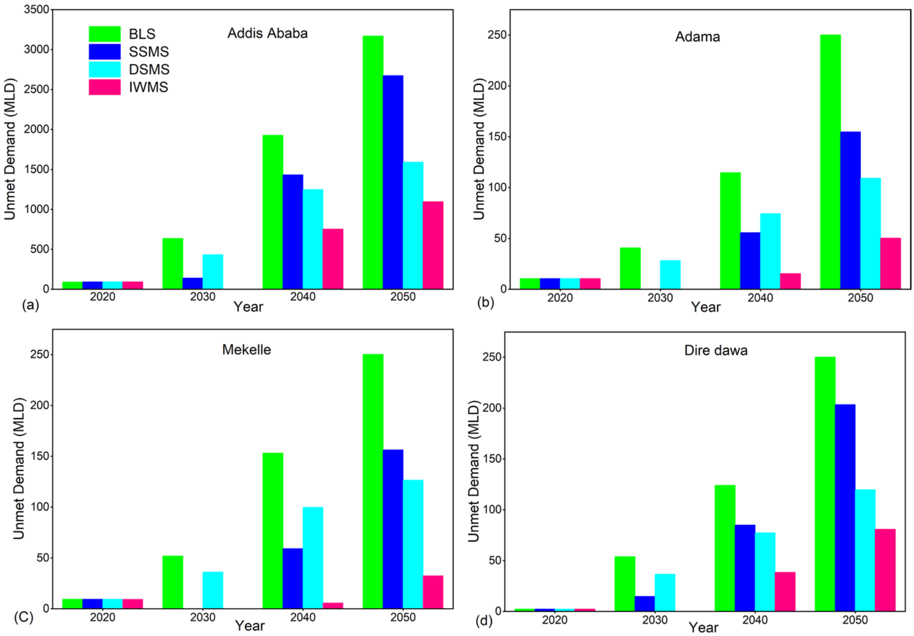

Fig. 12 Predicted unmet water demand for different scenarios/interventions for a city's case study

conservation, and demand-side management scenarios (DSMS) and (4) integrated water management scenarios (IWMS).

In the SSMS (developing stormwater storage), the city's annual stormwater potential or rainfall-water harvesting (RWH) results are presented in Table 4. For this study, 60% of annual RWH potential can be considered, whereas studies considered 60% (Hunt & Lombardi, 2012) and 50% (Kitessa al et., 2022) of RWH potential. Consequently, about 495 MLD can be stored annually in AA by considering 60% RWH potential. The analysis of this scenario indicates that unmet water demand will reach 2674, 156, 155, and 203 in MLD by 2050, which represents about a 16%, 38%, 19%, and 16% decrease compared to baseline scenarios (if no intervention is taken) for AA, Adama, Mekelle, and DD city, respectively, as shown in Fig. 13. Additionally, the results revealed that the optimal percentage of water demand that RWH will meet is about 13%, 33%, 17%, and 14% in 2050 for AA, Adama, Mekelle, and DD city, respectively.

Similarly, with the effective implementation of different management strategies at the demand side (DSMS), unmet water demand will be 1590, 127, 167, and 120 in MLD by 2050 for respective cities (Fig. 12). These values are about 50%, 49%, 47%, and 51% decrease compared with the reference scenario (BLS) for AA Adama, Mekelle, and DD cities. Finally, in the IWMS scenario, the supply and demand side management are considered simultaneously to improve the overall efficiency of the entire water system.

The integrated water management scenario will have better improved the unmet demand than the SSMS and DSMS, as shown in Fig. 12, which will support the achievement of SDG 6 of clear water and sanitation. Studies also support this study's results that IWMS is better than another scenario (Alemu & Dioha, 2020; Kitessa et al., 2021a). Furthermore, Fig. 13 illustrates the predicted water savings in different scenarios. The results obtained

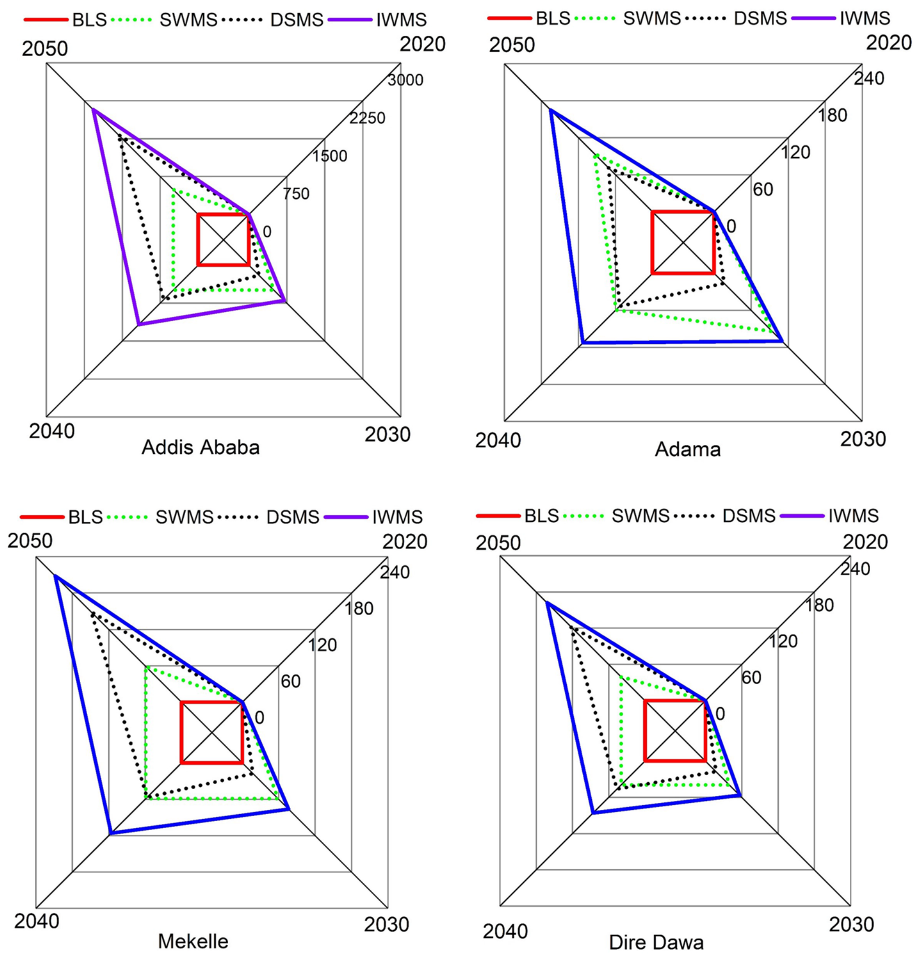

Fig. 13 Optimal water-saving potential under different water system scenarios for a case study of cities

for case studies revealed that the IWMS has significantly saved water compared to the other scenarios for all cities (Fig. 13).

Recent studies indicated that IWMS intervention saves more water than individual management approaches (Alemu & Dioha, 2020; Kitessa et al., 2021a, 2022). DSMS that include structural water-saving and advanced or technical water-saving technology can result in water-saving potentials of 6.97% and 9.82% by 2050, respectively (Kou et al., 2018).

4.2.2 Technological interventions

The main problems related to the WDN of the cities were the high water loss (actual water loss) mainly due to increased pressure above the recommended limits and insufficient water due to low pressure at nodes. Practical and short-term measures should be applied to minimize these challenges. High pressure and low pressure at nodes are a reason for

Table 5 The nodal pressure simulation results after and before intervention taken at minimum hourly demand period (1:00 am) for AA and DD WDN

WDN	Pressure range (m)	Before intervention		After intervention	
		Junction (number)	% of node covers (%)	Junction (number)	% of node (covers)
AA	0–14	13	11	13	11
	14–30	19	15	27	22
	30–50	51	41	73	59
	> 50	40	33	10	8
	Total	123	100	123	100
DD	0–14	3	2	4	2
	14–30	3	2	43	26
	30–50	97	58	106	63
	> 50	65	38	15	9
	Total	168	100	168	100

reducing the hydraulic performance of the WDN. High pressure above recommended values (60 m) is a cause for pipe burst that leads to water loss and pipe failure (Dual, 2020). The low pressure at a demand node decreases the amount of water delivered to the consumer. Installing pressure regulating values (PRV) at critical points is a cost-effective and short-term measure that significantly minimizes and regulates the high-pressure problem at nodes, considerably reducing physical water loss in the system. Table 5 presents the results of the simulation of WDN for two cities (AA and DD) at 1:00 am after and before the intervention was applied (installing PRV at different parts of the network). The cost-effective intervention, PRV, was installed at the critical area (J63, J85, J89, and J108) to decrease pressure on the AA network, which reduced the percentage of the high-pressure range (> 50 m) by 76% (Table 5). Similarly, five PVRs installed around nodes of high pressure (J56, J87, J91, and J148) reduced the pressure significantly by 77% for DD networks, as presented in Table 5. There is a direct relationship between the pressure and the leakage value in the WDN (Dual, 2020).

Lower pressure (water deficit) at the nodes is resolved by introducing an overhead tank near the affected area to increase the head at nodes responsible for the low water flow at maximum hourly demand. Further, low velocity in the pipes is resolved by redesigning the system and changing some old pipelines in a problematic area with the recommended diameter size. Other water loss problems in WSS can be minimized by active leakage control, pressure management, infrastructure management, and repair speed. Monitoring and controlling the entire WDS using advanced and computerized systems is crucial to operating components properly. So that is vital to apply the SCADA system and the IoT. The SCADA system is a computer-based system that gathers and analyzes the period of knowledge to trace (real-time), monitor, and manage WDN. The system can be monitored, controlled, and supervised from a central location. Installing sensors (hydraulic and water quality) and controllers can be directly interfaced with the managed systems. It is significant to resolve the problems that appear during operation and maintain the normal functioning of the entire WDN.

4.2.3 Interventions for water quality sustainability

Water quality is crucial for the health of water users. There is a possibility of accidental contamination in WDS, so measures to address water quality issues should be implemented. One of the main problems observed was very low residual chlorine concentration out of recommended limit in WDN. To keep the residual chlorine concentration within recommended limits, water utilities should install additional booster chlorination within the distribution system at critical nodes in addition to conventional chlorination in the treatment plant. Kansal et al. (2004) have discussed the advantages of booster chlorination. This study also proposed water quality monitoring (WQM) as the remedy for problems related to information on water's physical, chemical, biological and radiological characteristics via statistical sampling. It is an essential aspect of overall water quality management. WQM in a drinking water supply scheme is undertaken at all three levels: the source, the treatment plant, and the WDN. Monitoring in the WDN can determine the quality of water delivered to consumers and indicate the risk of water-borne diseases.

In many cases, the WDN samples significantly differ from water samples at the WDS entrance. Hence, water quality monitoring (regular sampling and testing) in the WDN is essential to ensure the proper protection of public health. For tracking in WDN, a specific program must be developed for minimum sampling frequencies, sampling locations, and testing procedures. Further, this study also proposed advanced water quality monitoring systems such as the IoT and SCADA systems to control and monitor real-time water quality tracking in WDN.

4.2.4 Interventions for source protection and environmental sustainability

This section provides an overview of the proposed methods for protecting the water source quality in Ethiopia. Most studies, including the presented research, agreed that water from reservoirs, rivers, and streams in Addis Ababa, Adama, Mekelle, and Dire Dawa is polluted, affecting public health. Hence, effective pollution detection, mitigation measures, and monitoring, including the development of bioassessment tools and cost-effective management measures, are urgently required to reverse Ethiopia's water quality decline, especially in the major metropolitan cities. Quality of water source protection is achieved by applying for effective catchment management (CM) programs; hence, CM aims to minimize the amount of contamination that enters the water bodies, thereby reducing the amount of treatment required to supply safe and clean water. CM has included hazard identification and design and implementation of control measures. The influence of all aspects must be understood before effective control measures, including treatment before the domestic and industrial wastewater is joined to the water bodies, are considered.

One of the impediments to implementing available water pollution policy and law in Ethiopia could be that most of these policies and legislation in Ethiopia are based on those produced in western countries and Northern America, with minor revisions or a copy, without regard for local technologies and resources. In order to monitor and manage water pollution, Ethiopian policies, regulations, and formal governance structures should be evaluated in a way that takes into account the local technology and resource. To protect the water bodies from pollution, they can put them into practice or enforce them. Before releasing their discharges into water bodies, industries should treat them to an appropriate level. A competent authority should fix the minimum allowable polluting substances to be allowed into the water bodies around the cities.

4.2.5 Interventions for institutional and governance problems

Political pressure, states, and influence coming from administrative failures at many levels of government (Phel-West 2017) and institutional and organizational reforms are needed in Ethiopia's urban water sectors. Private sector participation and decentralized governance are suggested as solutions. The current water policy and management are complex in Ethiopia. Adapting to new perspectives, concepts, and frameworks such as adaptation and transformation, social education, self-organizing systems, and informal networks is crucial. Furthermore, it is essential to promote institutional and organizational development and support reform of the urban water sector through capacity building, knowledge sharing,

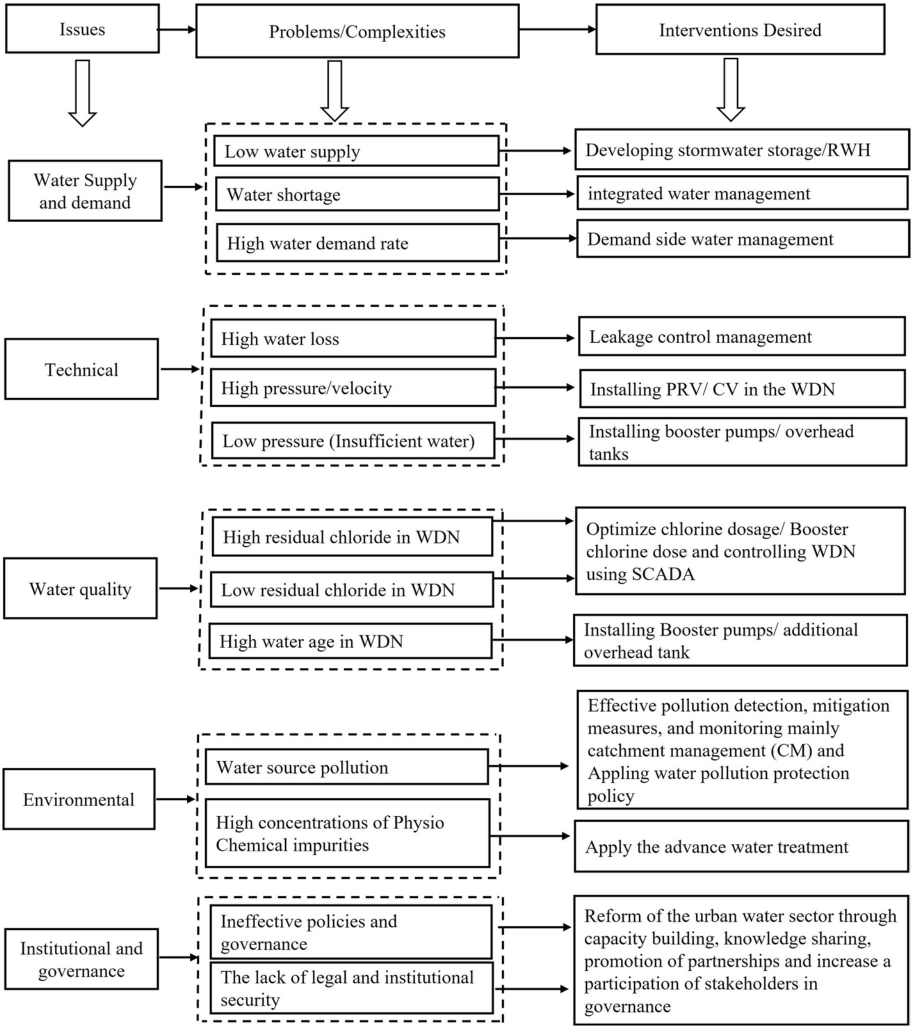

Fig. 14 Summary of issues, the main results of problem/complexities, and proposed sustainable intervention

and promotion of partnerships. This study also proposed good governance principles (accountability, transparency, participation, consciences oriented, equitably, and inclusive effectiveness and efficiency) as the remedies for the institutional and governance challenges in Ethiopia UDWS and the water governance aspect given by the UN for water-related governance. The good water governance principles are used as the water governance parameters. Good water governance is the key to the sustainable management of water resources, which is essential for realizing SDGs, particularly SDG6, which deals with water and sanitation. Many of the water utilities in the urban area of case studies have not applied good governance principles to the drinking water sector of Ethiopia. The implication is that for the urban local government to deliver effective water supply service, this study contends, the decentralization process needs to ensure a reliable water distribution system for the cities in a case study. Figure 14 summarizes or synthesizes the main results in both parts. It also links the results of both parts (challenges and their sustainable intervention).

5 Conclusions

Developing countries in various parts of the world are passing through rapid urbanization, which has mounted pressure and has caused tremendous stress on the existing urban drinking water systems. The situation is getting worse in countries like Ethiopia in sub-Saharan Africa. This is mainly due to various anthropogenic activities, population growth and migration to urban areas, changes in hydroclimatic conditions, and reducing freshwater sources. In addition, the weak policies, ineffective governance, poor socio-economic conditions of the people, and weak institutional framework have magnified the problem of safe and adequate drinking water in Ethiopia. This study has highlighted these complexities in various cities of Ethiopia, which are facing problems of drinking water on a sustainable basis. The study contributes to the knowledge base toward water accessibility and management, taking care of SDG 6 under challenges of climate change and increased anthropogenic activities. The study concludes based on the scientific study carried out on the basis of expert opinion through key informant interviews, field observations, and various advance computer-aided applications. The present work intends to analyze issues and challenges in a comprehensive manner through well-developed and supported valid and reliable information and data.

Ethiopia is one of the least developed SSA nations as far as freshwater availability and accessibility is concerned. The main issues and challenges for UDWS in Ethiopia are (1) a huge gap in water supply and demand, high NRW, high/ low pressures, and low velocities of water in the WDN, (2) stagnation of water and hence low water quality in the WDN, (3) contamination due to various environmental issues of water sources, and (4) weak institutional and inefficient governance of urban water utilities. It is felt that such issues can be addressed through various structural and non-structural sustainable interventions, such as integrated water resource management, frequent use of various appurtenances like PRVs, and CVs in the distribution network, controlling and monitoring of WDN through SCADA and IoT, effective and long-term planning and policy, and effective pollution management, catchment management (CM) and adopting water pollution protection policy, etc.

The study reveals that about 66%, 79%, 52%, and 94% of the population had access to water from the WSS in AA, Adama, Mekelle, and DD cities, respectively. Further, the non-revenue water/water loss/unaccounted water varies from 35.2% (Mekelle) TO 42.8% (DD). Besides, more than 33% and 38% of the nodes had very high pressure (more than

50 m) in AA and DD networks, which caused heavy leakage and water loss during mid-high flow demand. In contrast, low pressure was observed at several locations in AA and DD networks during peak hourly demand, thereby resulting in insufficient water at these nodes. Therefore, it is felt that integrated water management is required to minimize the unmet water demand by 65%, 87%, 66%, and 67% (compared to BLS) in 2050 for various cities of AA, Adama, Mekelle, and DD in Ethiopia. Furthermore, installing appurtenances like PRVs at the critical nodes will minimize the losses. For example, it was noticed that installing 5 PRVs at critical locations in the DD network, it reduced the high-pressure nodes from 38 to 8%. The study also recommends adopting sustainable interventions like controlling and monitoring WDN through SCADA and the Internet of Things (IoT), effective and long-term planning and policy, etc.

It may be noted that this study has certain limitations. For example, the study has used the geometric increase method for population projection, which is more appropriate for fast-growing cities like Addis Ababa, Adama, and Mekelle but may not be appropriate for a medium-growing city like Dire Dawa. This may lead to overestimating the population, but will be on safer side for decision-making. Similarly, in this study, only four Ethiopian cities are considered due to limited resources and time. One may like to consider other bigger cities like Hawassa, Bahar dar, Gonder, etc., as well as the other big cities of SSA, which may highlight some more issues. Further, the study lacks detailed discussions on socio-economic issues which will be considered in future studies.

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Data availability statement All relevant data are included in the paper or its Supplementary Information.

Declarations

Conflicts of interest The authors declare that there are no conflicts of interest.

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