

Research Article

Examining Non-Revenue Water and Identifying Its Root Causes in Debre Markos Town, Ethiopia

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Abstract

NRW poses significant challenges for water utility institutions worldwide, impacting sustainable access to potable water and the financial viability of utility operations. This issue is particularly severe for water utilities in developing countries, like Ethiopia. This research aimed to examine NRW and identify its root causes specifically for the Debre Markos Water Utility. Data collection involved a desk review, field observations, and semi-structured key-informant interviews, which included both open and closed-ended questions. The research findings indicated that the average NRW was estimated at 35.94%. The impact assessment revealed that NRW had a significant negative effect on both the water utility and its customers. The study found that leakage and its triggers, theft, lack of NRW components awareness, infrastructure development, poor data handling practices, a low number of gate valves, great distances from master control points, inaccurate water meters, and failure to utilize the latest water meter technology were the main root causes of NRW. Therefore, the water utility should have an awareness of NRW components and develop appropriate reduction strategies. Additionally, the utility should adopt the latest technologies in water supply components and implement robust scientific investigation and monitoring mechanisms, supported by a legal framework, to recover the revenue lost.

Keywords

Unbilled Authorized Consumption, Leakage, NRW Components, NRW Impacts, Non-Revenue Water, NRW Root Causes, Commercial Losses

1. Introduction

The current urban drinking water systems face significant stress and are unsustainable due to changing hydro-climatic conditions, population growth, evolving socioeconomic factors, government policies, land use patterns, water pollution, rapid urbanization, and various other policies [13, 16, 36, 42]. Consequently, water scarcity has emerged as a global issue driven by both anthropogenic and natural factors [54]. Globally, two-thirds of the population encounters difficult water

shortages for at least one month in a year [44]. Universally, about 2.3 billion people live in countries facing water stress, with 733 million residing in nations classified as highly or severely water-stressed [59].

One significant contributor to this problem is non-revenue water (NRW), which impacts water supply services by causing revenue losses and increasing the costs of distribution [30, 45, 71]. Research by Santos [58] indicates that water loss in

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urban supply systems presents considerable challenges for water utility companies globally, affecting both sustainable access to clean water and the financial viability of their operations. Reports by Asian Development Bank [15] and Abebaw [2] highlight that a major challenge facing water utilities is the substantial amount of water lost in distribution networks. This issue is particularly severe in developing countries, especially in areas facing extreme water scarcity [35]. Therefore, reducing water losses is deemed essential for sustainable water management, although it proves to be quite challenging [53, 69]. High levels of NRW often serve as an indicator of a water utility's performance, with elevated NRW levels typically suggesting poor management practices.

Non-revenue water (NRW) is demarcated as the change between the over-all sum of water provided to the supply network and the quantity billed to consumers [4, 9, 15, 38, 72]. It consists of three main components: real losses, apparent losses, and unbilled legal consumption [66, 72]. Another classification by Wyatt and Press [71] divides NRW into physical losses (such as pipe leaks) and commercial losses (which include illegal connections, unmetered public use, meter errors, unbilled metered water, and unpaid billed water). Many water utilities experience significant water loss in their distribution systems because of leakages, illegal consumption, or accounting errors [51]. Physical losses involve leakage from all parts of the water supply system, including overflows from the utility's storage tanks. These losses arise from poor operations and repair, inadequate active leakage control, and the substandard quality of water supply components [22, 50].

Physical losses can be severe and may go undetected for months or even years. The volume lost largely depends on the characteristics of the pipe network and the leak detection and repair practices employed by the utility. Typically, around 90% of the water that is tangibly vanished through leaks is invisible over the ground [15]. While some leaks may finally turn out to be noticeable after numerous years, vast quantities of water are lost each year. Undetected leaks can be substantial, especially those that flow directly into sewers or drains. Thus, a water utility that does not implement an effective and proactive leakage control policy will likely experience high leakage levels unless its infrastructure is newly installed or in excellent condition [15].

According to Farah [27], water seepage is a critical issue in delivery networks, with the majority of NRW being lost through supply line leakages. Leakages can also happen by the side of various points, such as joints, valves, fire hydrants, and service connections leading up to the customer meter. Several factors facilitate leaks, including the kind of pipe material, time of life, composition, and assembly approaches used [27]. Additionally, ecological and exterior situations - such as surrounding soil type, pressure from road traffic shakings, and ice loads - can induce leaks. Water circumstances, including velocity, pressure, and temperature, also play an important role in water losses. For example, greater water pressure can be able to rise seepage rates by flared current cracks in pipes, whereas high temperature differences

could be a reason for pipe materials to enlarge or shrink, resulting in additional repeated breakdowns [70].

Commercial losses, also known as apparent losses, occur due to various factors including customer meter under-registration, inaccuracies in water metering, data-handling errors, illegal water consumption, and theft of water in its many forms [25, 47]. Additionally, unbilled official ingestion encompasses water consumed by the water supplier for operational purposes, water utilized for firefighting, and water provided without payment for some consumer collections [20]. Moreover, challenges such as low water pressure, aging infrastructure, leaks, and inefficient operation and maintenance of the water delivery network further contribute to the issue of non-revenue water (NRW) [35]. According to a report by Ociepa [49], key factors associated with high levels of NRW include leaks, theft, inaccurate metering, and outdated infrastructure. Mutikanga et al. [46] noted that many water utilities lose substantial amounts of water within their distribution systems due to leakages, illegal consumption, or accounting errors.

The initial step for any water utility seeking to reduce water losses is to establish a baseline that reflects the current levels of water losses. This can be achieved by carrying out a water audit that leads to the formulation of a water balance, which is essential for designing an NRW reduction strategy [15]. By categorizing the volume of water that exits the water utility into pieces of fragments, it becomes possible to manage non-revenue water more systematically and effectively (Figure 1). According to the American Water Works Association, the system input volume is divided into two main categories: authorized consumption and water losses (Figure 1). Authorized consumption includes both billed and unbilled authorized consumption. Billed authorized consumption refers to the volume of water that is legitimate and for which a water utility bills its customers, encompassing both billed metered and billed unmetered consumption.

Billed metered water consumption is the quantity of water usage charged on a customer's bill based on readings from a water meter. The bill reflects the change between the present and earlier meter readings, demonstrating the amount of water consumed throughout that period. In contrast, billed unmetered water consumption is calculated according to estimates or a fixed rate, rather than being measured with a meter; this is common in areas lacking widespread metering or for certain consumers, such as those with fixed-price water bills. On the other hand, unbilled authorized water consumption includes water used by the utility for legitimate purposes but not billed to the user. According to Ahmed [8], this encompasses water for operational needs, firefighting, and free distribution to certain consumer groups, such as public institutions. Unpaid official ingestion also includes non-owned measured ingestion and unpaid unmeasured ingestion. Unbilled unmetered water consumption refers to usage that is authorized but neither billed nor metered. This typically includes water used for activities such as firefighting, flushing

mains, and street cleaning. Unbilled metered water consumption, on the other hand, refers to the volume of water that is measured by a meter but is not included in the customer's water bill due to various reasons, such as utility purposes or certain authorized types of consumption.

The second category, water loss, comprises commercial and physical losses. Commercial losses arise from non-legitimate ingestion, inaccuracies in customer meters, and data-handling errors, while physical shortfalls are caused

by leaks in transmission and distribution mains, leaks from storage and overflow from storage tanks, and service connection leaks leading up to the customer meter. The commercial loss is a loss because of an unauthorized consumption, customer meter inaccuracies and data management mistakes, but the physical losses are losses caused from leakage in transmission and distribution mains, leakage as of storage and overflows from storage tanks, leakage from service connections and leaks equal to the end user meter (Figure 1).

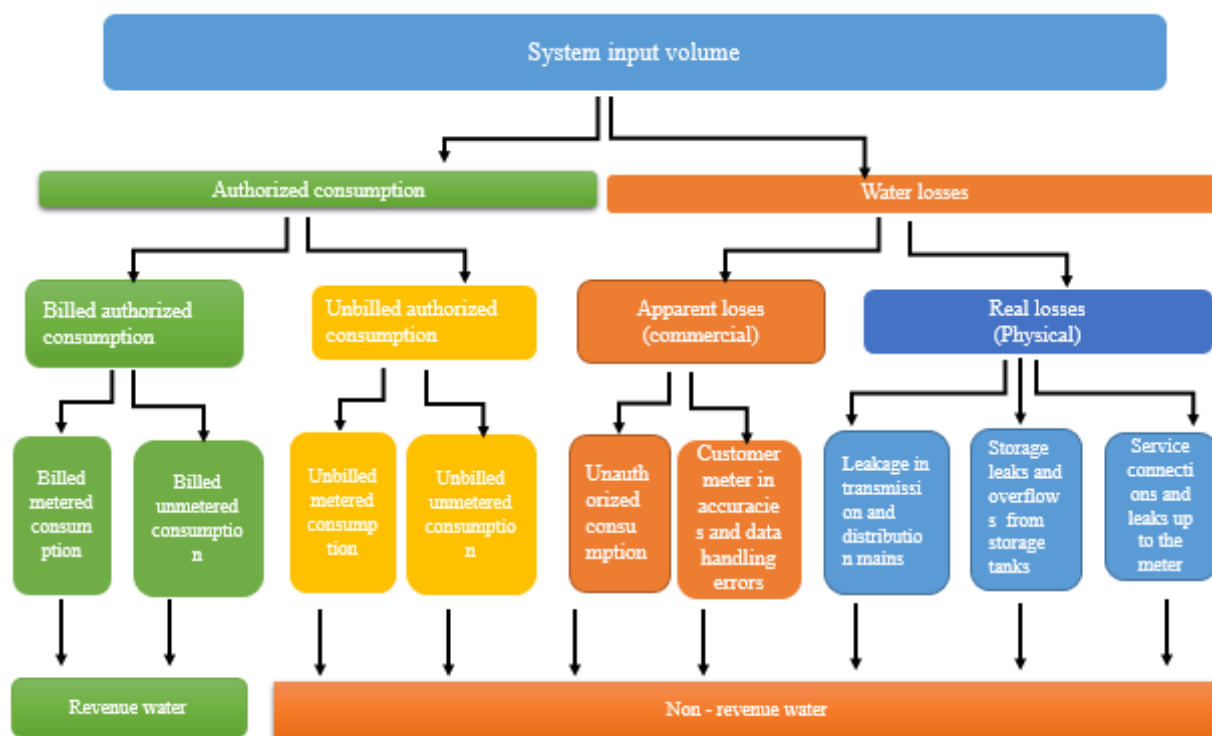


Figure 1. Components of system input volume. Source: S&P Global Ratings, American Water Works Association.

Even though water shortage is anticipated to become a global issue, it is astonishing that 32 billion cubic meters of treated water are lost to urban supply systems worldwide as unaccounted water [38, 56]. The annual price of water for water utilities due to NRW globally be able to be conventionally calculated at \$141 billion, with approximately one-third of that occurring in developing nations [38]. According to Farely et al. [28], the universal normal level of unaccounted water is 35% of the produced water, whereas in emerging nations, this average increases to between 50% and 60% [41, 45].

A recent report by Liemberger and Wyatt [40] estimates the global volume of NRW at 346 million cubic meters per day, equating to 126 billion cubic meters per year, with the cost of the lost water amounting to \$39 billion annually, conservatively valued at \$0.31 per cubic meter. The Asian Development Bank's study estimates that annual NRW is 29 billion cubic meters, costing water utilities nearly \$9 billion each year, assuming a water value of \$0.30 per cubic meter [15]. By halving the current physical losses, it could be possible to

supply 150 million people with already treated water [15]. Additionally, Kingdom et al. [38] report that nearly 45,000,000 m³ of water is lost every day due to leakage in emerging republics. Furthermore, about 30,000,000 m³ of water is distributed daily to consumers, but then again goes unpaid owing to metering mistakes, illegal consumption, and unethical utility workers, leading to losses of approximately \$6 billion annually for water utilities. This situation directly impacts the capacity of utilities in emerging nations to continue to be monetarily feasible and to fund necessary service expansions, particularly for the impoverished.

If the worldwide bulk of unaccounted water was reduced by just one-third, the investment could provide water for 800,000,000 population, considering the per person per day water demand of 150 liters. Beyond this, reducing NRW would enhance water service reliability, improve supply to the municipal low income residents, better water quality, decrease energy ingestion, and, in some cases, postpone the necessity for capacity expansions [4, 40]. While completely eliminating

unaccounted water in a water service provider could not be feasible, aiming to reduce current losses in nations under development by half seems realistic. Such a reduction could generate an estimated additional \$2.9 billion in annual cash for the water sector (through increased revenues and reduced costs), potentially accommodating an additional 90 million people without requiring new production facilities or further depleting limited water resources [38]. Therefore, reducing Non-Revenue Water (NRW) is essential, as it increases both water availability and the revenues from drinking water [9].

In Africa, approximately 45,000,000 m³ of water is deficit every day due to pipe bursts and leakages, while an estimated 16,000,000,000 m³ is lost due to water theft, commonly referred to as commercial losses [68]. In each nation, a substantial amount of water is unaccounted for in the delivery network beforehand it can be billed [55]. For example, in South Africa, closely partial of the treated water (47.4%) meets drinking quality standards but leaks from the supply network. These losses result from pipe leaks and bursts, meter inaccuracies, unauthorized consumption, billing errors, administrative inefficiencies, and unbilled consumption of clean water [7]. In municipal parts of Cameroon, the sum amount of unaccounted water or non-revenue water is about 100,260,000 m³ per annum, representing 52.5% of the entire produced water. Reducing Cameroon's NRW by half could potentially supply about 2 million people [34]. In Malaysia, the amount of unaccounted water is also high, increasing from 4,912 mega liters per day in 2018 to 5,389 MLD in 2022, representing a 10% upsurge in 5 years [6]. Similar to other developing countries, non-revenue water pretenses a substantial contest for water service providers in Ethiopian cities [16]. For instance, the average NRW in many urban areas of Ethiopia exceeds 35% of the amount of water produced by the water service provider [5].

Debre Markos is among the largest towns in Ethiopia and is currently facing a significant water supply shortage. Despite the utility having added several boreholes to its water distribution network, many residents still do not have access to a sufficient amount of potable drinking water. Additionally, there are frequent interruptions in the water delivery network, which have been increasing over time. Residents now receive water only once every two weeks, which is inadequate for their daily activities. This shortage has led to various socio-economic problems for the community. A considerable factor contributing to this issue could be the presence of non-revenue water (NRW) within the water supply system. Several master's dissertations have examined the water provision scheme in Debre Markos, focusing on topics such as water loss [2, 26], and the impact of network expansion [74]. However, a detailed examination of the non-revenue water issue has yet to be conducted. Furthermore, none of the previous studies have assessed or identified the root causes of non-revenue water, resulting in a limited understanding of the main factors contributing to it.

Assessing NRW and identifying its root causes are crucial

for effectively managing NRW. This will enable the water utility to establish appropriate strategies for reducing NRW and accessing the unserved population. Therefore, this research aims to examine NRW and identify its root causes in Debre Markos. The findings will provide valuable insights into the factors contributing to NRW in the water supply system, which are essential for planning effective NRW management strategies. Such strategies will help mitigate NRW, improve water resource management, increase the utility's revenue, and facilitate informed decision-making. Moreover, the outcomes of this research could serve as a benchmark for future researchers and policymakers concerned with NRW management. Additionally, the findings will contribute to the existing literature on water loss management and financial performance in the water utility sector, offering insights for policymakers, water utility managers, and stakeholders to enhance financial sustainability and reduce water losses.

2. Materials and Methods

2.1. Study Area

The study area, Debre Markos town, is located in the Amahara National regional state, within the East Gojjam Administrative Zone, specifically in Gozamin Woreda. It is positioned 265 km from Bahir Dar, the regional capital of the Amahara region, and 300 km from Addis Ababa, the capital city of Ethiopia. The town lies at the intersection of 10° 21' north latitude and 37° 43' east longitude, at an elevation of 2,446 m relative to the mean sea level (Figure 2). According to the 1994 national census, Debre Markos had a total population of 49,297 in 9,617 households, comprising 22,745 men and 26,552 women [23]. The 2007 national census, conducted by the Central Statistical Agency of Ethiopia (CSA), reported a population of 62,497, with 29,921 men and 32,576 women [24]. Based on the latest estimate in 2021, the town's population is approximately 133,810, according to the Mayor's Office. However, billing statistics from the Debre Markos town water utility suggest that the estimated total population exceeds 320,000 (Debre Markos Town water utility service).

The town's climate is classified as subtropical highland, despite its proximity to the Equator. Average minimum and maximum temperatures range from 14°C to 20°C, with a mean annual air temperature of 17.3°C. March and April are the warmest months, with an average temperature of 19.8°C, while July and August are the coldest months, with average temperatures around 15.7°C. The average annual temperature is 17.5°C. Rainfall varies significantly throughout the year, ranging from 15 mm in January to 433 mm in July, serving as the primary factor distinguishing the seasons. In terms of water supply, there are 224,600 active connected customers, of which 91.47% are domestic customers, 7.01% are commercial, 1.45% are institutional, 0.04% are public fountains, and 0.035% are industrial, with no unbilled authorized usage.

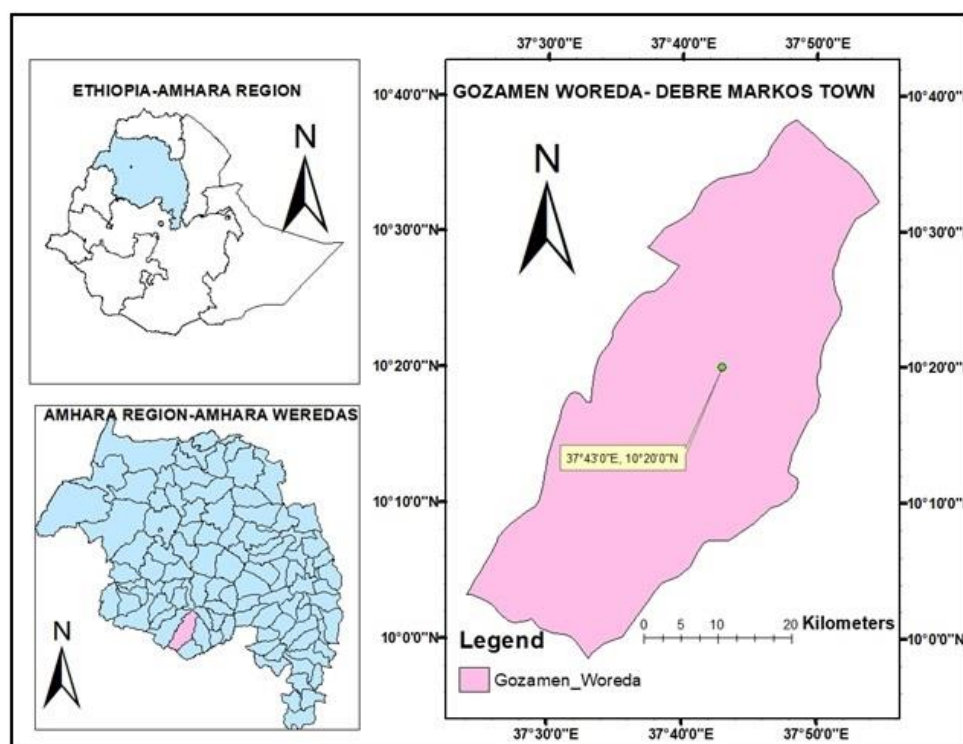


Figure 2. Study area.

2.2. Existing Water Sources

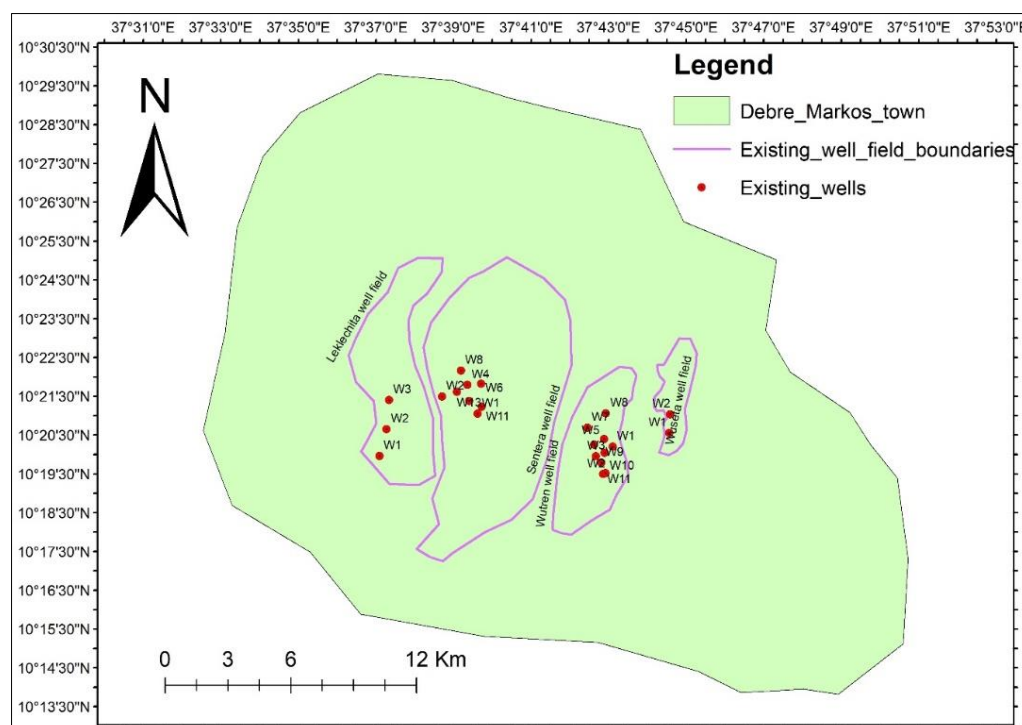


Figure 3. Debre Markos water utility well fields and existing wells.

The present water supply network for Debre Markos town is sourced from four well fields (WF), which contain a total of

twenty-three deep wells (Figure 3). These well fields are known locally as Wutren, Sentera, Wuseta, and Lekilechita.

In the Wutren well field, there are ten existing wells, designated as W1, W2, W3, W5, W6, W7, W8, W9, W10, and W11 (Figure 3). The first five wells were drilled in 1979, while the remaining four were drilled in 1998, 2008, 2015, and 2016, respectively. These wells have a design discharge capacity of 54.98 liters per second (l/sec) and a current discharge rate of 16.68 l/sec. The Sentera well field contains eight wells, labeled W1, W2, W4, W6, W8, W10, W11, and W13 (Figure 3). All wells in this field were drilled in 2000, except for W13, which was drilled in 2011. The total design discharge for the existing wells in Sentera is 120 l/sec, but their current discharge has reduced to 60 l/sec. In the Wuseta well field, there are two existing wells named W1 and W2, which were drilled in 1979 and 1987, respectively. These wells have been allocated to the university and possess a design discharge of 34 l/sec, with a current discharge rate of 23 l/sec. The newest well field, Lekilechita, consists of three wells designated W1, W2, and W3 (Figure 3). These wells were drilled in 2015 and were connected to the water supply system in April 2025. They have both the design and current discharge rates of 37 l/sec. In summary, the existing wells within Debre Markos town's water supply system total eighteen deep wells, with an overall design discharge capacity of 345 l/sec and a current discharge rate of 45 l/sec.

2.3. Data Collection

The research was carried out from November 2024 to May 2025. For this research, qualitative and quantitative data were collected from various sources. The quantitative data included secondary information such as water production, billing data, and water tariff rates, all sourced from the database of the Debre Markos town water supply and sewerage service office and desk review. Additionally, relevant published journals obtained were utilized in the research. To gather qualitative data on the water utility's awareness of NRW components, the impacts of NRW on the water utility and its customers, besides the root causes of NRW, the researcher conducted semi-structured key informative interviews using open-ended and closed questions and field observations. These methods aimed to gather insights from key informants regarding how water was being lost, where the losses occurred, and the underlying reasons for these losses. For the key informative interviews, purposive sampling was employed. A total of 30 individuals were interviewed, comprising 4 members from the management team, 9 water meter readers and billing data collectors, 3 members from the electro-mechanical team, 4 workers from the water extension, rehabilitation, and construction team, and 10 individuals from the water production, distribution, and loss control team.

The data collected were analyzed using MS Excel 2013. Qualitative statistics, such as percentages and means, were utilized to interpret the results. The analyzed data were presented and interpreted using graphical methods. Additionally, Google Earth Pro and ArcGIS 10.1 were employed to map the

study area and the existing wells.

2.4. Non-Revenue Water Estimation

The NRW for the town was calculated by comparing the annual volume of water distributed through the system to the volume of water billed, which was obtained from individual customer meter readings. Each month, billing data is collected, and the totals for monthly water tariffs are aggregated to evaluate the annual billed water. Consequently, the annual NRW is demarcated as the change between the total annual water production and the total annual billed water. This value was estimated using Equation (1) [11, 29]. Additionally, the percentage of NRW able to be calculated using Equation (2) [11, 34, 73].

$$\text{NRW} = \text{AWP} - \text{BAC} \quad (1)$$

Where, NRW is the non-revenue water; AWP is annual water production and BAC is billed annual consumption.

$$\text{NRW (\%)} = \frac{\text{AWP} - \text{BAC}}{\text{AWP}} * 100 \quad (2)$$

Where, NRW is the non-revenue water in %; AWP is annual water production in (m³/year), and BAC is billed Annual authorized consumption in (m³/year).

2.5. Data Availability and Reliability

The quantitative secondary data regarding water production and consumption is sourced from the water utility database. Water ingesting data is collected monthly using a technology called water meter reading, conducted by data collectors and managed by database professionals. Additionally, the yield of each existing well is recorded monthly by data collectors, but the reading is not carried out using a mobile technology like water consumption and managed by data base professionals. The researcher validated and calibrated the reliability of the secondary data by assessing how and when it was collected and managed through key informative interviews. It was confirmed that all the secondary data used in this research were gathered and managed effectively, ensuring their reliability. However, the water service provider has not yet implemented the latest water meter technology in the water supply system, which may lead to certain uncertainties in the data regarding water production and billed water usage in the town.

3. Results and Discussion

3.1. NRW Estimation

The non-revenue water (NRW) in the studied years ranged from 26.57% to 43.68%, with an average value of 35.94%

(Figure 4). This result is lower than findings reported by Dinku [26] and Abebaw [2], both of which indicated NRW levels exceeding 40%. In contrast, research by Yilkal [74] reported an average NRW of 29.65%, significantly lower than the findings of this study. The result was also comparable to those observed in several sub-Saharan African countries, where NRW varies from 15.86% in Niger to 61.80% in Nigeria, with an average value of 39.72% [34]. However, the current study's finding exceed the global NRW approximations of 30% to 35% reported by Liemberger and Wyatt [40] and Stankovich et al. [64]. Many nations, along with governmental and non-governmental institutions, have set maximum limits for NRW in water supply systems. For instance, the World Bank recommends that NRW should be 25% or lower. In emerging nations, the NRW threshold for well-performing water utilities is estimated to be around 23% [63] with 15% in North America and 13% in Western Europe [21]. None of the years studied in this research met these threshold values.

A similar finding was observed in Cameroon, where NRW values are two times higher than the threshold for emerging states and three times higher than the thresholds in North America and Western Europe. The average NRW in this study aligns with the averages reported for the water supply systems in Addis Ababa, Adama, Mekelle, Dire Dawa, and Dangila in Ethiopia. According to Adem et al. [5] and Amogne [11], the average NRW for these cities exceeds 35% of the freshwater produced - significantly higher than the upper limit of 25% suggested by the World Bank. Research by Abueltayef et al. [3] estimated NRW in Palestine to be 33%, lower than the cumulative result of this study at 35.94%. In Singapore, Ismail and Puad [33] reported water loss levels ranging from approximately 40% to 50%, which are considered high by international standards and higher than the average value of this

research. Additionally, a study conducted in the Accra East Region of Ghana from January 2015 to June 2019 showed an average NRW of 40.3%, which far exceeds the finding of this research and the 25% threshold established by the World Bank for developing economies and greater than the cumulative result of this study [61].

According to the Asian Development Bank [15] report, the average NRW for Asia is 28.7%, comprising 21.4% physical losses and 7.3% commercial losses, indicating the lower value of NRW in this research. Research conducted in a similar town from 2007 to 2013 indicated total water loss varying from 32.70% to 35.80%: 2007 (34.30%), 2008 (35.0%), 2009 (35.80%), 2010 (35.10%), 2011 (33.20%), 2012 (32.70%), and 2013 (34.60%), with an overall average of 34.4% [1]. This finding is nearly similar to the finding of this study, which was 35.94%. Reports indicated that the average non-revenue rate in Israel was 12.9% [17]. The Dhaka water supply system experienced total system losses of 50.49%, 55.54%, and 49.86% during the years 2002–2003, 2003–2004, and 2004–2005, with an average water loss of 51.96% [29]. The NRW trends in the target town over the studied years showed fluctuations: it increased from 2011 to 2012, decreased from 2012 to 2013, and increased from 2013 to 2014. After another decrease from 2014 to 2015, it once again increased from 2015 to 2018, remained the same in 2019 and 2020, increased from 2020 to 2021, then decreased from 2021 to 2022, and finally increased from 2022 to 2024 (Figure 4). This demonstrates a fluctuating trend in NRW, with increases and decreases, except for the stable period from 2019 to 2020 (Figure 4). The decreasing trend could be attributed to the implementation of integrated passive leakage control and water theft prevention measures by the utility, while the increasing trend may reflect a lack of attention or a weakening of these organized controls.

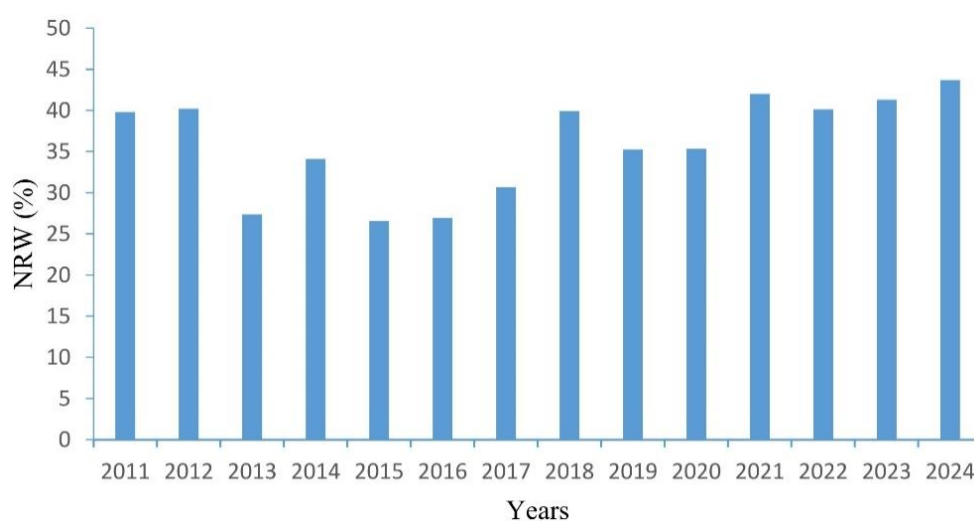


Figure 4. Non-revenue water in Debre Markos town (2011 to 2024).

3.2. NRW Cost Estimation and Its Impacts

The NRW value for the Debre Markos water utility was estimated based on an average cost of 61 Ethiopian Birr (ETB) per cubic meter. Between 2011 and 2024, the NRW value fluctuated between 17,736,360 ETB and 55,333,867 ETB, with an average value of 33,900,575 ETB or 273,391.73 USD (Figure 5). Figure 5 indicates that the water service provider (Debre Markos town water supply and sewerage service office) has consistently lost significant revenue each year, resulting in a profoundly negative financial impact on the utility. The analysis indicates that if the mean NRW were reduced by 80%, an additional 20,302 people could access treated water daily without requiring further capital investment, assuming a per capita usage of 60 liters per day. Moreover, this reduction could save the utility approximately 2,260,038.32 ETB or 18,226.12 USD each month.

Key informants highlighted several negative impacts of NRW on the utility, including high capital and operational expenses, water infrastructure insecurity, project delays, poor well field management, difficulties in reducing NRW, environmental impacts, inadequate well development, lack of

water safety and planning, hindered water extension and construction, diminished public trust, poor data management, and organizational challenges. Collectively, these issues have resulted in substantial revenue loss and increased costs for water distribution, rendering the utility inefficient. Additionally, the key informants noted that NRW significantly affects customers, leading to intermittent water supply, which poses serious health risks, incurs additional expenses, disrupts businesses and production, causes customer dissatisfaction, and elevates psychological stress. These challenges contribute to unnecessarily high tariffs and disproportionately impact girls and women, creating a burden for them. Consequently, NRW undermines daily operational performance and serves as an obstacle to sustainable development.

Overall, NRW compromises the general management and customer perception of the utility. According to Santos [58], NRW presents considerable challenges for water service providers, affecting both sustainable access to potable water and the monetary viability of their operations. Another researchers noted that no business can thrive for long if it loses a significant portion of its marketable product, which is precisely the reality many water utilities face [15].

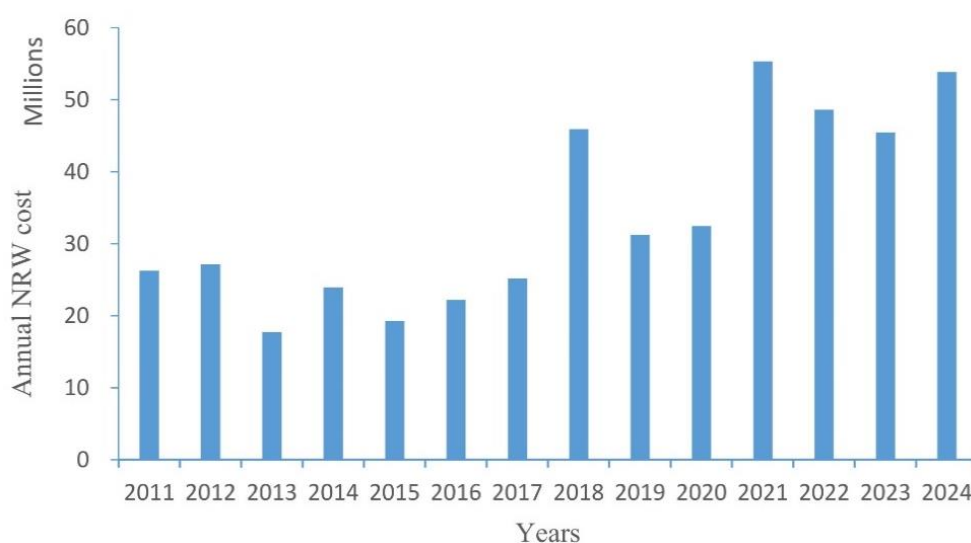


Figure 5. Trends of revenue loss in Debre Markos water utility (2011 to 2024).

3.3. Root Causes of NRW in the Water Utility

3.3.1. Lack of Awareness for NRW Components

Understanding the components of Non-Revenue Water (NRW) is essential for grasping its underlying nature, identifying root causes, and planning effective reduction strategies. According to Science et al. [60], the important to emerging a management strategy for NRW is to get a deeper sympathetic of the causes behind it and the issues that affect its constituents. This insight allows for the modernization of techniques

and procedures tailored to the specific characteristics of the water supply system and local factors, enabling a targeted approach to each component of NRW. Despite the significance of understanding the scientific terminology associated with NRW, the utility lacks a clear awareness and detailed information about its components. Currently, the utility defines NRW primarily in terms of leakage (referred to in Amharic as “fisash”) and theft (known in Amharic as “sirqot”). According to Finance [32], the terminology used can determine which types of non-revenue water are included in the metric.

A significant majority of respondents (93.33%) did not

have a separate awareness of the components of NRW, while only 6.67% of the key informants had a separate awareness for the scientific terminologies of NRW (Figure 6). Those who expressed awareness identified theft and leakage as the components of NRW. However, the current understanding of NRW includes three key components: physical or real loss, apparent or commercial loss, and unbilled authorized consumption. Respondents were asked to identify the specific reasons of NRW, and they noted that the key drivers of physical losses, which they referred to as leakage, include infrastructure aging, inadequate infrastructure development, poor design (especially concerning the dimensions of water supply components), and a lack of preventive upkeep and looking after. Additionally, respondents identified the primary drivers of apparent losses, known as theft, as illegal connections. These connections often involve individuals or professionals attaching their own lines to the water supply before the meter, typically without the utility's permission. This practice is particularly common among businesses such as pension houses and hotels, which have a high customer volume. Furthermore, respondents highlighted that another mode of theft in the water supply system is associated with construction sites, where connections are made without a water meter or the utility's approval. Overall, the main root cause of commercial losses stems from these illegal connections at construction sites.

3.3.2. Unbilled Authorized Consumption

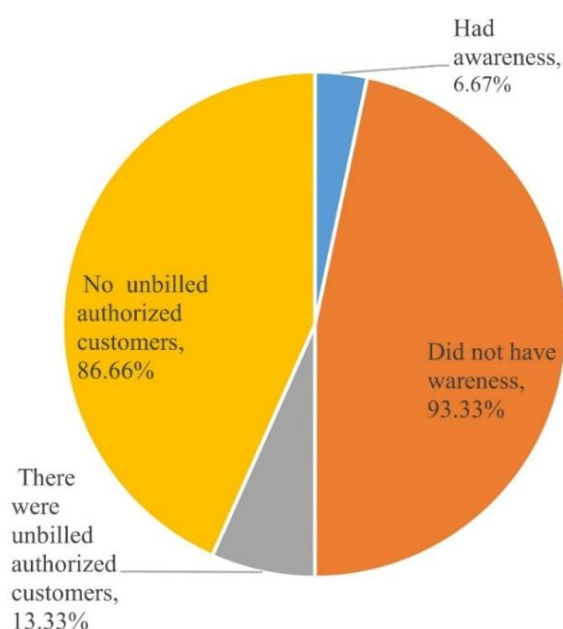


Figure 6. Respondents' reaction to unbilled authorized consumption and NRW components awareness.

Unbilled authorized consumption refers to the legal use of water that is not billed, resulting in significant revenue losses for water utilities. About 86.66% of respondents said that

unpaid official use does not exist in the water supply system, suggesting that no customers are permitted to use water without payment (Figure 6). These respondents said that there are no customers allowed to use water in the water distribution scheme without payment. On the other hand, 13.33% of the respondents believe that there are unbilled authorized customers in the water supply system (Figure 6). This respondents considered that those customers, which get water online as unbilled authorized customers. However, during field surveys, the researcher confirmed that health centers in the town do receive water online but are billed for the amount they consumed.

3.3.3. Leakage

Water leakage in a water distribution network refers to the accidental escape of water from pipes, fittings, or storage tanks, leading to water loss. This loss can occur due to various factors, including corrosion, aging, damage, or faulty connections [39]. According to Bhagat et al. [18], leakage represents water that is neither distributed to clientele nor used for legitimate purposes, resulting in wasted resources and increased costs for the utility. Respondents identified leakage as the primary cause of NRW in the town's water provision scheme. They mentioned that several factors attributed this issue, including aging infrastructure, infrastructure development, pipe bursts, reservoir overflow, the excellence of water supply components, the considerable distance of master control points, a lack of preventive maintenance and repair, a low number of gate valves, and the absence of district metered areas.

During field observations, the researcher confirmed that these issues significantly contributed to increased leakage. For instance, a damaged PVC pipe in a sub-branch community line was noted due to infrastructure development, resulting in a substantial water leak (Figure 7a). Additionally, a large leak from an iron pipe was observed, caused by the detachment of an old iron pipe and the replacement of an iron elbow (Figure 7b). Another significant leak was noted from an HDPE main pipe due to poor connections (Figure 7c). It was observed that these leaks persisted for over 24 hours, from the start to the end of the shift, without maintenance or repair, leading to a significant loss of treated water and, consequently, revenue. The resulting leakage contributed to large runoff during heavy rainfall (Figure 7d).

Respondents stated that leakage related to reservoir overflow was minimal, as there was no reserve storage due to high demand in the town. The water pumped from the wells flows into the reservoir and is immediately distributed to meet this demand. They also linked pipe bursts to design flaws, pressure issues, and aging infrastructure, noting that they frequently occur in small diameter pipes, high-pressure areas, and regions with old installations. Furthermore, the respondents highlighted that the considerable distance of master control points from distribution zones complicates the response to leaks. The time taken to detect a loss and reach the

master control point is lengthy, resulting in higher water losses. According to research conducted by Karema et al. [37],

leakage and the poor quality of underground assets are major contributors to NRW.



Figure 7. Leakage due to various factors: (a) damage of PVC pipe and followed by leakage due to collider development, (b) leakage due to detachment of aged iron pipe and rehabilitated iron elbow, (c) leakage due to poor HDPE fitting, and (d) flow of treated water over the earth surface.

3.3.4. Theft

In a water distribution system, water robbery refers to the illegal usage of water as of the piped network without proper payment or permission [48]. This includes failing to pay the amounts specified by local water regulations, such as tampering with meters or installing unauthorized connections to the water distribution systems [14, 62]. Key informants said that water stealing is a significant factor causing to NRW in the water supply system of Debre Markos town. They reported two primary methods of theft within the town's water supply system: the first involves illegally connecting a customer's line to the community line, and the second consists of connecting a customer's line before the water passes through the meter. Informants highlighted that these illegal activities are primarily conducted by business centers rather than individuals or domestic customers. During field observations, the researcher confirmed the occurrence of theft in these two modes within the water supply system. According to research conducted by Karema et al. [37], theft is identified as the main cause of NRW. The respondents noted that the challenge in

addressing theft arises from collusion between corrupt workers within the utility, business centers, and the plumbers used by these centers.

3.3.5. Data Handling Practice

Proper data handling practices are indispensable for dipping NRW within the water supply system. In contrast, poor data handling practices that lead to errors can exacerbate the NRW issue. These errors, often categorized as apparent losses, can arise during meter reading, data entry, or billing processes, resulting in inaccurate water consumption accounting. Such inaccuracies are able to result in financial losses and operational inefficiencies. According to a survey, about 26.67% of respondents viewed the water utility's data handling practices positively (Figure 8). These key informants noted that the utility employs a system-based approach to manage billing data. For example, water bill collectors utilize mobile reading technology to collect data and automatically enter it into the water billing system, minimizing the probability of data entry errors. The researcher confirmed this practice through field and office observations.

However, the majority of respondents (73.33%) believed that the water utility did not maintain good data handling practices (Figure 8). This group expressed concerns that, at times, collectors rely on previous billing data under unsuitable conditions. They also mentioned that during winter, algae can develop in water meters, which may lead to under-reading and meter failures. Additionally, unlike the billing data that is managed through a system, the management of water production data is conducted manually. This manual approach can result in errors in reading, registration, and management of data. The researcher confirmed during the office and field survey that water production data management is carried out manually, contributing to poor data handling practices, which in turn can lead to NRW issues. Key informants indicated there is a significant training gap for data management staff, both for those handling billing and water production data. Training is provided only upon joining the water utility, with no ongoing training available for these individuals. This lack of continuous training could negatively affect NRW management.

As the complexity of NRW management increases and technology continues to go forward, it is crucial to implement ongoing training programs for data management staff. This will help them understand the complexities of NRW monitoring and adapt to the latest technologies in the field.

3.3.6. Preventive Maintenance and Repair

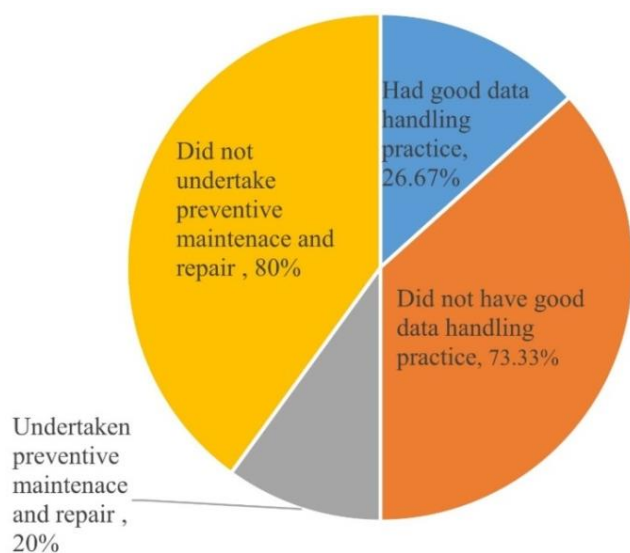


Figure 8. Respondent's reaction in data handling, preventive maintenance and repair.

Poor maintenance and repair of water distribution systems directly contribute to higher levels of non-revenue water (NRW), which is water that is produced but not billed to customers. This situation can arise from leaks, bursts, and other infrastructure failures due to a lack of preventative maintenance. Inadequate maintenance also increases the risk

of aging infrastructure failing, which leads to more leaks and breaks [67]. Approximately 80% of the respondents said that the water utility did not conduct preventive upkeep and repair (Figure 8). They noted that the utility only performs maintenance and repair when a failure in the water supply system occurs. The researcher confirmed this observation, noting that maintenance and repair are only addressed after a failure, which further increases the NRW in the system. Additionally, a significant lag time exists between the detection of a failure and the initiation of remedial action, leading to further water loss. Conversely, 20% of the respondents stated that the water utility does engage in preventive maintenance and repair (Figure 8). These respondents believed that the field observations conducted by the utility every two weeks qualify as preventive maintenance and repair.

3.3.7. Water Meter Inaccuracy

Inaccurate water meters have a significant impact on non-revenue water (NRW) within a water supply system. Accurate meters are essential for fairly billing customers, identifying leaks, and effectively managing water demand [12]. Meters that under-register consumption result in substantial income loss for water utilities and increase the volume of water lost before it reaches customers, further exacerbating NRW issues [31]. Respondents reacted that there are not enough water meters in the water supply system beyond those located at billing or customer points. They noted that the existing meters at billing points have been in use for several years, resulting in inaccuracies where they sometimes fail to measure the water passing through. The respondents also mentioned that the water utility still relies on single jet water meters, which are less accurate compared to the newer types of water meters used globally today. The researcher confirmed during field observations that the water utility employs single-jet water meters, which were installed several years ago and have not yet been rehabilitated. Key informants reported that they frequently receive meter readings below the minimum standard. However, when they recalibrated the meters, the readings were above the minimum standard, indicating an issue of under-registration. Additionally, the informants mentioned that they often encountered stuck water meters during readings, which contributed to significant non-revenue water (NRW). They explained that the water utility replaces these meters when such failures are encountered.

3.3.8. Poor Pressure Management

Pressure control is among the furthestmost crucial water demand administration interferences that a water service provider can implement to decrease leak [43]. According to Ore [52], managing pressure in municipal water delivery systems is a key strategy for significantly decreasing water loss. Systems [65] also notes that inadequate pressure management in a water supply system directly contributes to higher leakage rates, resulting in substantial water loss. High

pressure increases the flow rate through existing leaks, while fluctuations in pressure can worsen the situation [75] and even lead to new failures (Figure 9b). By controlling and reducing pressure, particularly during periods of low demand, water utilities can minimize both leakage and non-revenue water. Conversely, low pressure results in decreased flow rates through existing leaks (Figure 9a). Key informants have indicated that the water utility currently employs a poor pressure management mechanism. According to respondents, the utility manages pressure through shift scheduling, providing water to customers at different elevations at various times while conducting infrequent field observations at high-pressure points in the system, indicating a poor pressure management mechanism.

The researcher confirmed that the utility supplies water to

customers at high-pressure points at one time and to those at low-pressure points at another, which is a very inadequate approach to pressure management. Furthermore, the researcher did not observe the installation of pressure-reducing valves (PRVs) or the use of variable speed pumps (VSPs) in the water supply network where high pressure exists. Additionally, there were no quantitative reports available on the pressures in the water provision scheme, and no established requirements for minimum and maximum pressure levels delivered to customers, further contributing to poor pressure management. According to Ore [52] and Al-washali [10], achieving a uniform distribution of pressure and reducing excessive pressure in the water network throughout the day can be accomplished by installing pressure-reducing valves (PRVs) and variable speed pumps (VSPs).



Figure 9. Leakage at various pressure situations (a) leak at low pressure and (b) leak at high pressure.

3.3.9. Pipe Aging

Pipe leakage is regarded as a significant issue by numerous water establishments, together from an ecological perspective and because of the associated costs incurred from over-designing sewer schemes and the purification of extra drinkable water lost through leakage [19]. One major factor affecting the extent of water loss, particularly physical loss, is the age of the pipes. According to Sadeghioon et al. [57], older pipes are more likely to experience greater water loss through leakage compared to newly installed pipes. Respondents have said that many pipelines in the water delivery network are quite old, more than 30 years. Key informants estimate that approximately 80% of the pipes were installed over 30 years ago, including ductile cast iron (DCI), polyvinyl chloride (PVC), and galvanized iron (GI) pipes. They also mentioned that there are pipes, some of which are very old, running through densely populated areas where maintenance and repairs are difficult as a result of the built-up surroundings, leading to significant leakage.

Field observations by the researcher revealed a substantial amount of water leaking from aged iron pipes within the water

supply system (Figure 10). Abebaw [2] estimates that more than 57.74% of the pipe system was installed over 25 years ago. This includes DCI, PVC, and steel pipes, with the oldest pipes primarily situated in the central part of the town and in densely populated areas. All these pipes are vulnerable to humiliation over time due to operational factors, environmental conditions, and general wear and tear, which consequences in increased network leakage. Hence, it is vital to replace older mains to reduce leakage [2].



Figure 10. NRW due to iron pipe aging in the water supply system.

3.3.10. Infrastructure Development

According to the respondents, there is significant water leakage, which they define in terms of physical loss due to infrastructure development such as collider construction, building projects, and improvements to ditches and roads. Many existing pipeline installations in the town did not adhere to modern urban planning standards, resulting in considerable damage from these developments. The respondents noted that the existing streets (pista) and earthen ditches in the town have undergone extensive upgrades. During this process, numerous water pipelines laid alongside the roads have been damaged, leading to high leakage rates - particularly at night when no one is monitoring the situation. Field surveys confirmed that the transformation of the streets from earthen ditches to lined ditches has caused significant damage to the existing pipelines, resulting in substantial water loss when leaks occur (Figure 11a).

Furthermore, urban development is rapidly expanding from the town center to the periphery. This expansion often replaces lower-quality, unplanned housing with taller, multi-story buildings. During the construction of these new structures, existing water infrastructure (pipes) has frequently been damaged, contributing to further water loss. Field observations indicated that water supply pipelines made of HDPE and PVC were compromised due to excavation for multi-story building foundations, impacting the overall water supply system (Figure 11b). Key informants mentioned that collider development, which commenced this year (2024), involves widening sidewalks where the water pipes are located. This ongoing construction has already resulted in significant damage to previously installed pipes, causing substantial water leakage.

These circumstances can lead to not only increased leaks but also under-registering meters and other inefficiencies in water delivery. Collectively, these human activities are exacerbating the issue of leak in various ways. However, the key informants also suggested that while collider development has led to considerable revenue loss for the water utility, it could ultimately benefit future reductions in non-revenue water (NRW) for two reasons: (1) it provides an opportunity to install pipes along improved routes, and (2) it allows for the installation of advanced piping technology that is better at reducing NRW than previous systems.



(a)



(b)

Figure 11. Damaged water supply pipes due to various reasons: (a) damaged PVC pipe due to ditch upgrading, and (b) exposed and damaged HDPE and PVC pipes due to building foundation excavation.

4. Conclusion

This research aimed to examine non-revenue water (NRW) and identify its root causes in the town of Debre Markos. The results indicated that the NRW ranged from 30.57% to 43.68% over the studied years, with an average value of 35.94%. This average is comparable to that of most towns in Ethiopia and several countries in sub-Saharan Africa, although it is higher than the estimated global NRW. The findings also revealed that the NRW values for all studied years were above the threshold limits set by the World Bank (25%), Western Europe (13%), and North America (15%). Additionally, the research found that if the average NRW were reduced by 80%, approximately 20,302 people could gain access to treated water without requiring additional capital investment, resulting in a monthly saving of 2,260,038.32 ETB. Such a reduction would help mitigate the negative impacts of NRW on both the water utility and its customers.

The study identified several root causes of NRW in the water supply system, including a lack of awareness regarding NRW terminology, leaks, theft, aging infrastructure, developments in infrastructure, poor quality of water supply components, long distances to master control points, insufficient preventive maintenance and repair, a low number of gate valves, absence of district metered areas, ineffective pressure management, outdated water meter technology, inadequate data handling practices, and inaccuracies in water meters. To address these issues, the water utility should enhance its understanding of NRW terminology and subsequently plan and implement appropriate reduction strategies. Furthermore, it is crucial for the utility to adopt an instrument-based investigation and monitoring mechanism, supported by a legal framework, to recover lost treated water and minimize its negative impacts. Finally, utilizing the latest technologies in water supply components and prioritizing preventive maintenance and repair are essential to reduce NRW in the water supply system.

Abbreviations

NRW	Non-Revenue Water
MLD	Mega Liters per Day
CSA	Central Statistical Agency of Ethiopia
AWP	Annual Water Production
BAC	Billed Annual Consumption
BAC	Billed Authorized Consumption
ETB	Ethiopian Birr
USD	United States Dollar
HDPE	High-Density Polyethylene
PVC	Polyvinyl Chloride
PRVs	Pressure Reducing Valves
VSPs	Variable Speed Pumps
DCI	Ductile Cast Iron
GI	Galvanized Iron

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Author Contributions

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Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Conflicts of Interest

The author declares no conflicts of interest.

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