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College of Business Administration
Department of Management and Marketing**

Impact of Smart Metering on Water Losses Reduction: Case Study of the Kingdom of Bahrain

This thesis is submitted in partial fulfilment of the requirements for the
degree in Master of Business Administration

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- ☐ Without making any changes to the thesis.
- ☒ After making the modifications attached with this decision.

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Abstract

Targeting to reduce the gap between produced and invoiced water, the Kingdom of Bahrain has implemented a smart water metering system. Smart water metering is intended to provide more accurate (than conventional meters), timely automatic meter readings, and reduce the apparent and real losses in the network. The study's objective is to investigate the strategies developed and practices by the Kingdom of Bahrain to limit water losses, study the influence of smart metering on water losses, and quantify the actual financial impact of smart metering. Secondary data was used to test the research hypotheses and answer the research questions statically. The study includes qualitative data gathered about the NRW control strategies adopted by the Kingdom of Bahrain, and statistical testing of NRW's historical data. Added to that, the study involves a case study of NRW in 32 DMAs, to investigate the real impact of smart meters. The study revealed that smart metering affects the water revenue increase in Bahrain. A model was developed to predict the NRW ratio. The study findings can be used by decision-makers to quantify the predicted impact of NRW factors and assess in developing programs that focus on these factors. Further implication of study results is encouraging the water utility to continue the smart meters' replacement program.

Keywords: Smart Metering, DMA, NRW, Water Management, Kingdom of Bahrain

Dedication

I dedicate this work to my beloved family, friends and colleagues for
their endless love and support.

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The success and final outcome of this thesis would not have been possible without the active guidance, help, and encouragement of many people. At this junction, I would like to extend my sincere thanks to all of them.

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List of Abbreviations

AC:	Authorized Consumption
AL:	Apparent Losses
ALC:	Active Leakage Control
ALI:	Apparent Losses Index
AMI:	Advanced Metering Infrastructure
AMR:	Automatic Meter Reading
AWWA:	American Water Works Association
BC:	Billed Authorised Consumption
BDHE:	data handling errors
BL:	Background Losses
CAAL:	Current Annual Apparent Losses
CARL :	Current Annual Real Losses
DAVL:	Average Leak Duration
DMA:	District Metered Area
EMAG:	Electromagnetic
EWA:	Electricity and Water Authority
GCC:	Gulf Cooperation Council
ILI:	Infrastructure Leakage Index

IWA:	International Water Association
KPIs:	Key Performance Indicators
LLI:	Linear Leakage Index
Lm:	length of the mains
LNF:	Legitimate Night Consumption
Lp :	total length of the house connection between the edge of the street and customer meter
MED:	Multi-Effect Desalination
MIG:	Million Imperial Gallons
MI:	Customer meter inaccuracies
MNF:	Minimum Night Flow
MPE:	Maximum Permissible Errors
MSF:	Multi-Stage Flashing
N:	leakage exponent
Nc:	number of service connections
NDF:	Night-Day Factor
NNF:	Net Night Flow
NRW:	Non-Revenue Water
Pavg :	average operating pressure of the network
Pi:	average pressure during the day hours
PI:	Performance Indicators
PLC:	Power Line Communication
Pmin:	average pressure during the minimum night hour
PRV:	Pressure Reducing Valves
Q1:	minimum flow rate
Q2:	transitional flow rate
Q3:	permanent flow rate
Q4:	overload flow rate
QAVL:	Average Leak Flow Rate

qcap:	per capita water consumed
Qex :	exfiltration volume
Qin :	infiltration volume
Qind:	industrial and commercial wastewater discharge
Qww:	WWTP inflow volume
RAAL:	References Annual Apparent Losses
RB:	Reported Burst
RF:	Radio Frequency
RL:	Real Losses
RO:	Reverse Osmosis
RW:	Revenue Water
SDG:	Sustainable Development Goals
SIV:	Supply Input Volume
TAVL:	Total Annual Volume of Leakage
UAC:	Unbilled Authorized Consumption
UARL:	Unavoidable Annual Real Losses
UC:	Unauthorized consumption
UL:	Unavoidable Background Leak
WL:	Water Losses
WRI:	World Resources Institute
WWTP:	Waste Water Treatment Plant

Chapter One: Introduction of the Study

1.1 Introduction

The Kingdom of Bahrain is composed of over 80 artificial islands. It is located in the Arabian Gulf, situated between the north-eastern coast of Saudi Arabia and Qatar. It is the smallest country in the Gulf Cooperation Council (GCC), with a total area of about 780 km² and a relatively high population of 1,701,575 inhabitants. Figure (1-1) shows the 2008 - August 2020. The Kingdom is considered one of the most densely populated countries worldwide (about 2,239 inhabitants per km²). (Bahrain Authority for Culture & Antiquities, 2018; Worldometer, 2020)

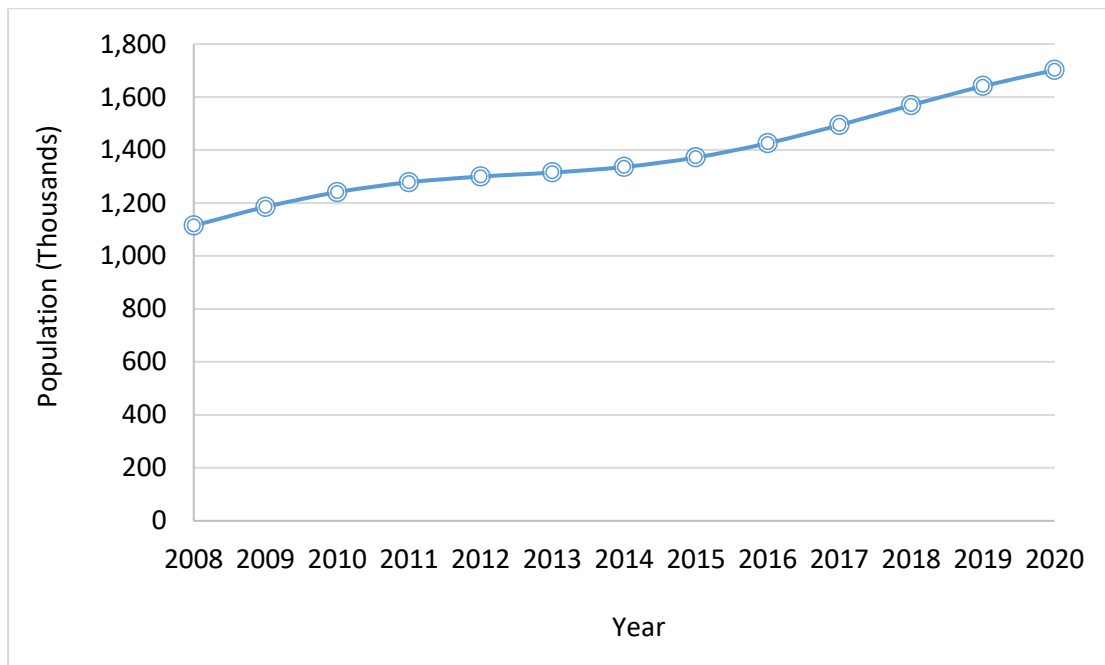


Figure (1-1): Population of Kingdom of Bahrain in Years 2008-August 2020 (source: Worldometer, 2020)

It is located in an arid region, where harsh drought environment, the water in the Kingdom of Bahrain is ultimately precious. This is referred to the lack of surface water resources and renewable groundwater resources, as the mean evaporation exceeds rainfall. (Al Noaimi, 2005; Al Rashed & Sherif, 2000) Added to that, water demand is continuously increasing due

to the increase in population and accelerated socio-economic development which result in limitation of the fresh ground water resources.

To substitute water deficiency and meet the water demand, the Kingdom has used desalination technologies to produce potable water since the mid-1970s and has put policies to reuse the treated municipal wastewater for agriculture and landscaping since the late 1990s. A study conducted by World Resources Institute (WRI) announced that Bahrain had been listed among the ten top countries facing a water crisis by 2040. That is explained due to low water security as it depends on the desalination of sea water. (Ahmad, 2019)

The water supply system in the Kingdom consists of three stages: production, transmission and distribution. In the production stage, desalination technologies are used through five plants (there are independent), namely: Sitra Power and Water Station, Ras Abu Jarjur, Al Dur Company, ALBA and Hidd Power Company. There are two main technologies for desalinating water: thermal evaporation (by mean of Multi-Stage Flashing (MSF) and Multi-Effect Desalination (MED)) and membrane separation (by mean of Reverse Osmosis (RO)). The total water production capacity is 189 million gallons per day. Table (1-1) shows the production capacity per plant in Bahrain. (Marzooq et al., 2018) Furthermore, the government has set plans to increase the production capacity by 72% by 2030, as shown in Table (1-1). (Water Infrastructure in Bahrain, 2020)

Table (1-1): Water Production Capacity in Bahrain (Source: Water Infrastructure in Bahrain, 2020)

Plant	Year of Operation	Ownership	Production Capacity (MG per day)
Sitra	1975	Government	25

Plant	Year of Operation	Ownership	Production Capacity (MG per day)
Ras abu Jarjur	1984	Government	16.5
Hidd	1999	Private Sector	90
AlBA	2001	Private Sector	9.5
Al Dur – Phase1	2012	Private Sector	48
Al Dur – Phase2	2020/2021	Private Sector	50
Ras Abu Jarjur	Planned 2023/2024	Private Sector	50
North City	Planned 2028	Private Sector	30
Sitra	Planned 2029	Private Sector	25

The water is distributed to the distribution network through a transmission network consisting of an approximately 495 km pipeline and 143 tanks with a storage capacity of 568 Million Imperial Gallons (MIG). Thus, the water distribution network comprises of 3,082 km main pipeline and a 2,908 km pipeline that serves 374,808 customer accounts.

The supplied water triggers various usage, namely; domestic, commercial and industrial. Figure (1-2) demonstrates the water consumption in Bahrain during the period 2000-2018. Obviously, the water cubic meters consumed has increased drastically over the period which can be explained due to increase of population and the economic change in the Kingdom.

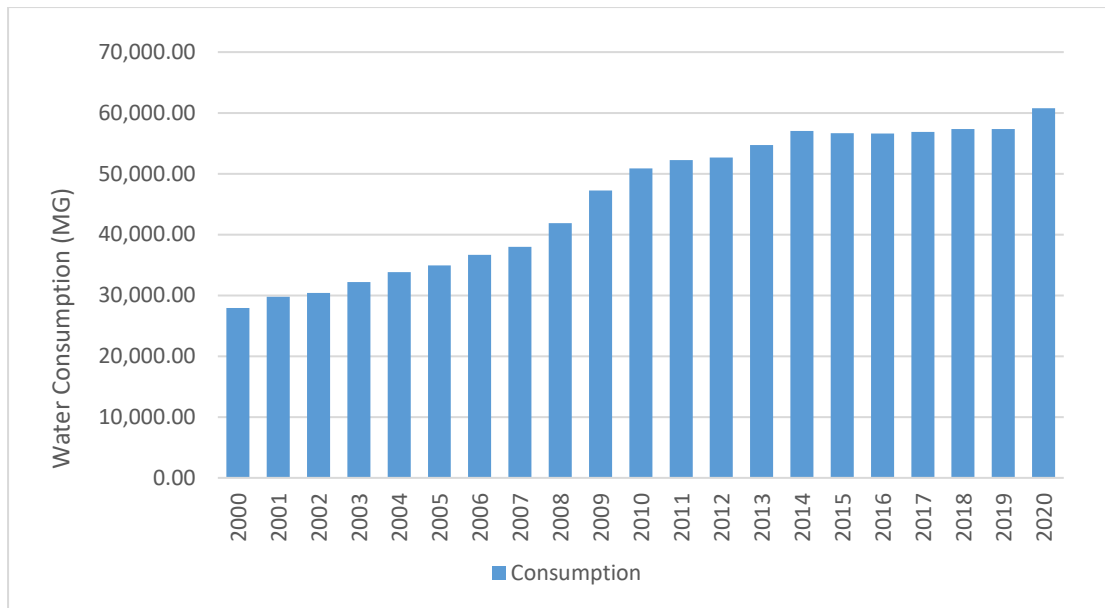


Figure (1-2): Yearly Water Consumption in Bahrain (Source: EWA Statistics)

Figure (1-3) illustrates the distribution of water among the main consuming sectors in 2018. As recorded by Electricity & Water Authority (EWA), the domestic sector is the major consumer of water with a consumption of 143 million m³, followed by the commercial and the industrial sectors which consumed 37.1 million m³ and 5.7 million m³, respectively.

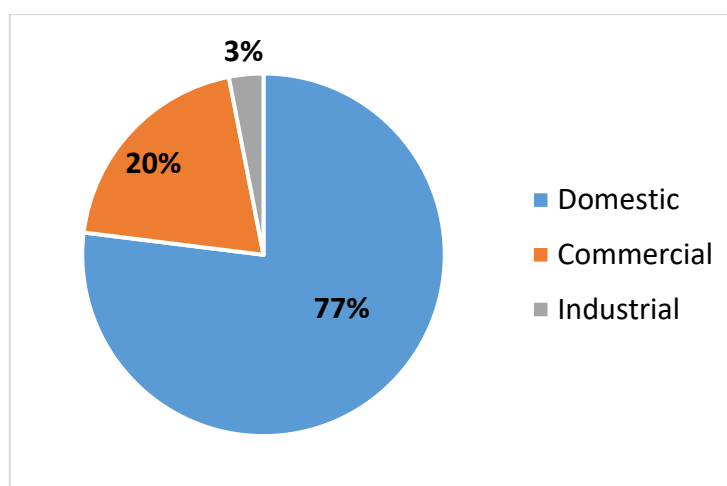


Figure (1-3): Distribution of Water Consumption by Sector in 2018 (Source: EWA Statistics)

Water consumption is charged based on a block-rate water supply tariff structure. The water tariff in the Kingdom of Bahrain was established in 1986 (Ministerial Order No. 3 for the year 1985) and modified in 1992 and 2013. Achieving the Kingdom's economic vision 2030 concerning reduction of costs and avoidance of scarce resources overconsumption, the subsidies for water and electricity have been revised and the tariffs have been reformed. In March 2016, the Electricity and Water Authority of the Kingdom of Bahrain announced the new water supply tariff. (EWA, 2018). The current tariffs for usage of domestic and non-domestic sectors (commercial and industrial) are shown in Table (1-2). The block-rates for domestic Bahraini first accounts remained as before March 2016, while the other categories' tariffs were increased to BD 0.750 regardless of consumption blocks. That tariff is based on the cost of producing and supplying the water to consumers, which is calculated as BD 0.750.

Table (1-2): Water Supply Tariff in Kingdom of Bahrain (Source: EWA Website)

Consumption Units	Price (BD)
Domestic for Bahraini National, First Account (Subsidized)	
First 60	0.025
61-100	0.080
Above 100	0.200
Domestic for Bahraini National, Second Account, Non-Bahraini National Accounts	
First 60	0.750
61-100	0.750
Above 100	0.750
Non-Domestic Account	
First 450	0.750
451-1000	0.750
Above 1000	0.750

Before the reforms in water supply and charges were enacted, the government had to shoulder the financial gap created due to the rising cost of water supply. In 2016, the government subsidy program was extended to the primary residence of Bahraini citizens. As a result, as per the Government of Bahrain's Fiscal Balance Program, the electricity and water subsidies in 2018 were BD 189 million, about 46% less than in 2014 (BD 350 million).

1.2 Problem Statement and Study Significance

Globally, water utilities are under growing stress to address rapidly increasing water demand caused by population growth and overuse. The United Nations expects that water demand will increase by 30% by 2030, creating even more stress on the utilities, especially in countries already facing a water crisis.

On top of that, a significant volume of water is lost daily from the distribution system before it can be consumed or billed for several reasons, called Non-Revenue Water (NRW). Controlling the NRW is one of the challenging issues concerning utilities worldwide. United Nations countries are committed to achieving the sixth Sustainable Development Goals (SDG) to ensure efficient water use. Essentially, what is measured only can be managed. The limited capability and accuracy of mechanical meters motivate water utilities to search for initiatives that provide an advanced measurement of daily usage. Advanced measuring of water consumption will enable a better understanding of the underlying water consumption pattern and easily balance water produced against water billed, thus better water management.

In line with that, the Kingdom of Bahrain has developed and implemented different national strategies to contribute to attaining the goal. As one of the initiatives to reduce water losses in Bahrain, programs have been designed to implement a smart metering system all over the Kingdom, including deploying customer Advanced Metering Infrastructure (AMI) and establishing automated District Metered Areas (DMA). The customer AMI consists of installing smart water meters and an automatic meter reading network linked with smart metering software where the meters' data are presented. The advanced metering system helps the water utilities hopefully reduce the gap between produced and invoiced water by providing more accurate (than the conventional meters), timely automatic readings, which will reduce the apparent losses and assist in reducing the real losses in the network.

The study outcomes will redound to practical benefits for decision makers and researchers through the following:

- a) The study findings serve as a reference for NRW reduction strategies and historical NRW levels at the Kingdom of Bahrain.
- b) The study found that smart meters influence the control of NRW in terms of network monitoring and water audit. Thus, due to the complexity of the meters, it is recommended that they be replaced as soon as possible.
- c) It helps assess the justification of the meter's replacement program and the utility revenue increase.
- d) It gives an indication on the return of the huge investments on the smart metering in the GCC countries and supports fund providers' decisions.

- e) It assists decision-makers in quantifying the predicted impact of NRW factors and developing programs that focus on these factors.

1.3 Objectives of the Study

The main aims of the research project are:

1. To review the water losses situation and strategic plans to manage the NRW in the Kingdom of Bahrain.
2. To study the impact of implementing the smart metering system on *water management* in the Kingdom of Bahrain.
3. To investigate and assess the impact of smart metering on *water supply revenue* in the Kingdom of Bahrain.

1.4 Limitations of the Study

Some limitations with the study can be highlighted;

1. Types of data available were frequencies and percentages; utilizing volumes of water will provide more credibility to the study.
2. The NRW in Bahrain is expressed in percentage, limiting the understanding and research of the real impact of smart water meters.
3. There are no comprehensive details of water balance components related to the Kingdom of Bahrain for the whole study period.
4. The developed model, through regression analysis, found 36% of NRW, which means other predictors, such as authorised billed consumption, illegal consumption, and data handling errors.

1.5 Overview of the Thesis

The research problem, analysis discussion and results will be presented in five chapters as illustrated;

- **Chapter One: Introduction**

It provides an overview of the study area, defines the research problem, states research objectives, describes the significance of research and gives an overview of the thesis organization.

- **Chapter Two: Literature Review**

In the second chapter, the previous research papers and literature related to the non-revenue water, water losses and water meter accuracy are critically reviewed and analysed.

- **Chapter Three: Conceptual Framework and Methodology**

This chapter discusses the various steps involved in collecting, processing, and analysing data for a successful study.

- **Chapter Four: Data Analysis and Findings**

This chapter presents the data analysis results of the research variables.

- **Chapter Five: Discussion, Conclusion and Recommendation**

This chapter discusses the research findings and interpolates them to answer research hypotheses. It summarizes the research outcomes, introduces ways to employ practical and managerial relevant exercises and suggests topics for future researches.

1.6 Definition of Terms

- **Water Balance:** water balance analysis is a method suggested by the International Water Association, used to calculate water losses within a defined area.
- **NRW:** volume of water that flows into and out of a distribution network is measured in millions of gallons.
- **Apparent Losses:** consumed water but not measured due to unauthorized un-metered consumption (illegal connections), meters' inaccuracies, and data and billing systems failure.
- **Real Losses:** produced water, which is not consumed but lost due to various types of leakage, bursts and overflow in the water supply system.
- **Water Advanced Metering Infrastructure:** an integrated system that comprises smart water meters, communication networks, and data management software that enables remote meter reading.
- **District Metering Areas (DMAs):** discrete areas of a water distribution network segregated by boundary valves. The DMA is hydraulically isolated using water inflow and outflow to accurately estimate water losses within the district area.
- **Authorized Unbilled Consumption:** the amount of authorized water used for different purposes such as firefighting, training, street cleaning, and network flushing can be metered and un-metered but non-invoiced.
- **Infrastructure Leakage Index (ILI):** represents the international performance indicator for real losses. It was developed by the

International Water Association and measures the ratio of current annual real losses to unavoidable annual real losses.

- **NRW Economic Level:** the level of NRW where the marginal cost of water losses control equals the marginal cost of the water loss.
- **NETBASE:** Intelligent Leakage Detection management and data analysis software.
- **Electricity & Water Authority (EWA):** is a governmental entity that acts as a water supply utility in the Kingdom of Bahrain. The research is supported by the Ministry of Water Affairs & Electricity. EWA is responsible for providing reliable and quality electricity and water supply services to all Kingdom of Bahrain consumers.

Chapter Two: Literature Review

2.1 Introduction

This chapter reviews reports, papers, and articles on topics relevant to the study problem. It focuses on previous studies that discussed the Non-Revenue Water (NRW) concept and components, strategies to reduce water losses, and the influence of smart water metering on water losses.

2.2 The Concept of NRW

The water efficiency is the smart usage of water resources through use of water-saving practices and technologies. Efficient usage of water helps in attaining sustainable reliable supply of water. A part of water saving practices is water conservation actions that focus on reducing water losses or waste usage. (Water Sense, 2017; Al Maskati, 2018)

In 2000, International Water Association (IWA), employing the Water Loss Task Force and the Performance Indicators Task Force, published a standard international “best practice” water balance which describes elements of water in and out of the water supply system. The water balance model, shown in Table (2-1), generates statistics and quantifies water losses elements in a defined water network. Typically, all the water balance elements are calculated in terms of volume.

Non-Revenue Water (NRW) is the discrepancy between the volume of water input to the distribution network and the volume of invoiced water is called. It is a key indicator to measure the efficiency of the water distribution system and customers’ satisfaction. NRW comprises authorized unbilled consumption and water losses. (Lambert & Hirner, 2000; Al Maskati, 2018)

Table (2-1): IWA Standard Water Balance (Source: Lambert & Hirner, 2000)

Supply Input Volume (SIV)	Authorized Consumption (AC)	Billed Authorised Consumption (BC)	Billed metered consumption	Revenue Water (RW)
			Billed unmetered consumption	
		Unbilled Authorized Consumption (UAC)	Unbilled metered consumption	Non- Revenue Water (NRW)
			Unbilled unmetered consumption	
	Water Losses (WL)	Apparent Losses (AL)	Unauthorized consumption (UC)	
			Customer meter inaccuracies (MI) and data handling errors (DHE)	
		Real Losses (RL)	Leakage on transmission and distribution mains	
			Leakage and over flows from the utility's storage tanks	
			Leakage on service connectors up to the customer meter	

Water Losses (WL) are classified as commercial losses and physical losses. Typically, NRW is indicated in percentage and calculated using the following equation: (Lambert & Hirner, 2000)

$$NRW (\%) = \frac{\text{Produced Water (m}^3\text{)} - \text{Billed Water (m}^3\text{)}}{\text{Produced Water (m}^3\text{)}} \times 100\%$$

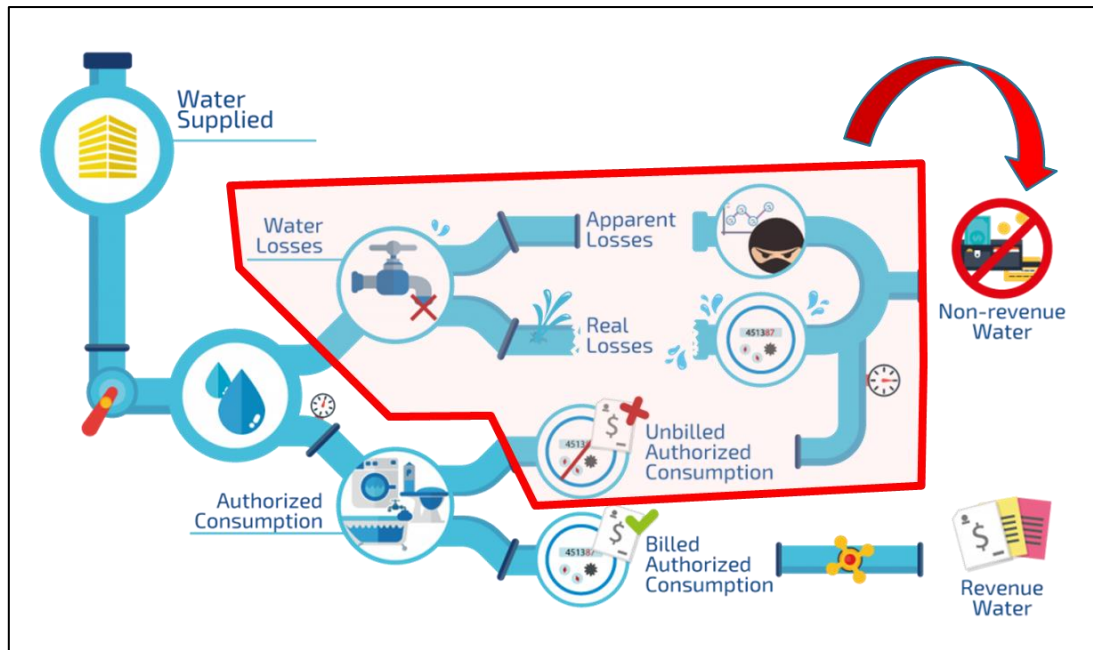


Figure (2-1): Components of Non-Revenue Water (Source: Open International, 2017)

However, Pedersen & Kristensen (2016) has argued that recognizing NRW as m^3 per km of pipe per day (or m^3 per connection litres per day) gives the most correct figure of the losses. Supporting that, Dalton, J. (2019) suggested that volumetric targets for NRW reduction are more appropriate than percentage, as determinants of NRW cannot be recognized in term of percentage. The volume of non-revenue water is an accurate indicator of lost income to the utility due to water loss. (Perera et al., 2018) For assessing the financial implication of NRW appropriate monetary values are used for each parameter of NRW; the authorized unbilled consumption and apparent losses are calculated at the retail water price while physical losses are calculated considering the production cost. (Lambert & Hirner, 2000; Ncube & Taigbenu, 2019)

Lambert & Hirner (2000) recommended that the best practice to manage water losses is by continuously calculating water balance components in combination with night flow measurements. Nevertheless, complete

accuracy in assessing the water balance components is difficult to be maintained. Farely, et al. (2008) explained that unavailability of essential information such as system input volume, average pressure, length of leading network and number of connections contribute to inaccurate and unreliable results. The accuracy of bulk meters (at the supply points), customer meter reading, and billing are the main factors affecting meters' accuracy of NRW calculation. Therefore, the confidence level can be improved by selecting the appropriate flow meters, continuous verification of flow meters' accuracy, and ensuring time equivalency of input volume and consumed volume by considering the average billing cycle.

2.2.1 Authorized Unbilled Consumption

Lambert & Hirner (2000) defined the authorized unbilled consumption as the amount of authorized water used for different purposes such as firefighting, training, street cleaning and network flushing, which can be metered and un-metered non-invoiced. However, according to Farely et al. (2008), it includes water consumed by the utility for operational purposes.

In 2018, about 782,230 m³ was recorded as authorized unbilled consumption in the Kingdom of Bahrain. This volume was consumed for firefighting, network flushing, and other authorized consumption. (EWA, 2018)

2.2.2 Apparent Losses

Apparent loss (AL), known as commercial loss as well, is consumed water but not measured due to unauthorized un-metered consumption (illegal consumption by consumers), meters' inaccuracies, and failures in data and billing systems (estimated reading, deficiencies in meter reading, and computerized billing system). (Lambert & Hirner, 2000) The apparent losses components can be minimized through suitable installation,

maintenance and replacement programs of water meters, proper customer management and data collection procedures.

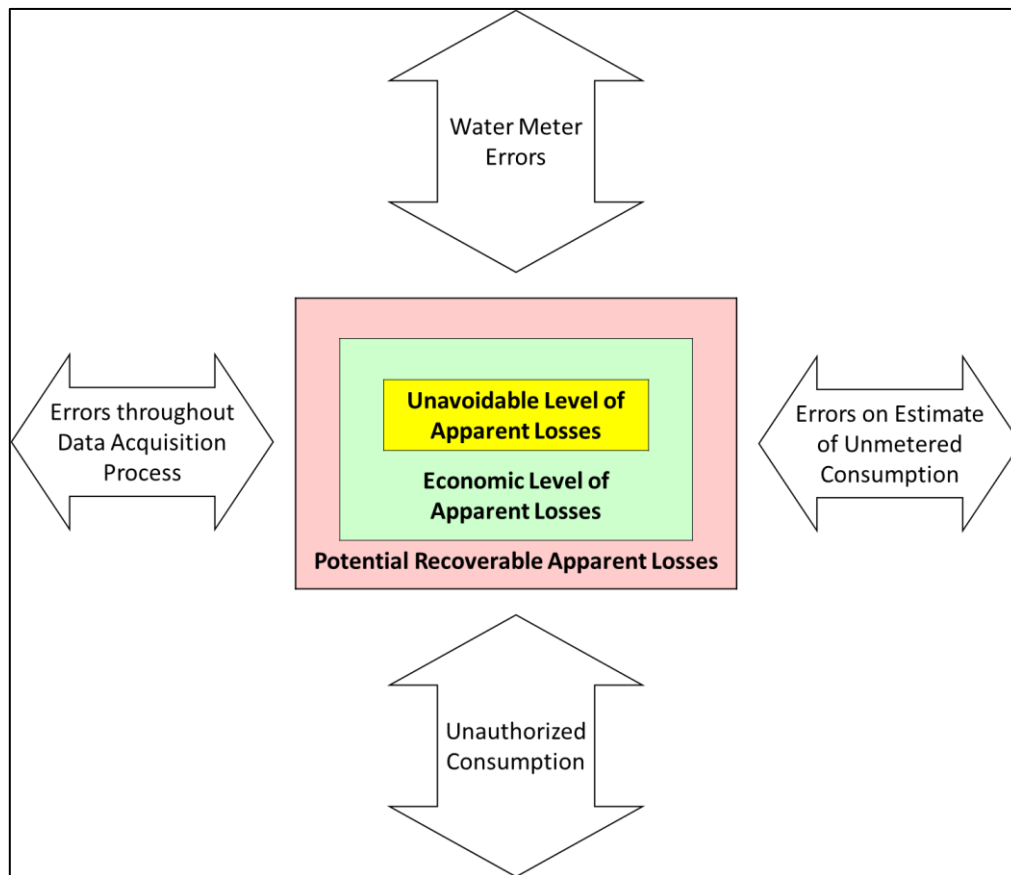


Figure (2-2): Dynamic Scheme of Apparent Losses (Sources: Vermersch, et al., 2016)

Figure (2-2) shows a dynamic scheme diagram of apparent losses' principal elements or causes. Each element has various factors that affect the losses; the following are examples: (Vermersch, et al., 2016)

- Water Meter Errors: different technical and human factors affect this element such as the meter's type, brand, metrological class, age, size, installation method, consumption profile, water quality and pressure.
- Errors throughout data acquisition: customer database information, meter reading data quality, and procedure of meter reading. In

general, meter reading and handling errors occur during the gathering of meters' readings and transferring the data to the billing system. (Mutikanga, 2011)

- Errors in estimating unmetered consumption
- Unauthorized consumption represents the customers' income, the country's regulations and legislation, and customer database reliability.

Farely et al. (2008) stated that apparent losses are higher in volume and have more excellent value than real losses, which explains the significant financial impact of a slight reduction of commercial losses. As well as that, the apparent losses are relatively easier to be quantified as financial loss of income by using the selling price. This type of loss is delivered and consumed by the customer but not paid. (Vermersch et al., 2016)

Farok (2017) argued that apparent water losses in developing countries are more significant than real losses, unlike in developed countries. Yet, many water utilities focus on investigating the real failures due to the invisible nature of the leakage. (Farely et al., 2008)

2.2.3 Real Losses

Real loss (RL), also called physical loss, is another aspect of NRW. It is produced water, which is not consumed but lost due to various types of leakage, burst and overflow in the water supply system, and never delivered to customers. (Lambert & Hirner, 2000; Smith, 2020) The real loss volume depends on pressure, flow rate, frequency, and average leak duration. The real losses are estimated using different methods; analysis of minimum night flows within District Meter Area (DMA), a record of leakages and network modelling calculations. (Lambert & Hirner, 2000)

Vermersch et al. (2016) explained that the real losses evaluation and management involve many elements which can be simplified as in the dynamic scheme shown in Figure (2-3). The large, bold bounded rectangle represents the current annual real losses for a specific system, calculated using water balance. The main factor increasing the tendency to increase the rate of leaks is the age of the water system. The system tendency for real loss rises can be managed through a combination plan of the pillar components of real losses management, represented in arrows (refer to Figure (2-3)). These management programs are pressure management, speed and quality leak repair, active leak control and asset management. The implementation of the programs depends on the response of real losses from year to year. Therefore, water audit exercise and calculating water balance volumes are essential to assess the extent to which programs should be applied.

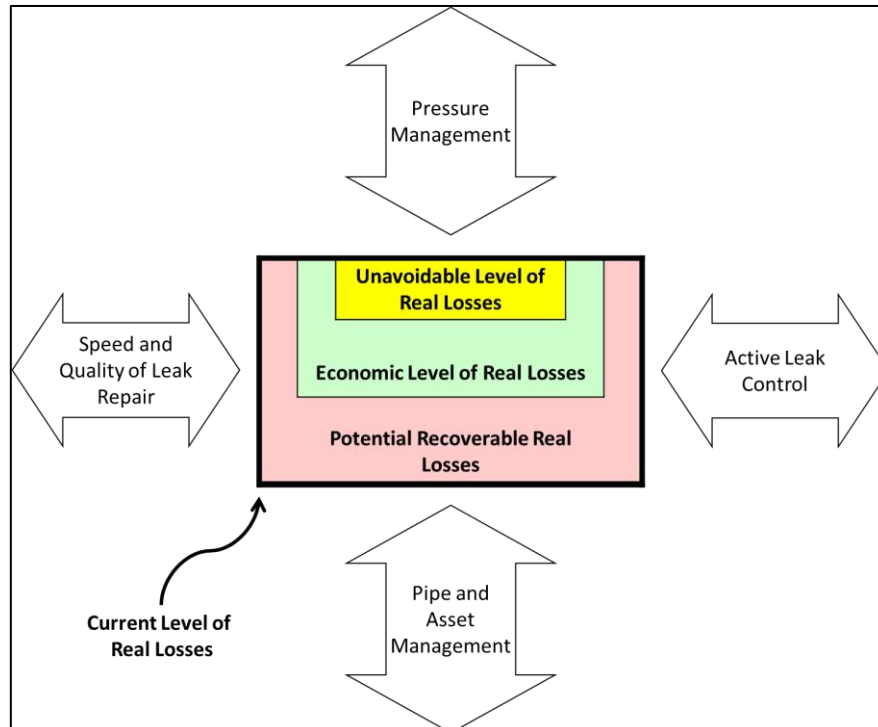


Figure (2-3): Dynamic Scheme of Real Losses (Source: Vermersch, et al., 2016)

The real losses are large relative to the apparent losses volumes. Nevertheless, both can be approximately equal to each other in terms of their financial impact on the utility. That can be explained by the cost of cubic meters of water lost in leakage being the same as the cost of producing the same volume. On the other hand, the cost of cubic meters of water supplied to customers but not counted is the higher sales price than the production cost. (Arregui et al., 2018)

Because of that, Figure (2-4) illustrates the results of the American Water Works Association (AWWA) survey of some water utilities in the United States. About 29.4 billion gallons of water were lost due to apparent losses, leading to a revenue loss of 151 million dollars. In addition to that, the water volume of 130.1 billion Gallons was recorded as a real loss equivalent to expenses of 77 million dollars. (Innovyze, n.d.) The figures indicate that though the real losses were three times higher than apparent losses, the financial value of apparent losses was approximately double the value of real losses. This is explained as the value of revenue loss is higher than the expenses.

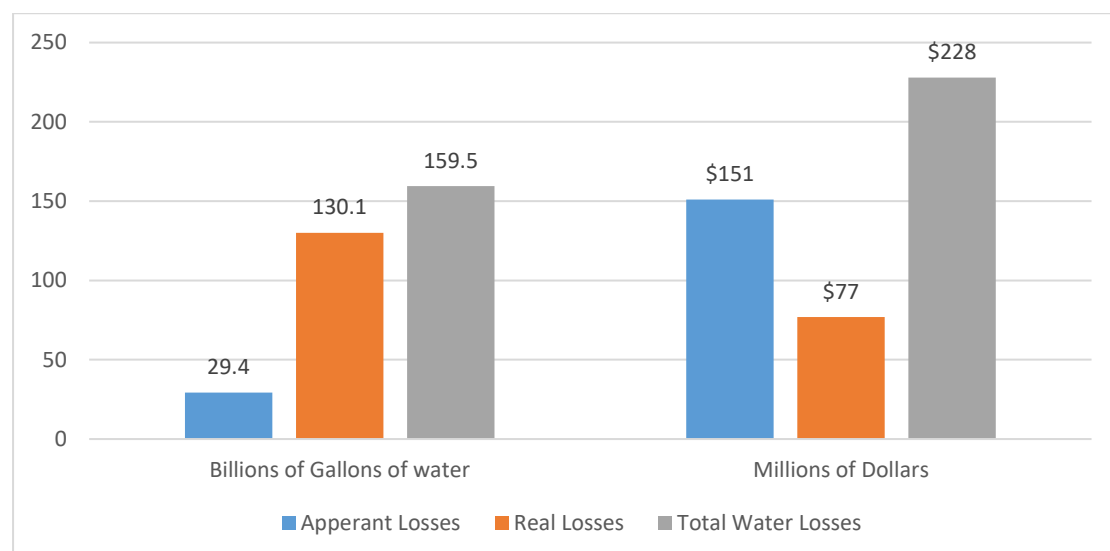


Figure (2-4): Volume and Value of NRW from Water Losses (Source: Innovyze, n.d.)

2.3 Water Audit and Losses Assessment

There are three main approaches reported by the literatures for breaking down water losses into real and apparent losses: top down, bottom up, and water and wastewater balance. All approaches are necessary and should validate each other. (Lembert & Tylor, 2010; Al Omari, 2013; Vermersch, et al., 2016; Al Washali, et al., 2018; Al Washali, et al., 2020)

2.3.1 Top Down Approach

In the top down approach, all water balance components are quantified and then the real losses are calculated by simple mass balance using the following equation: (Al-Washali et al., 2020)

$$RL = SIV - BC - UAC - AL$$

Where **RL** is real loss, **SIV** is supply input volume, **BC** is billed consumption, **UAC** is unbilled authorized consumption, and **AL** is apparent loss.

The system input volume and billed authorized consumption are attained simply from utility records, while unbilled authorized consumption and apparent losses are estimated using methods as follows.

2.3.1.1 Unbilled Authorized Consumption (UAC)

Unbilled Authorized Consumption (UAC) is assessed using metered consumption add to the estimation of unmetered consumption.

$$UAC = UAC_{metered} + UAC_{unmetered}$$

UAC is generally estimated as a percentage of the system input volume. For example, the American Water Works Association (2007) estimated the

UAC as 1.25% of the system input volume, while Lamber and Tylor (2010) estimated it as only 0.5% of SIV for New Zealand.

2.3.1.2 Apparent losses

The apparent losses are estimated by quantifying its sub-elements; meter inaccuracies, unauthorized consumption and data handling error as a percentage of system input volume based on utilities knowledge of their water supply system. (Al-Omari, 2013; Al-Washali et al., 2020) As per Vermersch, et al. (2016) field surveys and laboratory experimentations are essential to quantifying components of apparent losses. The apparent losses are calculated as the following;

$$AL = UC + MI + DHE$$

- Meter Inaccuracies (MI): It is estimated by testing meters at different flow rate values according to typical customer usage and meter's metrological data. Meter accuracy can be affected by several factors, such as age, water quality, and low flows through the supply pipes.
- Unauthorized Consumption (UC): Based on the water audits conducted by the American Water Works Association (2007), the UC is estimated at 0.25% of SIV, whereas Lamber and Tylor (2010) estimated the percentage at 1% for New Zealand. Al Omari (2013) and Al Washali et al. (2020) argued that this value is higher in the developing countries as a result of lack of public awareness, supporting Mutikanga et al. (2011), who suggested assuming the UC for developing as 10% of billed water or alternatively 10% of NRW.
- Data Handling Errors (DHE): Estimated based on historical data of billing data trends during a specific period. (Farley et al., 2008; Al-Omari, 2013; Al-Washali et al., 2020)

According to Al Omari (2013), the drawback of this method is represented in that the unbilled authorized consumption and unauthorized consumption are not scientifically based and differ per community. Added to that, the results of the laboratory survey, done to calibrate the meter's accuracy, are not necessarily representative as the incorrect installation negatively impacts the meter's accuracy. (Vermersch et al., 2016)

2.3.2 Bottom Up Approach

Managing the NRW, the distribution network is broken into District Metering Areas (DMAs), smaller manageable units that are hydraulically isolated. The DMAs will help formulate focused targets for water loss, controlling and managing the network's pressure. The design of DMA follows several criteria, including several connections, location of valves and ground-level variation. Boundary valves are to be closed, and a flow meter with a data logger is installed to divide the network. Established DMA should be calibrated by simulating the hydraulic model of DMA to ensure sufficient flow and pressure within the DMA. (Farley et al., 2008; Al-Omari, 2013; Al-Washali et al., 2020)

In the bottom-up approach, the real losses are evaluated using two methods; leak elements analysis and Minimum Night Flow (MNF), which are applied to the District Metering Areas (DMA). Therefore, the bottom-up approach requires a significant investment to establish the DMAs and, in some cases not applicable. Besides that, the practice has challenges in analysing minimum night flow results and calculating leakage for the area with illegal usage, which can be verified using the Night-Day Factor (NDF). (Vermersch et al., 2016)

2.3.2.1 Leak Elements Analysis

The real losses in the network is caused by various leak and burst events that categorized as avoidable and unavoidable. The volume of each avoidable event is calculated by multiplying flow rate and average duration of event using values estimated by IWA Water Loss Task Force, refer to Table (2-2). The Unavoidable Background Leak (UL) is calculated using the following equation and Infrastructure Condition Factor (ICF, 1-3): (Vermersch, et al., 2016; Al Washali, et al., 2019)

$$UL = (18 L_m + 0.80 N_c + 25 L_p) P_{avg}$$

Where:

UL = the unavoidable leakage volume.

L_m = the length of the mains (km)

N_c = the number of service connections.

L_p = the total length of the house connection between the edge of the street and the customer meter, and P_{avg} = average pressure of operating network.

There are three types of avoidable events in the distribution network; background burst, reported bursts and unreported burst. The type of leak and location affect the total running time and volume of the leak. The background burst combines small, hard and impossible leaks to detect and repair individually. Reported burst is usually visible and easily seen, while the unreported burst is invisible and discovered using leak detection equipment. (Farely et al., 2008) Considering that the water distribution infrastructure is mostly underground, leakages cannot be visualized until the water reaches the surface due to damage to the surface structure. Otherwise, special technological tools are used to detect the existence and location of the leak source. (Duffy, 2017)

Using data of detected leaks during the calculation period and estimated average flow rate, the Total Annual Volume of Leakage (TAVL) is calculated as:

$$TAVL = \text{Number of RB} \times Q_{AVL} \times D_{AVL}$$

Whereas, RB: Reported Burst, Q_{AVL} : Average Leak Flow Rate from Table (2-2) and D_{AVL} : Average Leak Duration, usually 12 months.

Table (2-2): Average Flow Rates for Reported and Unreported Bursts Source (Source: Farely, et al., 2008)

Location of Burst	Flow Rate for Reported Bursts (l/hour/m pressure)	Flow Rate for Unreported Bursts (l/hour/m pressure)
Mains	240	120
Service Connection	32	32

Also, Background Losses (BL) are to be considered in the calculation using IWA Water Loss Task Force values shown in Table (2-3), which are low flow individual events that may not be detected during leak detection survey exercise.

Table (2-3): Background Losses (Source: Farely, et al., 2008)

Location of Burst	Litres	Unit of Measure
Mains	9.6	l/km of mains/day/m pressure
Service Connection- main to property boundary	0.6	l/connection/day/m pressure
Service Connection- property boundary to customer meter	16.0	l/km of service connection/day/m pressure

2.3.2.2 Minimum Night Flow (MNF)

As per Farely et al. (2008), the leaks in the main pipeline constantly occur over 24 hours. The leaks from a connection at customer points fluctuate with demand during the day, which is usually minimum at night when most customers are inactive. The MNF is the lowest flow in the DMA within 24 hours, and it is identified through analysis of 24 hours' demand of DMA. MNF value is used to calculate the Net Night Flow (NNF) by subtracting the possible Legitimate Night Consumption (LNF), which is estimated by considering the hourly night flow of all non-domestic consumers and 10% of domestic usage. Correction Night-Day Factor (NDF) is deemed a possible variation of leak amount during the day as it varies based on the flow and pressure levels.

$$NNF = MNF - LNF$$

$$NDF = \sum_{i=0}^{23} \left(\frac{P_i}{P_{min}} \right)^N$$

$$RL = NNF \times NDF$$

P_{min} is the average pressure during the minimum night hour, P_i is the average pressure during the day hours and N is the leakage exponent that can be assumed as 1.

This methodology requires intensive fieldwork to isolate DMA and experienced personnel to recognize abnormal flow and pressure that could indicate a leak. As well as that, the real losses assessment methods help in detecting available leaks and further steps are to be taken to identify the location and volume of a leak. (Al Omari, 2013)

2.3.3 Water and Wastewater Balance Approach

Al Omari (2013) discussed that both approaches suffer from errors and uncertainties, which reduce the confidence level of results. Thus, the researcher has developed a new methodology based on water balance between the water supply system and wastewater treatment plant inlet using WEAP software. Likewise, Al Washali et al. (2018) suggested using the water and wastewater balance method to estimate the apparent losses. They have developed an apparent loss estimation equation, which is explained below.

The approach is founded on customers' commercial losses from the wastewater system's input, unlike the real losses. Therefore, the apparent loss volume can be calculated using the inflow volume of the Waste Water Treatment Plant (WWTP), based on the given equation:

$$AL = (\alpha + 1) Q_{ww} - (\beta - \gamma + 1) BC$$

Where Q_{ww} denotes the WWTP inflow volume in m^3 ; α , β and γ are factors for exfiltration-infiltration (3%-10%), UAC (0.5%-1.5%) and outdoor water use (4%-40%), respectively. These factors were assumed and then verified using the following equations:

$$\alpha = Q_{ex} - Q_{in} = N_p \times q_{cap} \left(1 - \frac{\gamma}{100}\right) + Q_{ind} - Q_{ww}$$

Where Q_{ex} is the exfiltration volume, Q_{in} is the infiltration volume, N_p is the population, q_{cap} is the per capita water consumed, Q_{ind} is the industrial and commercial wastewater discharge.

$$\gamma = \frac{Q_{bc} - 12 \times q_{bc.min.month}}{Q_{bc}} \times 100$$

Where Q_{bc} is annual volume of BC and $q_{bc.min.month}$ is the BC volume in the minimum consumption month.

The factor β can be estimated using the utility records, using 0.5% of billed volume (BC) or 1.25% of SIV.

This approach suffers from some limitations in estimating infiltration, exfiltration and outdoor volumes, which require good flow measurements in WWTP level.

2.4 Water Losses Reduction Strategies and Performance Indicators

As guided by Farely et al. (2008), the NRW and its components must be quantified to understand the NRW challenges and the importance of reducing water losses and formulate suitable strategies for managing the NRW considering appropriate performance indicators. Misunderstanding the complexity and importance of lowering NRW will lead to an unsuccessful reduction program. There are numerous techniques applied globally for managing water losses. The crucial point for improved water losses reduction is identifying suitable strategies. (Perera et al., 2018)

NRW has a severe impact on the natural resources and finance of water utilities through lost water resources, lost earnings, increased energy consumption and increased operational costs. High lost water level puts a burden on the water utility to cater to the rapid growth demand and fund necessary network expansion and rehabilitation to improve its reliability. Because of that, NRW indicates utilities' operational and economic performance in terms of autonomy, accountability, and technical and managerial skills. (Liemberger & Wyatt, 2018)

Based on a study conducted by the World Bank, about \$141 billion yearly is the cost of NRW worldwide, whereas 90 million m³ daily are lost in leakage; it could serve the water needs of at least 300 million people. (Open International, 2017) Generally, according to Liemberger & Wyatt (2018), reducing the NRW by one-third is an achievable target for most water utilities within two years. A reduction at that level will generate saving sufficient to supply about 800 million persons, a considerable increase in revenues, and reduce costs.

NRW management strategies focus on reducing water loss and increasing the utility's revenue. Nevertheless, the results have benefits for the water utility and consumers, as well as that: (Pedersen & Kristensen, 2016)

- The same water source will meet the reduced stress on the water resources and demand of more people.
- Adapting the system's pressure to the demand, and producing and distributing smaller volumes of water reduce energy consumption for the water supply system.
- Maintaining full pressure distribution 24 hours/ 7 days a week to improved water supply reliability.
- Improved water quality in term of chlorine content control in the distributed water and reduced risk of pollution related to burst and periods with low pressure.
- Better decision-making and customer service support form a basis for setting up a long-term network rehabilitation and investment plan.

It is crucial to build a solid and effective water loss management strategy that considers influencing factors such as population, connection density, number of leaks, and network length. (Gungor-Demirci et al., 2018). Water losses management is more than identifying water balance elements or

solving an isolating technical problem. It covers various processes of asset management, customer support and financial modelling. Management strategies require long-term commitment and involvement of management and all other concerned operational, finance, procurement, and human resources departments. (Farley et al., 2008) Based on that, the strategies which can be implemented in developing countries differ from those implemented in the developed countries due to variances in financial, economic, environmental and political conditions. (Perera et al., 2018)

Moreover, the strategy should consider the economic feasibility of losses reduction. Eliminating water losses seems a good target. However, it is not feasible technically and economically as more significant resources is required to be spent and employed, which causes lower marginal benefit. Figure (2-5) is a diagram that shows the relationship between the cost of water losses, NRW reduction, and the economic level of NRW. The NRW reduction team has to identify the economic level of water losses so that further investment will not result in cost-benefit savings. (Farley et al., 2008; Al-Washali et al., 2020) On the other hand, allocating an insufficient budget for losses reduction programs may result in higher losses. (Pedersen & Kristensen, 2016)

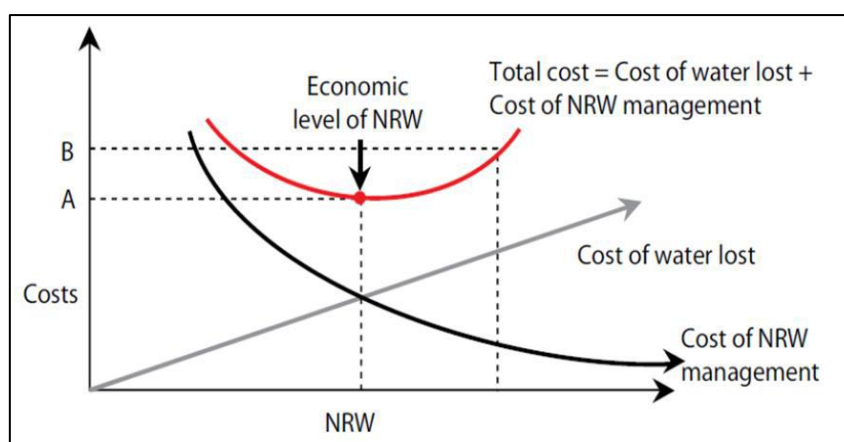


Figure (2-5): Economical Level of NRW Diagram (Source: Masheka, 2016)

Utilities have to concentrate on planning, operation, and to preserve high-quality, cost-effective products and skilled craft to achieve and attain the NRW economic level. Other factors to be focused on are availability and accessibility of data and integrity of management system, which are the keys for successful investment plans and actions prioritization to support securing fast return on investment. Furthermore, NRW reduction strategies and relative programs must be agreed upon and understood by the whole organisation, from the highest level to the lowest in the organisation chart. A suitable awareness campaign is to be done in the start-up phase to ensure that all people involved are fully aware of the goals and policies related to the reduction program. (Pedersen & Kristensen, 2016)

The master plan for NRW reduction is developed based on analysis of the water distribution network performance, assessment of the water balance components, setting of appropriate targets, and cost-benefit analysis results. The plan serves as the basis for upcoming investment plans on reduction programs and their projected returns. The goal should emphasise the importance of data collection to maintain as much information as possible. The master plan provides the following information and directives: (Water & Sanitation for the Urban Poor, n.d.; Farley et al., 2008; Pedersen & Kristensen, 2016)

- Supply baseline for the NRW level and guidelines for continuous monitoring of the IWA water balance components.
- Supply calculation of NRW Economic Level based on cost-benefit analysis.
- Supply of a prioritised list of activities in the NRW reduction programme on the basis of cost-benefit.
- Supply programs and activities to be conducted, such as pressure management, district metering, hydraulic modelling, active leak

management, procurement of NRW equipment and stocks of leak repair material.

- Supply strategy for the utilisation of management systems, databases, SCADA, GIS and modelling tools.
- Supply funds required by the NRW reduction activities and specific return on investment.
- Supply Key Performance Indicators (KPIs) that reflect the utility perceptions and operational strategy.

Many water utilities face challenging issues related to NRW control due to:

- Misunderstanding of the problem
- Lack of sufficient trained human resources
- Lack of financial capacity to replace an old pipeline

The NRW management is a long-run strategy that requires short and long term commitment and engagement of all involved parties. Usually, NRW reduction programmes fail to meet the target because of underestimation of the complexity of NRW. Utilities must implement a complete asset management system, operations, customer relations, financial capacity to achieve NRW reduction successfully. Therefore, all utility members shall be involved in achieving that, not only managers. (Water & Sanitation for the Urban Poor, n.d.)

2.4.1 Water Losses Reduction Strategies and Programs

Reduction and control of real losses can be achieved by implementing an integrated strategy that encompasses identifying leaks and understanding the leak's characteristics, locating and repairing the leak and continuous monitoring of the distribution system. (Covas & Ramos, 2014) Different

strategies and programs are considered to understand and address the water losses, namely: establishment of DMA, pressure management, Active Leakage Control (ALC), illegal connections reducing program and implementing smart metering system.

2.4.1.1 Establishment of DMA

For successful management of NRW, it is highly recommended that the network be split into discrete, manageable areas. DMA establishment should consider the hydraulic characteristics and operating regime of the network. Although DMA typically has 1,000-2,500 connections, the optimum sizing of DMA is based on the existing hydraulic structure and establishment cost. Smaller DMAs requires higher initial capital and operating costs. Each DMA is fully isolated from the other DMAs by closing boundary valves (except the inlet valve where the flow meter is installed). (Farley et al., 2008; Al-Omari, 2013)

The network pressure profile will be affected due to area isolation, causing shortage supply issues and dead ends that lead to quality issues. Therefore, the process of DMA design must be managed carefully to ensure sufficient pressure and supply. This is achieved by simulating the designed DMA using the calibrated hydraulic model. (Farley et al., 2008; Al-Omari, 2013)

The zonal consumption behaviour and characteristics like flow, pressure, Minimum Night Flow (MNF), daily peak demand, etc., can be easily identified by fixing loggers and the water meter. Consequently, the NRW analysis is conducted in each DMA, applying the abovementioned approaches. As a result, DMAs will help managers prioritise their strategies area wise and minimize efforts, time and cost of dealing with losses in the network. (Farley et al., 2008; Al-Omari, 2013)

2.4.1.2 Pressure Management

The leakage rate is a function of the pressure in the pipeline; there is a positive relationship between the leak rate and the pressure flow rate. Though it is complex, the managers have to assume a linear relationship initially. Thus, a suitable pressure regime has to be modelled to cater for the demand and, at the same time, control the leak rate.

Commonly, Pressure Reducing Valves (PRV) are installed at water tank outlets to control the pressure in the network. Alternatively, identified low-pressure areas within DMA can be supported from other supply routes or booster stations to maintain adequate pressure. (Farley et al., 2008)

2.4.1.3 Active Leakage Control (ALC)

Dividing the distribution network into zones or DMAs is an internationally recognized technique for better leak control by monitoring flows, quicker leak location, and speedy leak repair. Along with associated technology and equipment form typical network for active leakage control. (Aclara, 2017) Innovyze (n.d.) has recommended leveraging operational analytics using data from smart meters to improve the accuracy of leak source detection.

A vital part of the network that plays a critical role in detecting even small leaks is the flow meter and data capturing technologies (data logger). Data from the zone meter of the DMA meter is transferred through telemetry to the utility water control system; SCADA is an example.

After recognizing a leak within the DMA via water audit, leak detection techniques and tools/ equipment are to identify the exact location of the leak, avoiding excavation at suspected leak locations that reveal no leak. The leak detection field is continuously growing, advanced technologies

and adopted methods are used to expedite leak identification. Many ways and equipment are used to detect leaks categorized in three forms; passive, hydraulic, and acoustic, but the acoustic detection method remains the foundation for all. (Duffy, 2017)

In the passive observation method, the utility depends on inspectors who walk along the network to search for visible leaks or signs of leaks and the reported leaks by customers. Considering the nature of leaks which are usually unseen, this methodology is ineffective and time-consuming. Thus, it should be used in parallel with another method. Another method used to identify leaks is the hydraulic leak detection method which uses hydraulic characteristics, flow and pressure, of pressurized pipelines to locate and quantify leaks. (Duffy, 2017)

Acoustic leakage detection is a systematic method where listening equipment such as listening rods, noise loggers, noise correlators, stethoscopes and ground microphones are used in surveying the water pipeline to identify and pinpoint the location of invisible leaks' sound underground. The sound and vibration resulting from the pressurized pipeline's leak impacting soil are carried along the channel are recognised. Different pipe (the medium) materials, length, and size affect sound transmission. For example, small metal pipes carry the sound to a greater distance (approximately 1,000 feet) than large polyvinyl chloride pipes (about 100 feet). (Duffy, 2017) The acoustic technique is effective for metal pipelines. Still, its effectiveness with the plastic channel is challenging, as the transmitting distance of leak signal in the metal pipe is long relatively, whereas it is short in plastic pipe. (Boulos and Aboujaoude, 2011)

Alternatively, step testing can detect leaking network segments, especially in plastic pipes with less effective acoustic techniques. Step testing is associated with systematically isolating portions of the network using valves. Figure (2-6) demonstrates a schematic model of the step test. The test is conducted at night when the flow is minimum or relatively unchanged and avoids annoying the customers. After defining the step region, all boundary valves surrounding the area are closed. Then, data loggers are attached to the area's water meter. The test will start at the farthest pipe/ valve from the water meter and close step valves inside the area. The meter readings are to be taken after each valve close. Until the task is zero, the steps are repeated until reaching the water meter. (Boulos & Aboujaode, 2011)

The disadvantage of this method is that even a drop in flow can identify pipes with suspected leaks inappropriately. Also, it requires accurate details of water distribution system features such as valves. (Boulos and Aboujaode, 2011).

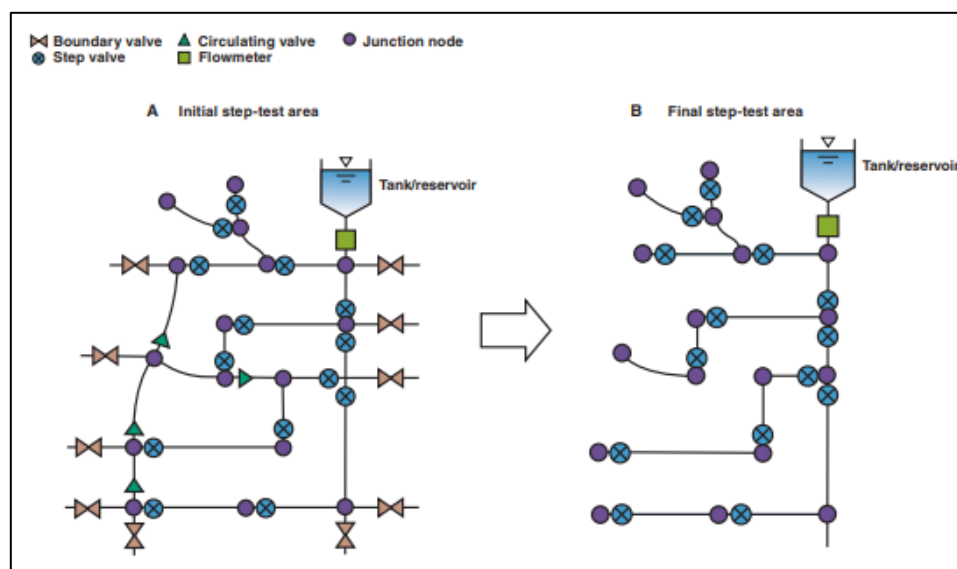


Figure (2-6): Schematic of Step Test Area Sample (Source: Boulos and Aboujaode, 2011)

2.4.1.4 Illegal Connections Reducing Program

Illegal connections are physical installation of connection to the distribution network without knowledge of water utility and meter. The program involves a customers' awareness campaign, placing regulations for penalizing water thieves, and conducting illegal connection surveys and reporting. (Farley et al., 2008)

2.4.1.5 Implementing Smart Metering System

Utilities need to have advanced technological tools that enable timely analytics and decision making related to losses control and revenue collection. (Open International, 2017) Randal and Koech (2019) stated that smart metering might be the most effective urban water management and billing worldwide. It provides frequent accurate consumption data that utilities can analyse to enhance water demand and losses management.

The smart metering system requires advanced metering infrastructure (AMI) to enable automatic, remote reading of meters' data. The AMI consists of smart water meters for measuring the used water, automatic meter reading (AMR) grid as a communication network that transfers data, and meter data management software for display and analysis. The smart feature of the water meter cannot be active unless it is connected to an Automated Meter Reading (AMR) system that allows automatic collection of meter readings. (Sensus, n.d.; Hope, 2011)

AMR is considered the first step into smart metering. A one-way communication technology collects real-time usage and transfers that data to a central collector based on touch, wire or Radio Frequency (RF) technology. (Sensus, n.d.) Cutler (2011) briefed that different channels deliver the communications meters' and water utility, namely: Power Line

Communication (PLC), fibre optic cable, broadband, telephony, cellular transmission and wireless radiofrequency. The meters' data are communicated to the water utility through concentrators, repeaters and gateways and uploaded into analytical software. The AMR can be of the following forms;

- In touch-based AMR, also called on-site AMR, the meter reader carries a handheld data collection device or computer with a wand or probe. By touching or placing the probe close to a reading coil enclosed in the touchpad, the device automatically collects the data from the meter. Collected data is saved in the device's software; thus that it can be downloaded later for billing or analysis purposes. (EJP Team, n.d.) It is used in congested areas that are not conducive to vehicles. (FERGUSON, n.d.)
- Wired AMR involves collecting meter data through the wire and transmitting them to a central collector, pushing all data to the meter data management software.
- Another technique of AMR is the RF. It is one of the technologies used to collect the usage data from the meter automatically. The data are collected remotely from the meter and pushed to the meter data management software. It can take three forms walk-by, drive-by and fixed network.
 - Handheld radio reading, Walk-by AMR: The meter reader walks past the property to collect the meter data from the transmitter by an RF handheld USB receiver. The data are automatically captured by the receiver connected to a PC or laptop. This system is less expensive than a vehicle and fixed network system. It is suitable for small areas. (EJP Team, n.d.)

- Handheld radio reading, Drive-by AMR: The transmitter is connected to the water meter. Thus, the pulses generated by the meter are counted, stored and allocated a time stamp. A USB receiver is fixed inside a vehicle. The meter reader drives the car along the road. As the reader drives within the radio range of the transmitter, the unit receives and processes the data. The collected data are sent to a laptop or PC. In some countries, the receiver is fixed in the garbage collector vehicle. Thus, they can save the cost of meter readers. (EJP Team, n.d.)
- Fixed Network: A radio tower is mounted in a central location. The building is connected to a central collection unit that captures the data from the meter transmitter. This system is used in urban areas where the population is high. (EJP Team, n.d.)
- The smart metering system is one of the pillars for smart water grids. The smart water grid is a promising technology to resolve water issues related to the distribution system. It combines information and communication technologies in a single, smart water management platform. (Jang et al., 2019) The information technology enables real-time, rapid decision making in operation and system level, integration of physical infrastructure and proactive asset management system, and predictive capability using advanced analytics of trends and behaviours. (Brooks, 2010)

The system provides real-time data the utility uses to issue accurate bills, analyse the network performance, better understand demand patterns, further optimize production, and better control the pressure to pursue the demand and customer services. Furthermore, the real-time data received

by the software and the real data from the DMA smart meter will help spot and rectify sudden increases in consumption, which may indicate a leak, an illegal connection, or insufficient functionality of the flow meter. This will result in a quick response to water losses event and subsequently reduce the NRW in the network.

The smart meter reading system allows one-way or hybrid data transfer between the meter and the system's database. It assists the strategic goals of water utilities in terms of increasing revenue by frequent accurate readings and automatic detection of meter fraud, reducing the operational cost of reading recording errors, and protecting the environment by fast water leak detection and repair. (FERGUSON, n.d.)

2.4.1.6 Applied Water Losses Strategies

Many countries worldwide have implemented integrated strategy plans that have revealed successful results in reducing the NRW level.

In Denmark, TREFOR Vand A/S, a water distribution company, has recorded a successful experience in reducing and sustaining the NRW level of below 10%. The company has developed an action plan for 2012-2014 after suffering from high NRW. The project included implementing KeyZones operational system, DMA establishment, pressure management, ALC, operation procedures optimization. Another investment were put on replacing the old cast iron and asbestos cement pipelines with polyethene pipelines and replacing mechanical meters' replacement with another smart. Data of smart meters are transferred to the company's system, where the meters' operation is monitored daily. KeyZones system compiles all data relevant to water loss, provides IWA water balance, KPIs, GIS charts and daily NRW levels in DMAs using accurate data from smart meters. (Pedersen & Kristensen, 2016)

Another successful water losses reduction story is of Gotland, a Swedish island. The island suffers from that hard water building up calcium, lime, iron, and sand in many mechanical meters. The deposits affect the accuracy of meters' measurement and stopping of some meters, forcing the utility to replace the meters before completing the meters' lifetime. Later, Region Gotland company decided to invest in ultrasonic meters to eliminate the problem of mineral deposits. They do not contain mechanical moving parts, ensure unrivalled accuracy and maintain more lifetime relative to the mechanical meter. The water meters with a built-in leakage detection facility alert the responsible team and pinpoints the leak's location, which quickly ensured leak attendance and fixing, reducing water loss. (Pedersen & Kristensen, 2016)

For Romania's 400km network rehabilitation, the water utility replaced old pipelines with modern equipment, such as gate valves and air valves. These enhancements lead to big savings on operational costs via better control on energy consumption, reduction of hydraulic problems and water losses in the network. (Pedersen & Kristensen, 2016)

The city of Al Ain in the United Arab Emirates has managed to reduce the NRW level of 19 DMAs by 35% within only one year. The project involved integrating various NRW management programs such as flow and pressure monitoring, noise reduction, and water balance. The objective was to provide a more robust and flexible NRW management system and a Holistic Management Information system (HOMIS). HOMES gathers operational data from different systems, namely: GIS, SCADA, noise loggers, water quality customer care and billing, and generate online KPIs report. That assisted the managers to initiate corrective measures at the right time. On top of that, they have concentrated on developing their

operational and management staff's expertise. (Pedersen & Kristensen, 2016)

Dalton, J. (2019) analyzed Bahrain's case to reduce the NRW by 15%. Bahrain's Electricity and Water Authority (EWA) has assigned a consultant to audit the Authority's NRW management practices, create a code of practice for NRW assessment and management to reduce the NRW level and establish automatically monitored DMAs in one of the governorates in the Kingdom. They have selected 35 DMAs with smart water meters and an automated monitoring system (Netbase) in cooperation with EWA, as the contractor was committed to investigating and identifying NRW sources. At the same time, EWA was responsible for construction and rectification activities on the field. Further, EWA has upgraded some automated pressure control locations, which contributed to a "quick win for real loss reduction", as Dalton described. Despite that, the NRW was still highly influenced by the high volume of apparent losses by industrial customers' meters, which were rectified by improving the metering and billing of these bulk consumers. (Dalton, 2018)

During 2020, DEWA replaced all the mechanical water meters with smart meters and operated The Smart Meters Analysis and Diagnosis Centre for monitoring and studying meter readings. The smart metering helps DEWA in improving the meter data availability to 99.9%. As an advantage of remote smart meters control, the utility was able to identify about 500,000 water leakage reports and 16,000 defects which led to a total saving of AED 324 million to the customers. Furthermore, approximately 8,000 increased load cases were recorded over the years 2018-2020, through the High Water Usage Alert facility in the smart meters. (Jones, 2021)

Towards digitalizing the water system, the Kingdom of Saudi Arabia has targeted completing the installation of 2 million smart water meters by 2020, as announced by the National Water Company (NWC). The smart meters' readings are read using a static wireless network that consists of reading collectors. Then, the data is transferred to the billing system four times per day without human interference. (NWC, n.d.) After installing two million smart meters, the customers were able to receive abnormal consumption alarms, based on which they identified and fixed causes of high consumption. As a result, the NEC reported a decrease in the monthly water consumption of 39%. (Staff Writer, 2020)

Recently in 2020, Oman's Public Authority for Water (Diam) introduced the smart water metering infrastructure installed in the governorates of Muscat and Musandam. The smart meters (post-paid) installed in the projects are being connected to its smart metering systems through the Internet of Things (IoT) technology. The project passed into several stages: the pilot, first and second stages. In the pilot stage, a number of 10,000 meters were installed in the Musandam. In the first stage, 4,100 meters were installed for the large consumers in the Muscat. After that in the second stage, a total of 179,300 are being installed for all categories of subscribers in the Muscat, that 98% was finalised. (Trade Arabia, 2020) As well as that, Diam has deployed the smart metering infrastructure in Muttrah, Quriyat, Seeb and Bausher. The smart meters' project is expected to contribute in reducing about 20% of water losses in the Muscat, through issuance bills to the actual consumption instead of estimated figures.

Moreover, the Ministry of Electricity, Water & Renewable Energy in Kuwait has started the first phase of smart meters' installation in 2021. The Ministry's strategy involves completing the smart meters' installation

within three years, which begins with the commercial and investment sectors. (Arab Times, 2021)

2.4.2 Performance Measures

Using Performance Indicators (PI), water utilities' operational and financial performance is measured by the NRW level and management strategy performance using performance indicators (PI). NRW performance indicators give a better picture of the water losses and help define targets, compare and monitor performance, prioritise investment, and monitor compliance. There are three categories of PI, indicators for NRW in general, indicators for real losses and indicators for apparent losses.

2.4.2.1 NRW Indicators

Traditionally, NRW is expressed as a percentage of the system input volume, which is sometimes referred to motivate utilities to initiate an investigation and formulate a strategy to manage it. Also, it can be an excellent financial indicator by valuing NRW based on the marginal cost of water. However, most practitioners do not recommend it as it does not differentiate between real losses and apparent losses or take into account pressure variance in the system. In other words, it cannot capture variables that determine the non-revenue volume. (Farley et al., 2008; Dalton, 2018) The NRW is evaluated using the IWA assessment matrix shown in

Table (2-4).

Table (2-4): International NRW Assessment Matrix (Source: Lambert & Taylor, 2010)

Technical Performance Category		Non-Revenue Water in Litres/connection/day when the system is pressurized at an average pressure of:				
		10 m	20 m	30 m	40 m	50 m
High Income Countries	A1		< 50	< 65	< 75	< 85
	A2		50-100	65-125	75-150	85-175
	B		100-200	125-250	150-300	175-350
	C		200-350	250-450	300-550	350-650
	D		> 350	> 450	> 550	> 650
Low and Middle Income Countries	A1	< 55	< 80	< 105	< 130	< 155
	A2	55-110	80-160	105-210	130-260	155-310
	B	110-220	160-320	210-450	260-520	310-620
	C	220-400	320-600	450-800	520-1,000	620-1,200
	D	> 400	> 600	> 800	> 1,000	> 1,200
Note: • Category A1: NRW management performance is outstanding unless there is still a potential for further reduction. • Category A2: Further NRW reduction may be difficult to justify unless there is a clear and compelling reason why the water supply is not being improved. • Category B: This process will help classify possible development areas and employ ways to enhance the efficacy of NRW. • Category C: Poor NRW record; tolerable only if water is plentiful and cheap; even then, analyse NRW level and causes of and intensify NRW reduction efforts • Category D: Highly inefficient. NRW reduction program should be implemented to avoid further losses.						

2.4.2.2 Real Losses Indicators

The effectiveness of real losses management programs is assessed using operational performance indicators, which are influenced by network

characteristics, mainly the number of service connections, length of mains and operating pressure. These PI were categorized as the primary, intermediate, and detailed levels per the IWA Manual of Best Practice. (Water Loss Committee Review, 2007; Vermersch, et al., 2016; Chelliapan et al., 2017)

- **Litres per service connection per day (l/c/d) and Litres per kilometre of pipeline per day (l/km/d);** basic level indicators give a general overview of network operational effectiveness and useful for target setting. Despite being better than the traditional NRW percentage, this indicator is misleading when the density of connections is low in compare to the mains length, as the connection density is a critical factor controlling the volume of leak.
- **Litres per service connection per day per metre of pressure (l/c/d/m pressure) and Litres per kilometre of pipeline per day per metre of pressure (l/km/d/m pressure);** intermediate indicators give better insight than l/c/d and l/km/d as the system pressure is accounted, considered as useful tool for comparing systems.
- **Infrastructure Leakage Index (ILI);** a detailed operational performance indicator that considers the density of connections, the length of service connection, and the average pressure in water supply system, is the most effective indicator for comparing systems and measuring how well the leakage is managed. It is given by the following equation:

$$ILI = CARL / URAL$$

CARL is the Current Annual Real Losses, calculated using IWA parameters analysis- top down and bottom up approaches-, and UARL is the Unavoidable Annual Real Losses. The UARL consists of background losses and other losses such as seepage through pipe and ferrule connections that are costly to be locate. In addition, it is influenced by length of mains in km (L_m), number of service connections (N_c), total length of pipe between the property boundary and the customer meter in km (L_p), and the system's average pressure in m (P). The UARL is estimated based on the following equation:

$$UARL = (18 \times L_m + 0.8 \times N_c + 25 \times L_p) \times P$$

Calculated ILI used to measure utility performance and is assessed using the IWA assessment matrix, refer to Table (2-5).

Table (2-5): Real Loss Assessment Matrix (Source: Lambert & Taylor, 2010)

Technical Performance Category		ILI	Real Losses in Litres/connection/day at an average pressure of:				
			10 m	20 m	30 m	40 m	50 m
High Income Countries	A1	<1.5		< 25	< 40	< 50	< 60
	A2	1.5-2		25-50	40-75	50-100	60-125
	B	2-4		50-100	75-150	100-200	125-250
	C	4-8		100-200	150-300	200-400	250-500
	D	> 8		> 200	> 300	> 400	> 500
Low and Middle Income Countries	A1	<2	< 25	< 50	< 75	< 100	< 125
	A2	2-4	25-50	50-100	75-150	100-200	125-250
	B	4-8	50-100	100-200	150-300	200-400	250-500
	C	8-16	100-200	200-400	300-600	400-800	500-1,000
	D	> 16	> 200	> 400	> 600	> 800	> 1,000

Note:

- **Category A1:** The potential loss reductions from leakage management are pretty small yet.
- **Category A2:** Further loss reduction may not be economically feasible unless there are shortages.
- **Category B:** The following categories are potential improvement areas: leakage control, pressure management, and network maintenance.
- **Category C:** If the water is cheap and plentiful, then improve the leakage record. If it is inadequate, then intensify the efforts to prevent leakage.
- **Category D:** Highly inefficient; leakage reduction programs essential and high-priority

- **Linear Leakage Index (LLI);** The linear leakage index is a French performance indicator recommended by French Water Agencies for measuring water distribution network performance. It considers the urbanization level and length of the main pipeline as the measurement of installation complexity. It is expressed in m³/h/km and calculated as follows:

$$LLI = \frac{\text{Flow rate loss during distribution}}{\text{Length of distribution main}}$$

The flow rate loss is measured in m³/h, and the length is in km. Therefore, LLI's confidence level is affected by the accuracy of the calculated flow rate loss and the primary size. Furthermore, the network is classified into three classes based on the urbanization level of the area (service connection density). Accordingly, the LLI value is compared to the reference values set by the French Water Agencies to evaluate the network as good, average, bad or poor, as illustrated in Table (2-6).

Table (2-6): Network Categories Based on LLI, values are in m³/h/km (Source: Al-Makati, 2011)

Network Type	Rural	Residential	Urban
Good	< 0.06	< 0.13	< 0.3
Average	$0.06 \leq \text{LLI} < 0.1$	$0.13 \leq \text{LLI} < 0.2$	$0.3 \leq \text{LLI} < 0.4$
Bad	$0.1 \leq \text{LLI} < 0.16$	$0.2 \leq \text{LLI} < 0.33$	$0.4 \leq \text{LLI} < 0.63$
Poor	> 0.16	> 0.33	> 0.63

The LLI can compare various areas of similar network types as an advantage. However, this index is limited in international comparison; it requires coordinated meters' readings. (Al-Makati, 2011)

2.4.2.3 Apparent Losses Indicator

Similar to real losses, IWA Water Loss Task Force developed an indicator for apparent losses in 2007, where the actual apparent loss is calculated against a benchmark value of 5% of the billed water using the given equation: (Farley et al., 2008)

$$ALI = \frac{CAAL}{RAAL}$$

ALI is the Apparent Losses Index, CAAL is the Current Annual Apparent Losses, RAAL is the References Annual Apparent Losses. The RAAL is calculated as a percentage of sold water, making it not applicable in systems with high unmetered consumptions. Usually, the RAAL is calculated as 5% of the billed water and later changed based on actual historical data.

Chelliapan et al. (2017) have studied the use of efficiency and economic indicators for NRW performance. The study was conducted on 14 water

supply companies in Malaysia, which uses NRW percentage as a performance indicator. In addition, the researchers used another indicator, ILI, to supplement the NRW percentage results.

Also, Ocieopa et al. (2019) have analysed and assessed water loss reduction initiatives implemented in Upper Silesia, where the water supply system is exposed to mining activities. Three water distribution systems operated and managed by different companies were under study. The researchers used percentage water loss index and IWA methods for loss determination, namely, real losses per network mains length and ILI, to check network condition.

2.5 Relationship between Water Meters and Water Losses

The water meters measure the amount of water supplied to parts of the network or consumers. OIML R49 is an “instrument intended to measure continuously, memorize, and display the volume of water passing through the measurement transducer at metering conditions”. At a minimum, it is comprised of a measurement transducer with a sensor, a calculator with an adjustment device or correction device, and an indicating device to display the data. The water meter provides the basis on which the revenue is generated equitably, and the precious resources are utilized efficiently. It represents the yardstick and revenue records for water-conscious utilities nowadays. In addition to using information, a water meter helps determine potential losses in the water supply system and monitor network performance.

Understanding the relationship between the water meter and water losses is very important to avoid experiencing issues with water quality.

2.5.1 Water Meters Types

Water meters are categorized based on the mechanism used to measure water volume passing through, into mechanical and electronic, whereas classified as conventional and smart based on the meter's reading and communication method. Figure (2-7) shows the different types of water meters discussed.

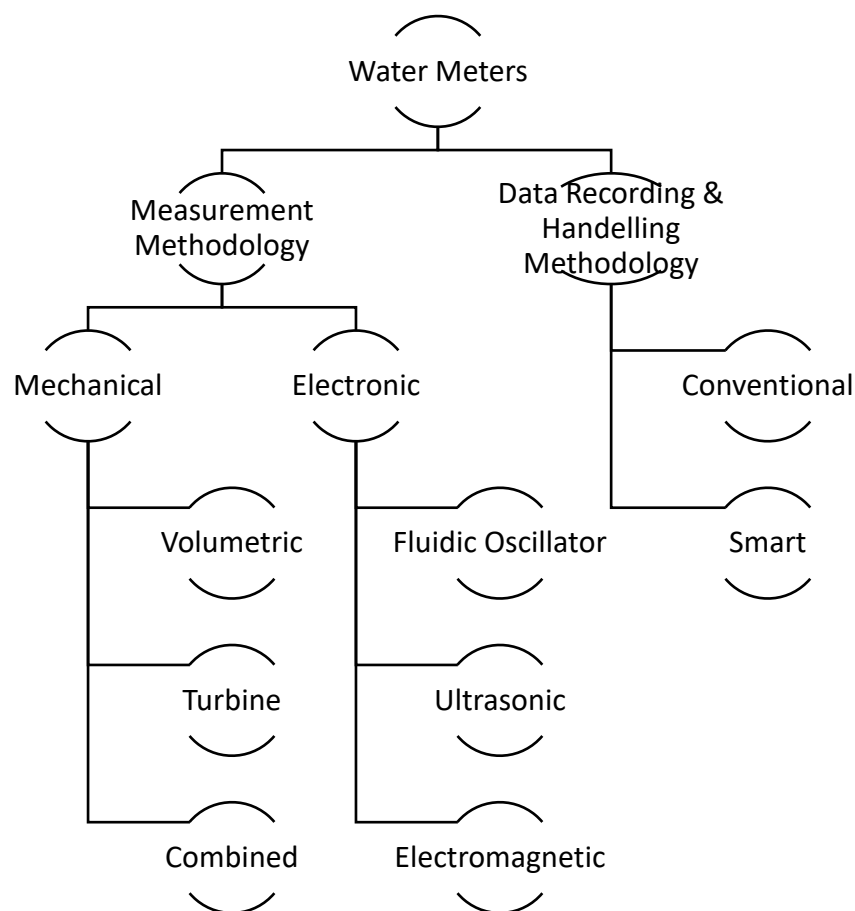


Figure (2-7): Various Types of Water Meters

2.5.1.1 Mechanical and Electronic Water Meters

The mechanical water meters measure the flow using mechanical components. There are several types of mechanical meters such as positive displacement meter, turbine meter and compound meter.

- Positive Displacement Meter, also called a volumetric meter or rotary piston type, is a mechanical water meter that measures the volumetric flow rate of water using an internal, known size, measuring element, a cylindrical piston. Water trapped in the meter moves the piston directly into the amount of water passing through the meter. (Max Machinery, n.d.; Sensus, n.d.)

The volumetric meter is a very sensitive meter to water quality, specifically solid particles in water that can be caught between the piston and the wall of the chamber, causing the meter to jam. As time passes, the meter's components wear, allowing water to leak easily, leading to under registration of the meter. The air inside the system can worsen the situation and affect the meter's accuracy. (Van Zyl, 2011)

- Turbine Meter is a mechanical water meter that measures the velocity of the flow with a bladed rotor (vane) axially suspended in the pipe. The vane revolves under the influence of the water's speed and mechanical energy. A frequency signal is then generated and sensed by the magnetic pick-up installed outside the pipe. Figure (2-8) shows the components of the turbine meter. (Oracle, 2009; Horison Regional Council, 2010; Sensus, n.d.)

Similar to volumetric water meters, vane in turbine meters are sensitive to water quality and measurement accuracy is affected by operational life of the meter. Moreover, the air in the system rotates the vane which is measured as consumption, resulting in meter over-registration.

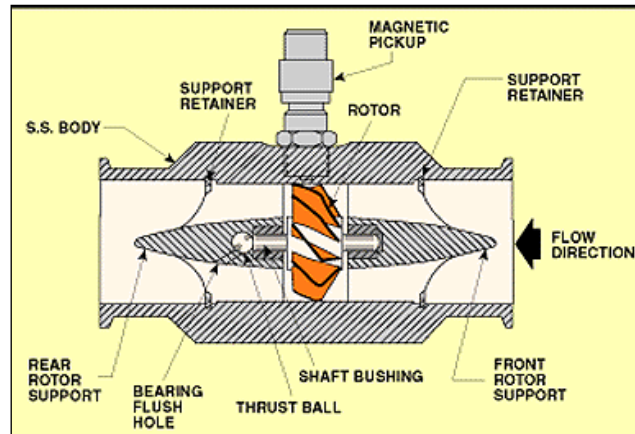


Figure (2-8): Turbine Meter Components (Source: Oracle, 2009)

- A compound meter is a mechanical water meter that uses two technologies to measure the volume of water; positive displacement and velocity. It is used where there is a highly variable flow rate. It consists of two measuring elements: a vane type meter and a piston type meter, and a check valve, as shown in Figure (2-9). The turbine meter measures the volume accurately when the flow rate is high. However, the check valve closes; thus, the water diverts to the volumetric meter, measuring the volume. (Horison Regional Council, 2010; Sensus, n.d.)



Figure (2-9): Compound Meter (Source: Horison Regional Council, 2010)

Typically, mechanical water meters' accuracy declines with usage by time and is affected by water quality and low flows, resulting in under-registration of consumption and hence adds-on utility's revenue losses. (Mutikanga, 2011) In contrast, electronic water meters' measure water flow by non-mechanical means, with no moving parts in the measuring chamber. Thus, tear and wear will not affect it, making them more accurate than mechanical meters over the operating lifetime.

The electronic meters used in water supply networks are mainly divided into three types based on their measuring technology: fluidic oscillator, ultrasonic, and electromagnetic meters.

- Fluidic Oscillator Meter measures the frequency with which a fluid entering the meter attaches to one of two opposite diverging side walls and the other due to the Coanda effect. The Coanda effect states that when a free jet comes into contact with a nearby surface, it will attach itself. (Sensus, n.d.)
- Ultrasonic Meter or transit time type, is an electronic water meter that measures the flow velocity using ultrasound. It consists of two ultrasonic transducers that emit upstream and downstream sound waves through the water in the pipe. Each transducer can transmit and receive ultrasound. As shown in Figure 2, the distance between two transducers is measured as the time it takes for the waves to reach the devices. The difference in velocity between the upstream and downstream waves is determined and translated into volume. The significant advantage of this meter is that it can be externally clamp-on, no need to cut into the line and shut the process down to install. (Sensus, n.d.; LongRun Industrial Instrument, n.d., Universal Flow Monitoring, n.d.)

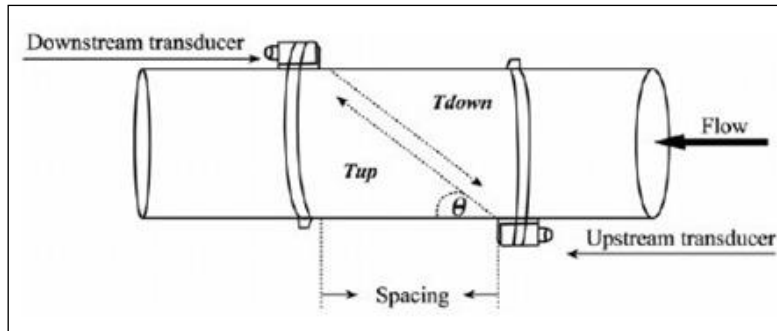


Figure (2-10): Ultrasonic Meter Principle (Source: LongRun Industrial Instrument, n.d.)

- Electromagnetic meter, also called EMAG, is an electronic water meter operated according to Faraday's law, "voltage will be produced in a conductor moving through a magnetic field". It comprises of a primary device and a secondary device. The primary device consists of an electronically insulated pipe section (meter tube) with coils and electrodes, see Figure (2-11). Energized coils, bypassing current through them, generate a magnetic field in the tube. When water (electrically conducted fluid) moves through the meter tube in the magnetic field, voltages are generated proportionally to the water velocity. Mounted inside the flow tube at a known distance, one or more electrodes pick up the voltages. A secondary device or transmitter extracts the primary device's output and converts it into usable signals. Usually, the primary device is mounted directly on the primary device. (Sensus n.d.; OMEG, n.d.)

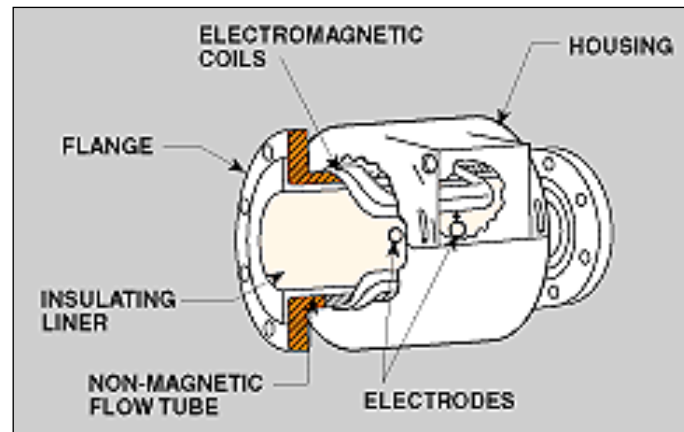


Figure (2-11): Components of EMAG Meter’s Primary Device
(Source: OMEG, n.d.)

2.5.1.2 Conventional vs. Smart Water Meters

Conventional water meters are those meters that have to be physically read at pre-set intervals. The process of this type of meter reading involves time-consuming and labour expenses. Also, the meter information provided is simply limited to overall usage used for billing purposes.

Unlike conventional meters, smart meters are read remotely to the utility’s monitoring system without the physical interference of humans. Smart meters are sophisticated devices that can measure consumption, detect abnormal events such as leakage, communicate data remotely with the utility system, and monitor the actual usage pattern. This technology is called Smart Water Metering, and it is implemented in many countries around the world. (Randall & Koech, 2019)

2.5.2 Water Meters Accuracy Classes

Water meter accuracy is an essential parameter for sustainable water management is also classified according to their accuracy performance based on ISO 4064 and OIML R49. The international standards ISO 4064-1 and OIML R49-1 concern the metrological and technical requirements of

water meters (both mechanical and electronic types) used for cold potable water and hot water flowing in a closed, fully charged conduit. These standards give an explanation of the accuracy envelope in consideration of the minimum flow rate ($q_{\min}$ or Q1) and maximum permissible flow rate (q_s or Q3) of various water meter metrological classes. Typically, water meters of the same size have the same permanent flow rate and overload flow rate regardless of the accuracy class.

Water meters are designed and produced with errors not exceeding the maximum permissible errors based on classification. Flow rates indicate the errors;

- $q_{\min}$ or Q1, is the minimum flow rate, which is the lowest flowrate that the meter provides satisfactory requirements in respect to the Maximum Permissible Errors (MPEs).
- q_t or Q2, is the transitional flow rate, which is the flow rate that occurs between permanent and minimum flow rates. The meter accuracy envelop is divided into two different MPE characteristics zones (upper and lower zones) at this flow.
- q_p or Q3, is the permanent flow rate, which is the highest flow rate that the meter will operate well under normal usage conditions.
- q_s or Q4, is the overload flow rate, which is the highest flow rate, can be measured satisfactorily by the meter for a short time without deteriorating.

Previously, the meters (based on accuracy performance) were classified into four classes, denoted by A, B, C and D. All these classes have the maximum permissible error in the lower flow zone (5%) and upper flow

zone (20%). The difference between the classes is transitional and minimum flow rates compared to permanent flow rates. In other words, as the permanent flow remains the same for a specific size, the minimum flow rate identifies the accuracy performance of the classes, where class A meter has lower accuracy performance than class D meter, which has the best performance among all classes. Figure (2-12) illustrates relative accuracy graphs for water meter classes A, B, C and D. (Van Zyl, 2011)

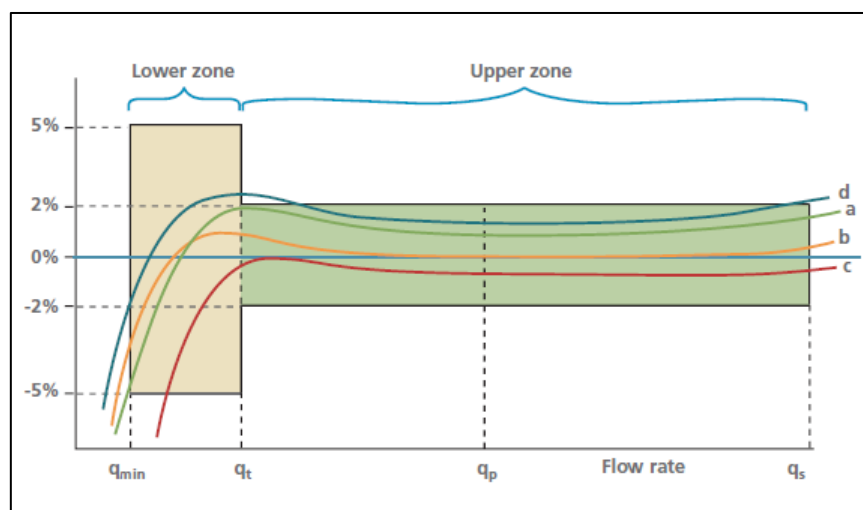


Figure (2-12): Relative Accuracy Curves for Water Meters Classes A, B, C and D (sourceVan Zyl, 2011)

Nowadays, water meters are recognized by two accuracy classes; class 1 and class 2. According to ISO 4064-1 and OIML R49-1, the maximum permissible error is $\pm 3\%$ between the minimum flow rate and the transitional flow rate, whilst it is $\pm 1\%$ (varies depending on temperature; $\pm 1\%$ for temperatures $0.1-30^{\circ}\text{C}$ and $\pm 2\%$ for temperatures above 30°C) between the transitional flow rate and overload flow rate in the case of accuracy class 1. On the other hand, the maximum permissible error is $\pm 5\%$ between the minimum flow rate and the transitional flow rate, whilst it is $\pm 2\%$ (varies depending on temperature; $\pm 2\%$ for temperatures $0.1-$

30°C and +/-3% for temperatures above 30°C) between the transitional and overload flow rates in the case of accuracy class 2. (Karadirek, 2020)

Another parameter related to measurement accuracy is recognized by international standards and the water meter market: meter dynamic range (R-value). It is determined as the permanent flow rate (Q3) ratio to the minimum flow rate (Q1). The appropriate accuracy class of meters of a given size depends on the minimum flow rate, which determines the measuring range boundary by different MPE values. (Mazur, 2017)

2.5.3 Smart Water Metering Contribution in Water Loss Reduction

A complete metering network assists in the audit of supplied water and calculation of NRW, and allows more straightforward monitoring performance indicators and leak detection. Obtaining timely, reliable, accurate readings and observing water consumption patterns lead to effective water resource management. (Al-Maskati, 2013; Randall & Koech, 2019)

Smart metering systems are an essential solution for urban water management, as they aid in the planning and operation of smart cities. The smart metering system uses intelligent electronic meters to record the consumption hourly or more often and send it to the water utility's database for billing and monitoring. That provides accurate data and supports demand management, modelling, planning and design of water supply systems. (Costa & Soares, 2020)

The high resolution, synchronized consumption data from smart meters gives the opportunity to estimate and monitor water losses. Bragalli et al.

(2018) claimed that their proposed a methodology considers incomplete readings by validating available data, yet provides near real time water losses monitoring. They tested a random sample, from the city of Fano in Italy, against un-increasing smart meters and corresponding errors. The authors recommended that accessibility to near real time synchronous water usage measurements enhance water losses assessment.

2.5.3.1 Smart Metering and Apparent Losses

Smith (2020) recommended that utilities look into apparent loss to align investments in infrastructure with water loss avoidance. As the apparent loss is associated with produced water that is not measured, improving metering capabilities through a smart metering network would help minimize this type of loss.

Different researchers have emphasised the critical role of water meter accuracy in controlling non-revenue water. The most important factors that affect the measurement accuracy and management of water losses are selecting the correct water meter type, size, and accuracy class. In addition, meter data accuracy is affected by several causes: tearing and wearing of the meter, incorrect selection of meter type and class compared to the demand profile, incorrect installation, insufficient maintenance, and meter calibration. (Farley et al., 2008; Karadirek, 2020)

Al-Maskati (2013) has stated that the accuracy of water losses volume relies on the quality and accuracy of collected data used to calculate water balance volumes and further assess water management strategies. Also, a case study conducted by Rimeika & Albrektiene (2014) has tested the effect of installing class B and class C water meters. The researchers concluded that water meters of higher accuracy classes assist in reducing the apparent losses.

Mazur (2017) has studied the impact of installing a static electromagnetic water meter on limiting apparent losses. The author has summarized that selecting the proper meter size is an essential factor that affects the accuracy of water meter measurements, especially in terms of low flow.

Arsdel (2017) has argued that metering inaccuracy is the most potent source of water apparent losses. In addition, the water meter measurement accuracy is affected by wear due to water quality and the movement of the meter's mechanical parts. Consequently, the author has recommended using electronic water meters to enhance flow measurement accuracy, as no moving parts are required. However, the meter size and setting are other factors that reduce the meter's ability to record the flow correctly.

The same was agreed by Arregui et al. (2018), who stated that water meter inaccuracies are the main contributor to apparent water losses in well-managed water supply systems. Based on that, the measuring performance of water meters strongly affects water revenue.

Smith (2020) has documented that mechanical water meters can experience performance issues in recording the actual consumption over time due to the wear of their mechanical components. Accordingly, the old meters are to be replaced to restore the accuracy level of measurements, which could help to increase revenue by 5-20%. In addition, he recommended that installing smart meters could lead to "jumpstart the revenue curve and potentially save millions of dollars".

In addition to meter inaccuracy, meter misreading and data handling errors are some of the water apparent losses.

Misreading and data handling errors arise when collecting the meters' readings, transferring these readings for billing and archiving the data in

the utility's system. Regardless of the data gathering method (manually or remotely), errors could occur when picking the readings from the meter, deficiency in capturing meter's data by Automatic Meter Reading equipment, wrong volume estimation, and shortcomings in adjusting bills. Well-developed metering technologies and billing procedures will minimize these errors. Migrating from conventional meter reading methods to Advanced Metering Infrastructure and usage of smart meters is a way to reduce apparent losses due to meter data errors. Besides that, it helps in leak detection and management. (Mutikanga, 2011)

A study by Beal and Flynn (2015) has shown that Smart water meters are beneficial for managing water infrastructure and are expected to have numerous advantages for the industry. The same findings were verified by Smit et al. (2015) in their study that various industrial and municipality stakeholders from Greece, Italy, Ireland and Netherland have participated. The study aimed to better understand the social, the economic and the environmental drivers for adopting smart water metering. In addition to Beal and Flynn (2015) findings, the researchers concluded that adopting an advanced water management system involves a stronger corporation-customer relationship in terms of reputation. That can be explained by the smart water metering technology facility in detecting leaks and help in rational use of resources, which supports economic activities sustainability and enhances the image of the water utility.

Conventional meters are read manually during the billing cycle, requiring each meter to be physically visited every month. The meters, in this case, are subject to misreading and errors in processing the data, which adds to the non-revenue water. Data handling is considerably reduced by using smart meters linked to automatic meter reading systems, which allows more accurate billing of water consumption. (Arsdel, 2017)

Smart water meters enable water authorities to collect and manage water consumption and supply data. They can also use the data to identify and prevent leakages, manage waste and conserve water. As well as that, utilities collecting and analysing of such reliable, real-time water usage data can potentially change water consumption behaviour. (Randall & Koech, 2019)

Smith (2020) reported that reading records gathered manually can be lost or transferred to the system with issues in measurement units if the system is not set up correctly. That can be reduced using a smart network and automated system solution.

2.5.3.2 Smart Metering and Real Losses

On top of that, water meter type and specifications could affect the control of real loss in the water network. District water meters are a more intelligent IT platform for remote water usage than water supply and purchase. This system increases the capability to focus on specific areas and assists in potential leak detection before it becomes a costly problem. Also, it allows a utility to prioritize preventive maintenance activities as it provides an understanding of regions suspected of water leakage. (Smith, 2020) Therefore, water utilities can better deal with real losses by smartening the water distribution monitoring and management systems.

Loureiro et al. (2014) have documented the usage of water metering data in improving control over water losses. They used a systematic approach for analysing the extensive meter reading data empowered by algorithms. They argue that the approach helps better understand and estimate real and apparent losses. Using this approach, researchers recorded a drop in non-revenue water of more than 10% in most DMAs involved in the study.

Alvisi et al. (2018) have done a case study on Gorino Ferrarese (FE, Italy) to test the benefits of a smart metering system in evaluating water losses at the DMA level. They monitored the hourly usage in specific DMAs equipped with electromagnetic water meters. The study assumed that water consumption data is available for part of the consumers within the DMA considering the error of that assumption. The study revealed that 60% of smart metering implementations had attained a minor error of 2% in estimating daily consumption by DMA. In other words, it improved the billed water calculation's accuracy and the closing water balance by 2%.

Cho & Park (2019) have reported the case of Cha-ri (a small village in Seosan City of Republic of South Korea). The village experienced a high NRW of 32%, leading water utilities to implement various smart water management solutions, including smart water metering. Smart metering was introduced to prevent actual loss and improve the services provided. As a result, the village reduced the NRW percentage to 10% (a drop of 22%) with a savings of about 514,925 dollars.

2.6 Summary

The literature review chapter covered previous literature, articles, and studies related to this study subject. The following parts will discuss comments on the literature reviewed and draw a summary of the most important articles and studies found helpful to this study's objectives.

Chapter Three: Conceptual Framework & Methodology

3.1 Introduction

Research is about repeating the search of a topic and argues that there is a gap in the earlier research and was not extensive in the sense that room for improvement still exists. (Sufian, 1998 cited in Al-Maskati, 2013) Business research is a systematic investigation that aims to increase knowledge in a particular field or managerial dilemma to guide administrative decisions. The process includes planning, collecting, analysing and disseminating relevant data and helps decision-makers take appropriate actions to maximise organisation performance. (Cooper & Schindler, 2014) The research design shows the logical sequence which links the empirical data to the problem and objectives of the study and consequently to the conclusion. It defines the strategy and the procedure which will be applied to investigate and approach the research problem. (Al-Maskati, 2013) Figure (3-1) illustrates different types of design, methods and strategies.

After understanding existing knowledge related to non-revenue water and water metering role in reducing water losses through pieces of literature were reviewed and presented in the previous chapter (chapter 2). This chapter outlines the methodology techniques adopted in this study. Details of the research strategy, method and approach, and conceptual model is provided. The methodological approach of the research is discussed, and the justification behind the selection is explained.

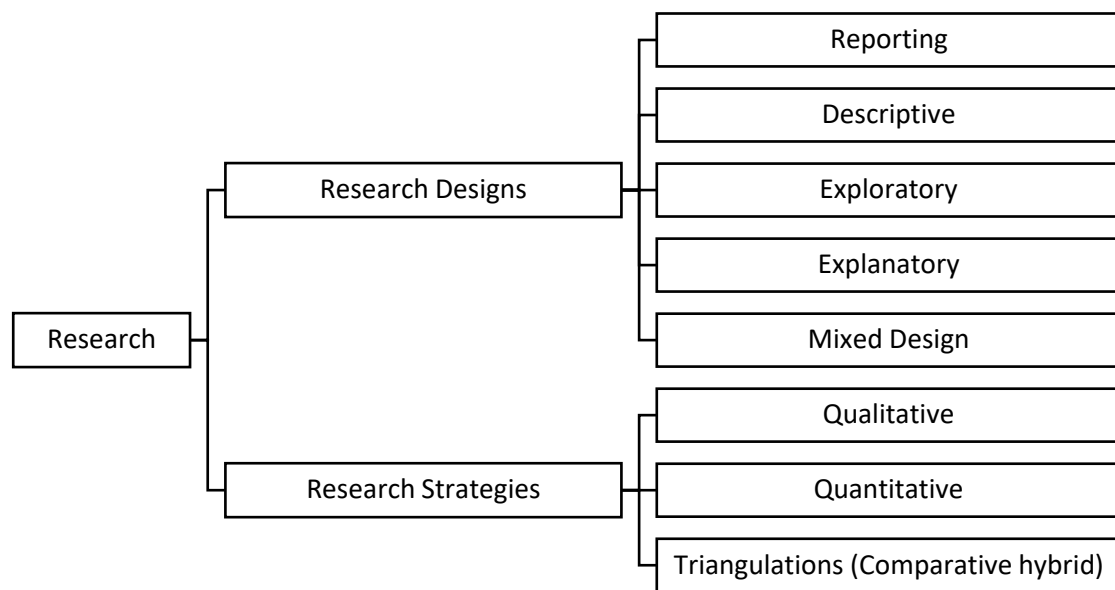


Figure (3-1): Types of Research Designs and Strategies (Source: Al-Maskati, 2013)

3.1.1 Conceptual Framework

As concluded from the literature review, implementing the smart metering system will cause a direct and indirect impact on controlling the non-revenue water level. It will directly reduce metering inaccuracies and data handling errors, apparent losses. Also, it indirectly assists in detecting leaks (real losses) and illegal consumption. Besides, a case study was conducted by Dr Hana Al Maskati, the Leak Detection & Control Group head at EWA of the Kingdom of Bahrain. She concluded in her investigation that the apparent loss is the major component affecting the NRW level in the Kingdom of Bahrain in terms of meter inaccuracy. Based on these facts, the significance of the relationship between smart metering system implementation and the reduction of NRW will be tested using the framework as shown in Figure (3-2). The framework is adapted from the

IWA water balance table. Table (3-1) illustrates the study's indicators against water losses elements.

Table (3-1): Comparing Water Loss Elements and Study Indicators

Water Balance Element		Indicators
Apparent Losses	Unauthorized consumption	Illegal Connection Cases
	Customer meter inaccuracies and data handling errors	Meters Inaccuracy (meter defect) Cases
Physical Losses	Leakage on transmission and distribution mains	Leakage Cases

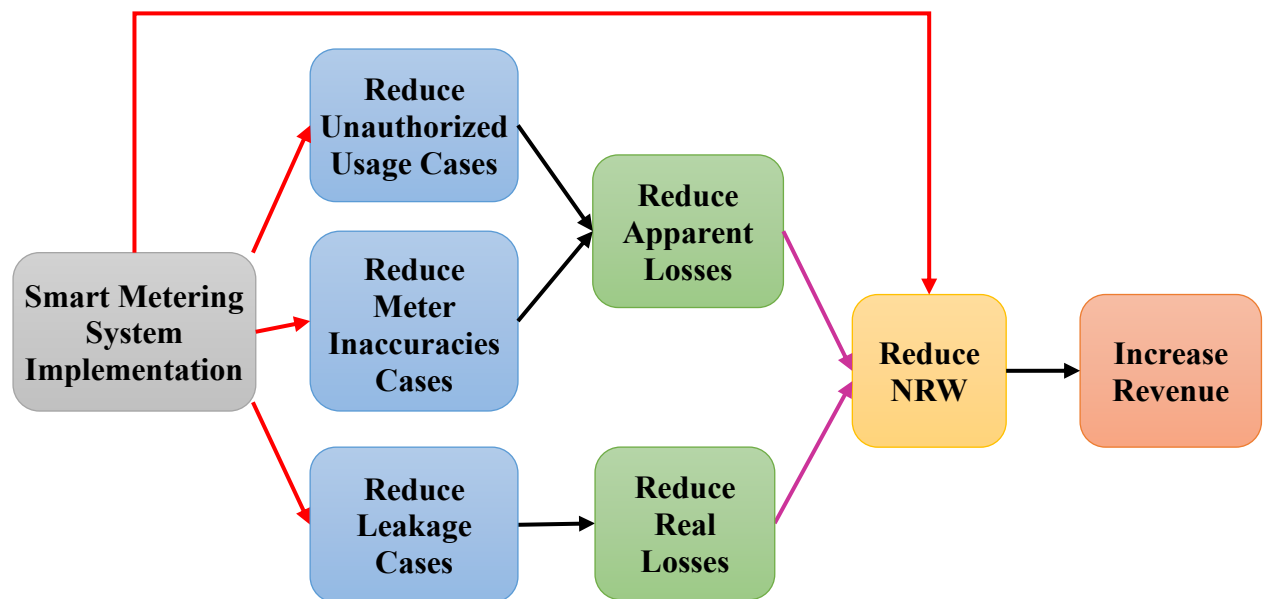


Figure (3-2): Research Conceptual Framework

This research project is conducted to answer the following questions:

1. What strategies are implemented by the Kingdom of Bahrain's government to manage the NRW?
2. What is the status of water losses in the Kingdom of Bahrain?

3. What is the impact of the smart metering system on water losses in the Kingdom of Bahrain?
4. How many increases in revenue did smart metering achieve in the Kingdom of Bahrain? How much is the saving if NRW is reduced by 1%?

To gain more understanding of the impact, the smart metering system on the water losses, the following hypotheses will be tested, as well as testing the extent to which the reduction in apparent losses and real losses influence the reduction of NRW:

- H1. There is a significant relationship between % Smart Meters and %NRW*
- H2. There is a significant relationship between % Smart Meters and customer meter defect cases*
- H3. There is a significant relationship between % Smart Meters and illegal connections cases.*
- H4. There is a significant relationship between % Smart Meters and leaks cases*

3.2 Research Methodology

This research is designed to gather information about the status of non-revenue water in the Kingdom of Bahrain and analyse the real impact of implementing the smart metering system on water losses and revenue. That will be performed through journals, magazines, government publications, official statistical information, involving three parts, as follows;

- Review the water losses situation and strategic plans to manage the NRW.
- Analyse the smart metering system's impact on water losses regarding leakage, meter inaccuracies, and unauthorized consumption.
- Calculate the financial impact of smart metering implementation on water supply revenue.

The researcher has to decide about design, strategy, and approach, collecting and analysing data to answer research questions. The research design is the plan to answer the research questions. In contrast, the research method is the strategy used to execute the plan.

3.2.1 Research Design

Cooper & Schindler (2014) documented no simple classification system of research design that describes all the variations to be considered in the research process. Table (3-2) summarizes research methodology descriptors defined by Cooper & Schindler (2014). Though research designs can be described using eight descriptors factors, as follows;

1. Degree of research question crystallisation, whether the study is exploratory or formal. The project's objectives and research questions are organized to be easily understood. The experimental studies are used to discover research tasks using loose structures. Formal investigations test hypotheses or answer research questions involving specific procedures and data sources. Usually, formalised studies pass through exploration before selecting the design type.

2. Method of data collection; two terms are used to distinguish between two types of data collection processes: monitoring and communication. Monitoring studies refer to research compromise data collection without the need to respond from anyone, and the information is collected from available records of observations. In contrast, communication studies involve collecting responses to personal or impersonal questions related to the subject. These questions are asked employing personal interviews, telephone conversations, self-administrative instruments sent via mail or electronically, or instruments accessible before and (or) after stimulus conditions in an experiment.
3. Researcher control of variables; two research designs are identified experimental and ex posts facto "from a thing done afterwards" according to the ability of the researcher to manipulate variables. In experimental design, the researcher controls the study's variables by changing or holding constant values of variables as per the research objectives. It is used for studies to discover the impact of a specific variable on other variables, where causation hypotheses are tested. In ex post facto design, the researcher has no control over the study's variables, and they can only report the changes. As the researcher does not influence the variables, they have to select the study sample carefully and statically interpolate the findings.
4. Purpose of study; research is carried out for different meanings based on which studies are classified into four types; reporting, descriptive, causal-explanatory and causal-predictive.

- Reporting study gives a summation of data, usually reorganise data to provide a deeper understanding of a specific topic or generate statistics for comparison purpose. Though this type of research is simple as available data, the data are sometimes difficult to obtain from the sources. The study is concluded by drawing interferences out of the collected information. The outcomes of reporting studies process are gathered carefully. Thus, they can be considered by various stakeholders and managers in decision making.
- The descriptive study attempts to describe a phenomenon by answering what, when, who, where and how much. The study is conducted using the significant existing database of fact findings. It is done by creating a profile of a group of events and factors to understand and observe the relationship between several events or research variables. Therefore, it focuses on fact findings and well-defined dimensions which are systematically measured. The study outcomes may not explain the reason behind the occurrence of an event or the existence of a relationship between variables. However, this type of study can help decision-makers discover factors or characteristics that enhance performance or support the organisations towards achieving their goals. The analyst of different management disciplines may use it. Descriptive investigations are used for planning, monitoring and evaluating policies and strategies.
- The explanatory study goes beyond descriptive research to explain the purpose of phenomenon occurrence by answering why and how questions. It is also known as a correlational study and concerns testing the relationship between several variables using theories and hypotheses.

- Predictive study concerns predicting time and situation in which the event will occur by making a high order of inference. It helps predict the implications of applying an action and forecast future values. This can be done by and simulation of models created to explain the relationships between variables. In addition, the predictive study contributes to the development of the theory of the phenomenon.
5. Time dimension: the research designs are classified into cross-sectional and longitudinal studies based on time scale. The cross-sectional studies are conducted on a snapshot of a specific point in time, while the longitudinal studies are carried out repeatedly over an extended period.
 6. Topical scope: the study's depth defines the study's design, either case study or statistical. While the case studies focus on a complete contextual analysis of interrelations between particular events, statistical studies target breadth, not depth. In the statistical research design, the population characteristics are captured from samples' characteristics which resulted from hypotheses tested quantitatively. Thus, the representativeness of the sample and design validity can control the generalisation of the findings. On the other hand, the hypotheses are tested using qualitative data in the case studies. Thus, it gives practical understanding for problem-solving, decision making, evaluation and strategy.
 7. Research environment: the different settings can also be taken for design environmental conditions, namely field and laboratory conditions.

8. Participants' perceptual awareness may undermine the usefulness of the research design. Participants may behave less natural that will affect the study conclusion.

Table (3-2): Research Methods Descriptors (Source: Cooper & Schindler, 2014)

Descriptor	Options
Degree of Research Question Crystallization	○ Exploratory study ○ Formal study
Method of Data Collection	○ Monitoring study ○ Communication study
Researcher Control of Variables	○ Experimental study ○ Ex post facto study
The Purpose of the Study	○ Reporting study ○ Descriptive study ○ Explanatory study ○ Predictive study
The Time Dimension	○ Cross-sectional study ○ Longitudinal study
The Topical Scope	○ Case study ○ Statistical study
The Research Environment	○ Field study ○ Laboratory study ○ Simulation
Participants' Perceptual Awareness	○ Actual study ○ Modified study

This study aims to collect data about the non-revenue water in Bahrain and analyse the effects of implementing a smart water meter system on reducing water losses. For that purpose, mixed methods are employed in the three different parts of the study.

- The first part consists of reporting the position of Non-Revenue Water in the Kingdom of Bahrain, reduction strategies and initiatives.
- In the second part, the influence of smart metering on NRW will be tested using longitudinal and cross-sectional formal descriptive and explanatory research designs. Cooper & Schindler (2014) quoted that formal studies have several aims. For example, he describes phenomena or characteristics of the population, assuming the occurrence proportions of these characteristics within the population and discovering the correlation associated among different variables. On the other hand, the correlational study is a type of descriptive study that is formal with clear hypotheses statements or investigation questions. Depending on the tested relations and several variables, the hypotheses or questions can be complex or straightforward. Furthermore, it can be univariate, bivariate or cross-tabulation.

The descriptive analysis considers the historical data, Key Performance Indicators (KPI). It describes the performance in comparison to a predefined benchmark. It aims to study past trends and probability to reflect future performance. (Simonton, 2003) As per Saunders et al. (2009), descriptive research is done to obtain an accurate profile of events, persons, or situations. Sometimes the descriptive studies become too descriptive, affecting the worthlessness of the study's outcomes. Usually, many studies incorporate the explanatory and descriptive parts to govern the causal relationship between the variables to avoid such a conclusion. In terms of a time dimension, the cross-sectional study design is an observational study type where the investigator measures variables

at one point in time. It can be a single snapshot of one point in time only or multiple snapshots one follows the other. (Levin, 2006) the cross-sectional studies are used to examine existing programs at different stages of intervention to evaluate the program's effectiveness. Assessment of intervention effectiveness is done by measuring the dependent variable among clients at starting and termination stages, which considers the impact of the intervention. (Kumar, 2011)

- The third part of this study will be assessing the financial impact of smart metering in respect of water supply revenue.

3.2.2 Research Strategy

The research strategy or approach is an action plan that guided the researcher's effort and thoughts to systematically conduct the research and produce quality and detailed reporting of results. (Jenny, 2014) There are three approaches, namely: qualitative, quantitative and triangulation or hybrid research strategies. Saunders et al. (2009) stated that qualitative data collection and analyses generate non-numerical data, mainly words, whereas the quantitative technique uses numerical data.

Qualitative research aims to understand the event and why it occurs and often generate theory. It employs interpretive techniques to describe, translate, and decode phenomena in terms of meaning, not frequency. The qualitative approach is used for data collection and analysis in different forms. Focus groups, semi-structured and unstructured interviews, ethnography, case studies, action research, observation, conversation analysis, and discourse analysis are used at the data collection stage. The data of qualitative studies are extracted or collected from sources including

people, organisations, publications, environment and events. (Fellows & Liu, 2003; Cooper & Schindler, 2014)

Quantitative research can provide precise measurements of a phenomenon by answering how often, how much, how many, when and who. It is usually used to test theory and understand data through statistical analysis. Quantitative data is often used to represent results of laboratory experiments like errors, frequencies and similar judgements, and correlational studies. (Simonton, 2003) The quantitative data is commonly collected through surveys, interviews, experiments, case studies, and document reviews. The most crucial step of the quantitative approach is selecting the appropriate sample size to guarantee the accuracy and consistency of results. The sample size is to be sufficient to consider the most reflective of the population. (Chipeta, 2020)

Qualitative and quantitative techniques can study various aspects of a person or a group. The main strength of qualitative work is its ability to explore various facets of a person or a group. (Yin, 1994). However, the findings are suspected of human errors in data collection and interpretation. Also, the sample results are too subjective and cannot be generalised to the population. (Blaxter et al., 2006; Cooper & Schindler, 2014). In contrast, the main strength of quantitative research is presented in the accuracy of findings obtained by the reliability of measurements and sampling design, which allow generalising the findings. (Bryman and Bell, 2003; Blaxter et al., 2006).

Nevertheless, the approach has limitations concerning analysing complex phenomena and providing less insight into human attitudes and behaviours. Thus, the approach is not considered a valuable tool for building theory. (Bryman and Bell, 2003)

Many researchers, such as Bryman and Bell (2003), Blaxter et al. (2006) and Cooper & Schindler (2014), have suggested using a mixture of qualitative and quantitative approaches. It is known as a hybrid method to minimise the limitations of both systems. This approach gives perspective to the phenomena under study. (Smith et al., 2002)

Based on the topical scope and nature of the research questions of this study, qualitative and quantitative techniques were utilised to address the objectives of this research.

3.3 Research Tools

The data collection was based on documents and record of field observation; the data was a combination of narrative and numbers. Yin (2009) has defined bases for matching research strategy to the research questions through three criteria.

1. The form of research questions
2. The control ability of the researcher on the actual behavioural events
3. The focus degree of research on contemporary versus historical events

Yin applied the above criteria on five robust research designs, namely: experiment, survey, analysis of archival information, history and case study. The following Table (3-3) illustrates how the methods are matched with the above conditions.

Table (3-3): Criteria for Selecting Research Design (Source: Yin, 2009 cited in Al Maskati, 2012)

Research Strategy	Form of Research Question	Requires Control of Behavioral Events?	Focuses on Contemporary Events?
Experiment	How/ Why	Yes	Yes
Survey	Who, What, Where, How Many, How Much	No	Yes
History	How/ Why	No	Yes
Archival Analysis	Who, What, Where, How Many, How Much	No	Yes
Case Study	How/ Why	No	Yes

An archival analysis is a study that investigates how events and people affect contemporary society. It consists of seven essential questions that can be asked to study how various people and events influenced culture. The archival research method is a broad range of activities conducted to review documents and reports generated by and about organisations. It often involves the study of historical documents created at some point in the past. It is also employed for non-historical investigation studies of documents produced about contemporary events. (Ventresca & Mohr, 2002; Saunders et al., 2009) Archival research includes consulting historical records or searching and extracting information from archives that preserve access to the original preliminary source of the material. (Allen, 2018) These archives enable researchers to view organisational life, events, and strategies across administrative space and time. Investigating archival material is essential as a helpful tool ubiquitously and strategically. (Ventresca & Mohr, 2002)

In Table (3-3), the survey research method is also used for the same conditions as archival research. According to Saunders et al. (2009), both ways are used for exploratory and descriptive questions. However, the surveys are quantitative; quantitative data is collected and analysed using descriptive statistics. In contrast, archival research is a qualitative approach; collected data are secondary and can be of qualitative or quantitative nature.

For this study, the research questions are “What is the water losses situation in the Kingdom of Bahrain?”, “What does the Kingdom of Bahrain’s government consider the strategies to manage the NRW?” “What is the impact of the smart metering system on water losses in the Kingdom of Bahrain?”, “How much is the increase in revenue did smart metering achieved in the Kingdom of Bahrain?”. Archival research and surveys can tackle such types of questions. However, as secondary data will be used, archival research is selected as the primary research strategy.

3.4 Data Collection

The secondary data type is defined as gathered data by entities other than the researcher and published in documents and literature. Sources of these data can be internal or external. The desktop review has been conducted to gather information from different secondary sources to attain the study’s aim. The data are extracted from published and unpublished documents: reputable journals, newspapers, policies, regulations and codes of practice, official government reports, and project documents.

Data gathered are in different forms, numerical and texts. The numerical data are historical data related to Bahrain's overall water distribution network for years 2015-2020, and cross sectional data of 32 DMAs.

3.4.1 Targeted Population

For first part of statistical analysis:

The collected data is for time scale of years 2015 to 2020 per quarter.

For the second part:

The water distribution network of the Kingdom of Bahrain is divided into 180 District Metering Areas (DMAs). This research will focus on 32 DMA, through which the Non-Revenue Water (NRW) is calculated for each initially, after water meter replacement, and after leak detection and repair exercises.

3.5 Measurement of Variables

Referring to Figure (3-2), for the first part of relationships represented in red arrows, the water losses parameters as demonstrated in Table (3-1) will be considered to test the association with smart meters variable (represented in %smart meters)

For second part of relationships represented in purple arrows, the dependent variable of this study is the Non-Revenue Water (NRW) and the independent variables are the apparent losses and real losses. The dependent variable (NRW) is measured by NRW%, unauthorized usage cases, meter inaccuracies cases and leakage cases.

3.6 Data Analysis

The collected data from various sources mentioned above will be analysed using computer software. The Microsoft Excel and SPSS software will be

utilized to statistically testing the correlation between variables and extent of effectiveness of smart metering and use cross-tabulations, ordinary frequency tables, and charts to check whether the smart metering effectively reduces water losses. The data analysis will be through the following steps:

Step1: Reporting of Kingdom of Bahrain Strategies and plans implemented to reduce NRW.

Step2: Reporting and descriptive analysis of NRW measure (percentage NRW and LLI) trend in contrast of targeted values during years 2015-2020.

Step3: Performing descriptive analysis of water loss cases during 2015-2020 and cross sectional data of NRW in 32 DMAs before and after meter replacement with smart meters, in form of trends, charts, percentages and mean.

Step4: Testing correlation between smart metering implementation (as % of smart meters) and NRW, unauthorized usage cases, meter inaccuracies cases and leakage cases, using historical, quarterly data of 2015-2020.

Step5: Performing multivariate regression analysis of the cross sectional data of NRW in 32 DMAs before and after meter replacement with smart meters.

Step6: Calculation of financial saving of reduction in NRW

3.7 Summary

To sum up, the researcher has selected a mixed research approach to meet the study objectives by applying archival analysis for data collection. In addition, the data will be analysed using descriptive and statistical analysis. Figure (3-3) shows the workflow followed in the study, and Table (3-4) links the analysis steps with study questions.

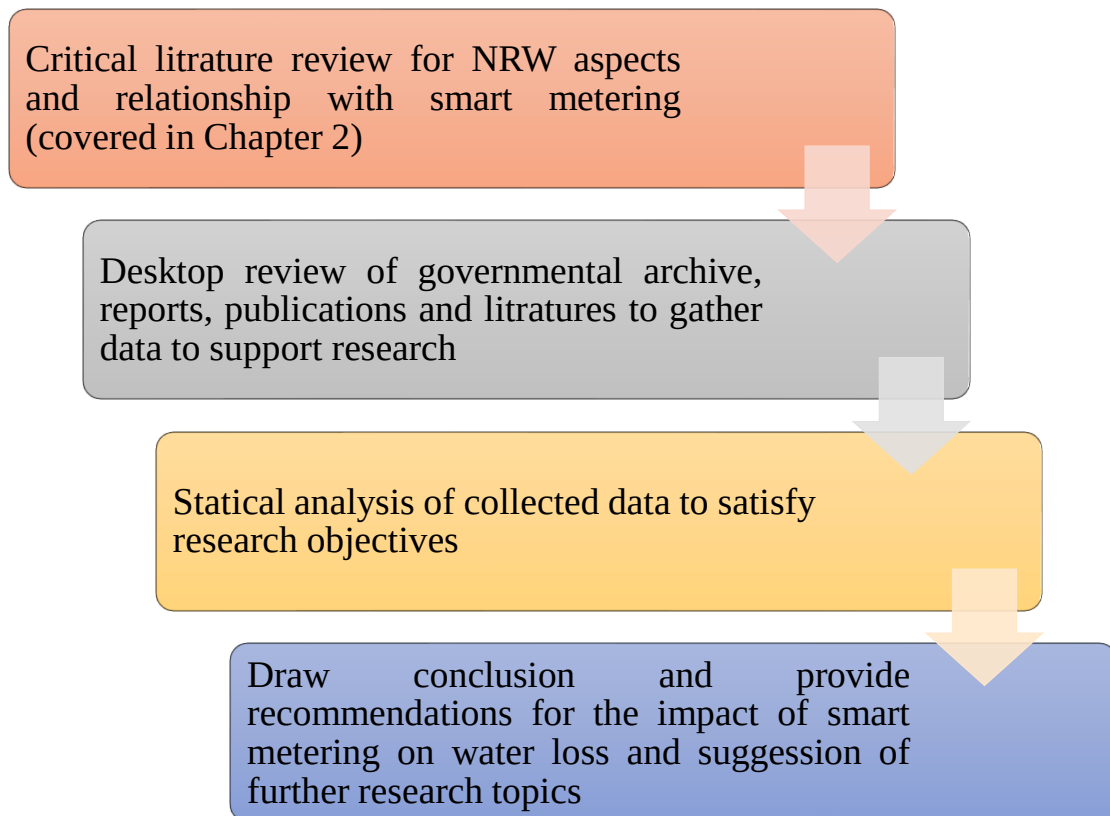


Figure (3-3): Workflow Used for the Study

Table (3-4): Analysis Steps and Research Question

Research Question	Step
1. What are the strategies implemented by the Kingdom of Bahrain's government to manage the NRW?	1
2. What is the water losses situation in the Kingdom of Bahrain?	2

Research Question	Step
3. What is the impact of the smart metering system on water losses in the Kingdom of Bahrain?	3, 4 and 5
4. How many increases in revenue did smart metering achieved in the Kingdom of Bahrain? How much is the saving if NRW is reduced by 1%?	6

Chapter Four: Data Analysis and Findings

4.1 Introduction

This chapter will discuss data analysis and findings under the following headings:

- i. Water Supply Tariff and Cost Recovery
- ii. NRW Reduction strategy and initiatives in Kingdom of Bahrain
- iii. NRW Data Analysis; which covers different statistical analysis tools, namely descriptive analysis, correlation and multivariate regression.
- iv. Financial Impact of Reducing the NRW

The data were collected from periodical reports, statistics, official documents and strategic plans of the Electricity & Water Authority in the Kingdom of Bahrain. Also, some data were extracted from published articles, conference proceedings and thesis. The data were analysed using Microsoft Excel and SPSS.

4.2 Water Supply Tariff and Cost Recovery

In the Kingdom of Bahrain, the water demand of municipal and industrial sectors is met mainly by desalination plants. 78% of total production capacity is by Independent Water and Power Plants (IWPP) and 22% by EWA's Power and Water Plants, as of the year 2019 that justify the expensive cost of potable water supply. In addition to production cost, the potable water supply cost covers the cost of transmitting, storing, distributing water to target customers and maintaining the supply system.

According to a research paper by Al-Zubari (2014), the production cost is measured by dividing the total expenses by the total quantity of water produced. The entire cost includes fixed and variable costs. The fixed

expenses consist of capital amortization, insurance, and fixed operation and maintenance costs like salaries, administrative expenditures, and equipment maintenance. The variable costs include the cost of energy used, chemicals, and other consumables. Generally, the cost of producing water varies based on the desalination technology used. Overall, the Electricity and Water Authority has announced that the total cost of potable water supply to consumers is BD 0.750 per cubic meter of water.

Regarding non-domestic usage and domestic usage by national second accounts and non-nationals, the water tariff is equal to the water supply cost. That means the EWA has achieved full recovery of the water cost used by these categories.

However, in the case of domestic usage by Bahraini nationals, the first account (subsidized account) that represents 27-35% of household use according to EWA statistics in the year 2018, the water supply tariff is relatively shallow compared to the cost, as shown in Table (4-1). The tariff structure marks that consumption falls within the first block (first 60 cubic meters per month) covers only 3% ($0.025 / 0.750 \times 100\%$) approximately of the cost, revealing subsidization of more than 95%. In addition, the high consumption in the third block is about 27% of the cost.

Table (4-1): Water Supply Tariff vs Cost for Subsidized Bahraini Accounts (Source: EWA Website)

Consumption Units	Price (BD)	Cost (BD)
First 60	0.025	0.750
61-100	0.080	
Above 100	0.200	

For instance, a subsidized domestic customer consuming water of 115 m³ per month will pay BD 7.700, whereas such amount of water costs BD 86.250. This implies $(7.7/86.25)$ only about 9% of the consumed water cost will be recovered as revenue, while the remainder of the price (91%) is compensated by government funding (subsidies). Therefore, the cost recovery is very low in the case of subsidized consumption. This issue is one of the main factors contributing to the kingdom's water shortage. This contributes to the non-payment of the water bills.

4.3 Kingdom of Bahrain's Strategy to Reduce NRW

Controlling NRW volume has been given significant attention by the Electricity & Water Authority (EWA), the governmental entity responsible for water supply in the Kingdom of Bahrain. Since 2006, EWA has spent efforts reducing the NRW and mobilising all resources to establish pillars to calculate the water losses. EWA has developed and implemented a comprehensive, integrated strategy to address and manage the real and apparent losses aspects of NRW within its water distribution system, aiming to reach 15% by 2022 (from 27% in 2020). The strategy involves:

- a. Establishment of smart metering system which consists number of the following programs;
 - i. Implementation of District Metered Areas (DMAs), that are properly designed, isolated, monitored and maintained.
 - ii. Replacement all conventional mechanical water meters by smart electronic meters all over Kingdom of Bahrain.
 - iii. Deployment of Advanced Metering Infrastructure (AMI) all over Kingdom of Bahrain, for automatic, remote real meter data transmission. Further, integration of smart metering

infrastructure with billing system to bill real, accurate consumption.

- iv. Implementation of Meter Data Management (MDM).
- b. Pressure Management Areas (PMAs) by system optimization and installation of automatic Pressure Relief Valves (PRVs).
- c. Rapid replacement of leaking water network and geo-referencing of leakage.

Several initiatives were implemented targeting real and apparent losses management based on that. The following parts will describe these initiatives and outcomes accomplished from 2015 to 2020.

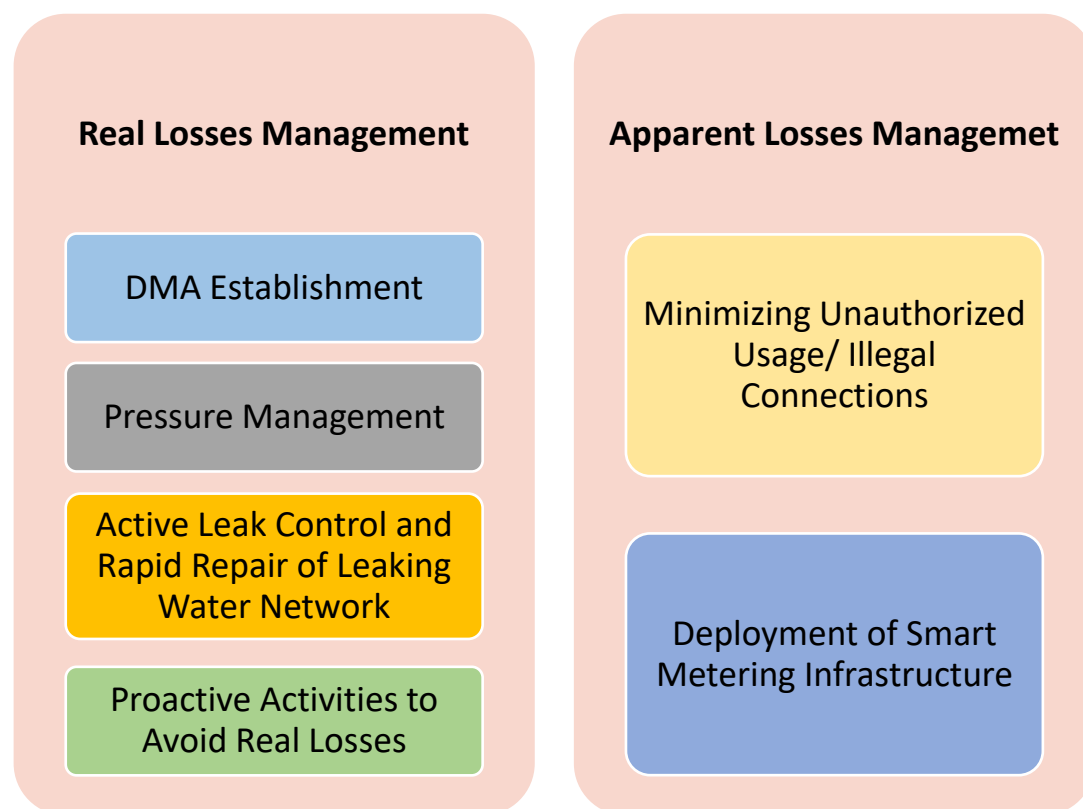


Figure (4-1): Group of Initiatives Implemented by EWA to Reduce Water Losses

4.3.1 Real Losses Management Initiatives

The primary practices followed by EWA to reduce real losses (presented in visible and invisible leaks) are DMA establishment and operation, active leak detection for invisible leaks, pressure management, and quick response to visible leaks. This combination of activities results organizes the network, controls the leak's intensity, and improves allocation and repair of the leak.

4.3.1.1 DMA Establishment and Operation

The separation of the water supply networks into manageable distribution areas has assisted in identifying the locations where water losses. DMA establishment passes through planning, design, field investigation and pressure testing, isolation, DMA meter installation and monitoring. The DMA is designed based on the network characteristics, several customers and demand. Finally, the designed DMA model is simulated, assessed and calibrated. Figure (4-2) is a model illustrates types of DMAs.

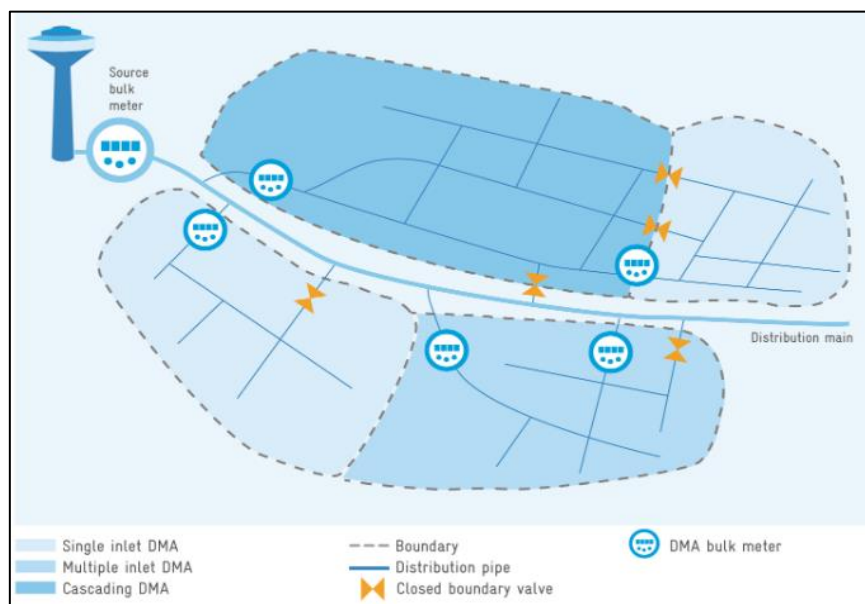


Figure (4-2): DMA Model (Source: EWA Statistics Report)

The establishment of the DMAs in the Kingdom of Bahrain began in 2013. There are currently 180 such centres operating in the country. Figure (4-3) shows Bahrain's map segments based on governorate, tank zones and DMAs. The four governorates are divided into 40 tank zones and 180 DMAs. Table (4-2) shows the number of DMAs within each governorate. The DMAs are equipped with smart water meters of electromagnetic and relevant equipment for automatic reading (data logger) monitored by NETBASE software. The NETBASE is a water network management system that enables detailed network analysis supported by graphical tools for organizing massive data. It has properties to store time-series data from various sources and estimate IWA water balance elements. The DMA details are uploaded in the Geographic Information System (GIS) to enhance analysing data related to DMA from various systems. To facilitate losses analysis, the NETBASE is integrated with SCADA (for tank zone data), GSM data loggers of DMA meters, CSS and GIS for automatic update of data.

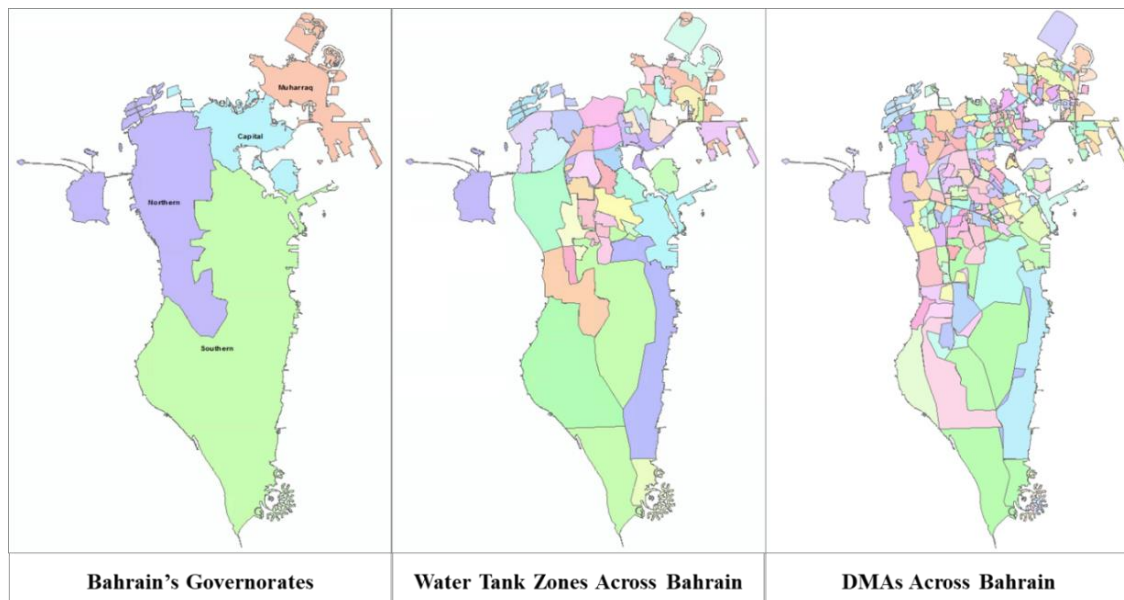


Figure (4-3): Map for DMAs in Kingdom of Bahrain (Source: EWA)

Table (4-2): DMAs Establishment as on Year 2020 (Source: EWA Statistics Reports)

Governorate	Number of Established, Active DMAs	Number of Customers
Muharraaq	38	56,632
Southern	53	48,659
Capital	50	94,048
Northern	39	75,539
Total	180	274,886

As reported by Dalton (2019), EWA has contracted a consultant in the year 2013 to evaluate the practice of NRW management at that time, conduct water auditing, prepare a code of practice for NRW monitoring and management, and reduce NRW in Muharraaq Governorate by 15% through the establishment of DMAs. The consultant has established 35 DMAs in the water distribution network in Muharraaq Governorate. The DMAs were equipped with Electromagnetic water meters and a data logger which transferred the data to NETBASE. Within three years (2013-2016) of operation, the NRW percentage has been successfully reduced from 36% to 17.5%. The project was considered as a pilot study for DMA application which ended successfully. After that, EWA has started to re-zone the network in the other Governorates.

Figure (4-4) shows progress of DMA establishment as percentage completion in reference of planned figures in years 2015-2020.

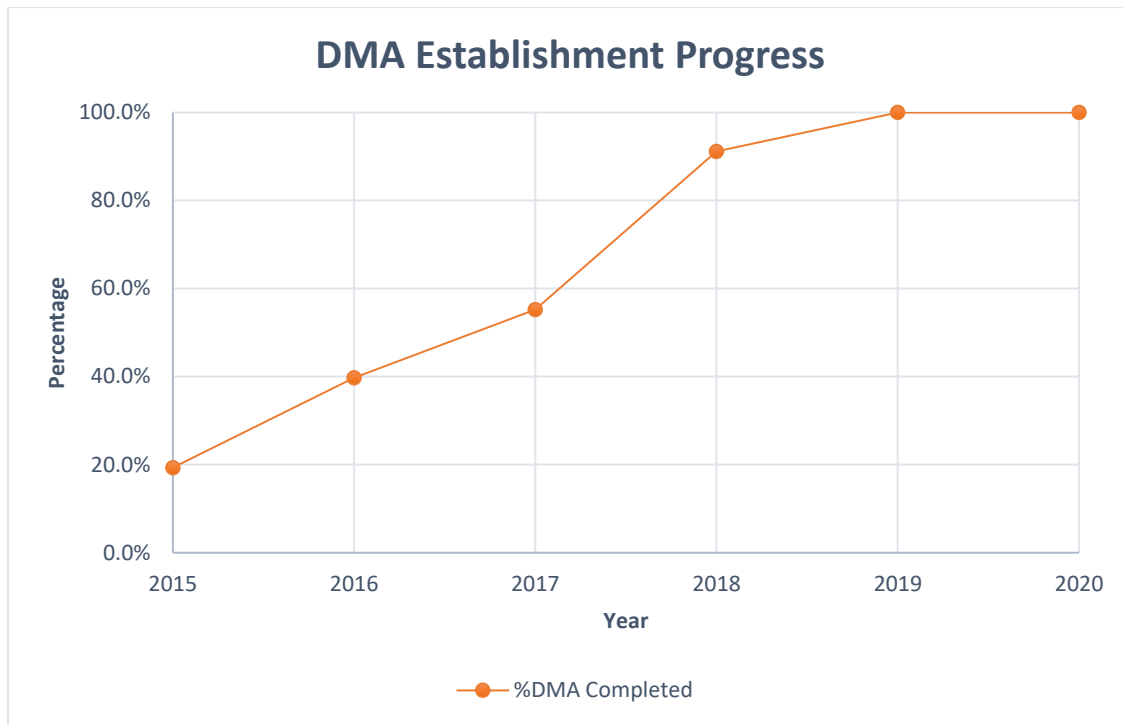


Figure (4-4): DMA Establishment Progress in 2015-2020 (Source: EWA Statistics Reports)

4.3.1.2 Pressure Management

The water pressure is a critical parameter in the distribution system; adequate pressure is mandatory to meet water demand, reducing the pressure will help minimise volume leaking water. EWA has designed and installed Pressure Reducing Valves (PRV) within DMAs in segments where the high pressure (relatively) is not needed to balance both requirements. Furthermore, the smart metering system equipped in the DMA has provided full reporting of the actual water usage behaviour, seasonal variation and leakage within the DMAs that enable the optimization of pressure to satisfy the customer expectations and minimise leaks.

4.3.1.3 Active Leak Control and Rapid Repair of Leaking Water Network

Active leak control activities mainly aim to detect leaks in the water distribution network. Annual plans are being executed to survey the network per DMAs to identify locations of potential leak. Advanced tools and equipment are used for leak detection such as noise correlators, localising equipment and noise loggers (mobile or permanent).

Besides that, reported leaks (burst) include those raised by customers as complains via EWA – customer communication channels in different forms, visible leak or meter leak. EWA has managed to resolve reported leaks within a maximum of 6 hours to minimise water losses in network leaks.

4.3.1.4 Protective Activities to Avoid Physical Losses

For many reasons, water leaks can occur in pipes, fittings or valves. Regrettably, these items are installed underground, making it difficult to investigate and identify the leak. Thus, EWA has continuously maintained valves, replace old valves and networks. In addition, the valves and ferrules in the distribution network are surveyed and exercised yearly to assess their conditions and take proactive actions to ensure reliable functioning. Regarding pipeline replacement, the program is put based on the age of the network and the leakage history of the area. Table (4-3) shows the number of pipeline replacement projects and valve replacements in 2015-2020.

Table (4-3): Protective Activities During 2015-2020 (Source: EWA Statistics Reports)

Period	Year					
	2015	2016	2017	2018	2019	2020
Pipeline Replacement Projects	26	13	22	35	28	14

Period	Year					
	2015	2016	2017	2018	2019	2020
Isolation Valve Replacement	Data not available		1,017	509	829	472
Fire Hydrant Valve Replacement	Data not available		161	44	81	67

Furthermore, EWA has experienced different methods to assess the inner condition of pipelines to anticipate potential leak locations and replace them. Currently, EWA is studying innovative techniques to detect leakage, such as satellite technology for leak detection. Using satellite images, it primarily analyses soil characteristics to identify potential leak locations. The leak location is identified within an area of 100 m² which is to be pinpointed by the leak detection team on-site either visually or using acoustic technology if the leak is invisible.

4.3.2 Apparent Losses Management Initiatives

EWA has developed various initiatives to reduce apparent losses associated with unauthorized consumption and customer meters' issues. Like introducing methods and policies to fight unauthorized usage, customer meter replacement by more accurate smart meters, building infrastructure for automatic reading, and managing customer meters.

4.3.2.1 Minimising Unauthorized Usage/ Illegal Connection

The Water Distribution Directorate of EWA carries out frequent field surveys to discover bypass connections, illegal pumps, and abandoned connections to fight unauthorised water usage. In addition to planned surveys, random surveys are conducted by all teams in EWA while functioning their responsibilities. Recently, EWA has formulated an Illegal Connection Group whose responsibility is to carry out field surveys and deal with reported illegal connections.

The detected illegal connections are disconnected immediately, then investigated and assessed to calculate the volume of fraud. The calculation depends on the condition of unauthorized usage, whether it is done by the metered customer or unmetered.

Figure (4-5) is a workflow followed by EWA to adjust and charge for unauthorized consumption.

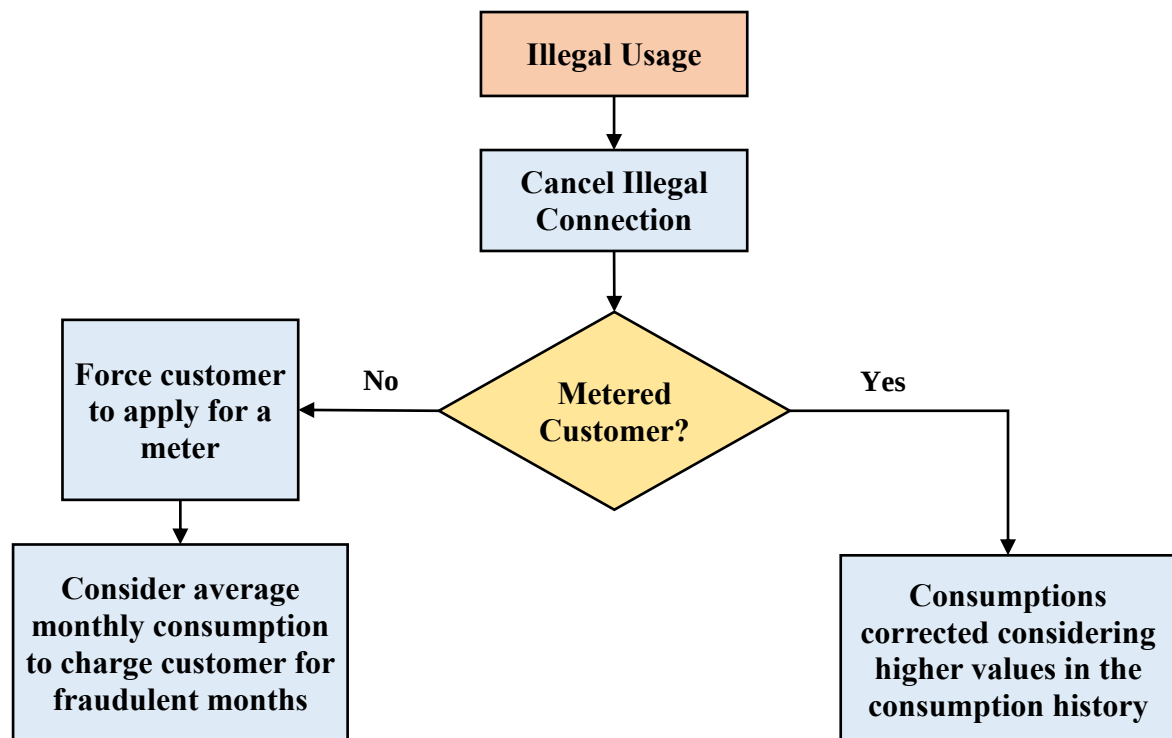


Figure (4-5): Workflow for Correction of Illegal Usage Account
(Source: EWA)

4.3.2.2 Deployment of Advanced Metering Infrastructure

The water Advanced Metering Infrastructure (AMI) has been implemented and deployed since 2015 to enhance automatic customer meter reading and build pillars for smart water grid. The AMI consists of smart water meters, Automatic Meter Reading (AMR) network and meter data management

software (Head-End system). Three AMI models were built based on the meter and AMR types, as demonstrated in Figure (4-6). In addition to these models, EWA uses drive-by and walk-by methods to collect meters' data in areas where the AMR network is not installed yet.

- Model 1- AMI for bulk customer meters. For bulk customer meters range from size 50mm and above, Electromagnetic water meters are used and linked with GSM data logger to transfer data to the Head-End System (HES) via GPRS.
- Model 2- AMI for domestic customer meters using Radio Frequency (RF). Ultrasonic or Electromagnetic water meters are used in this model with a radio frequency facility to transmit the meter data remotely. The data are captured by the AMR network, which is comprised of antennas and Radio Data Concentrator (RDC). The RDC stations are distributed to cover all meters in the targeted area. The data then is transferred by RDC to the HES via GPRS.
- Model 3- AMI for domestic customer meters using wired method, usually for multi-story buildings. Ultrasonic water meters are used in this model with wire. First, the data are transferred to the AMR network which consist of wired gateway and modem via wire. The data then are transferred to the HES via GPRS.

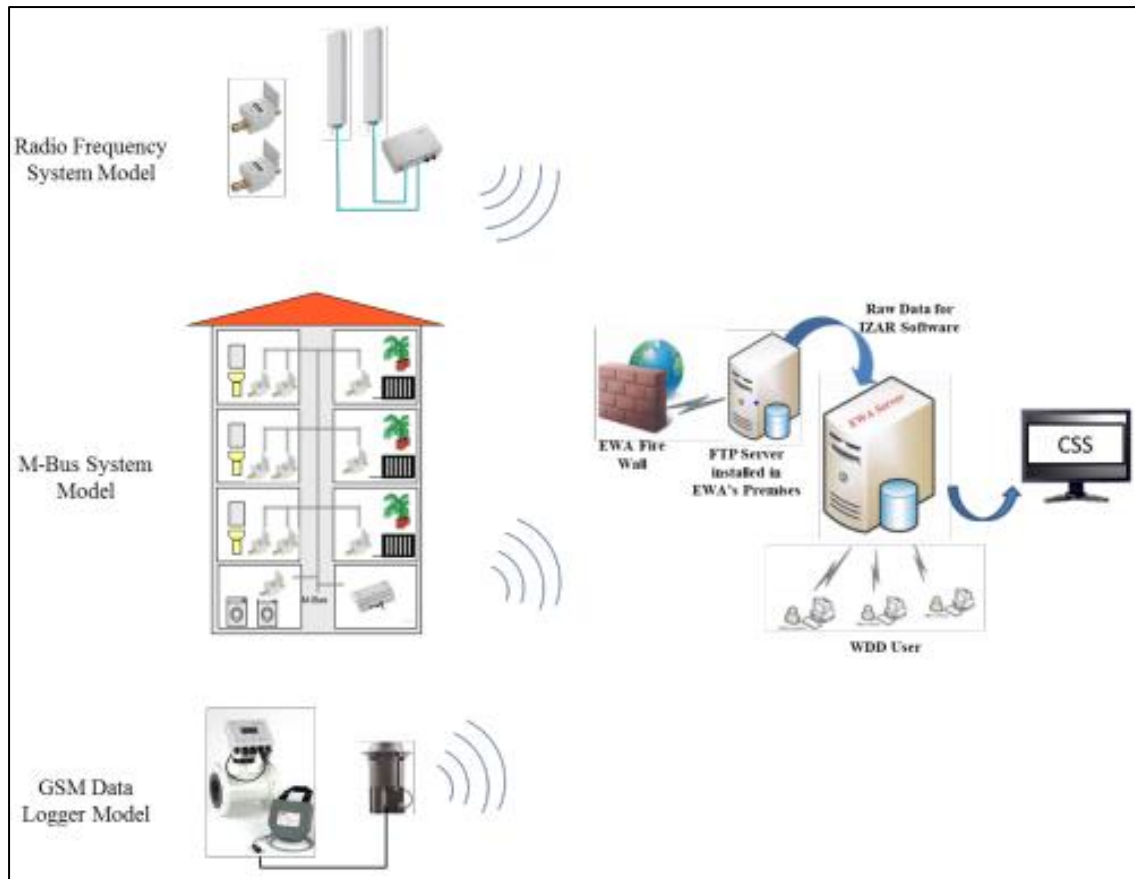


Figure (4-6): EWA Water Customer AMI Models (Source: EWA)

EWA has developed programs to replace all convention/ mechanical water meters with smart water meters and install AMR networks to fully automate the meter reading process to roll out the infrastructure all over the Kingdom of Bahrain. Furthermore, EWA has amended regulations to mandate developers to install smart water metering systems in their projects.

4.3.2.2.1 Water Meter Replacement

Customer water meters in EWA's water distribution network are divided into domestic and bulk water meters, based on the water flow rate passing through and the size of meters. The domestic meters are of sizes DN 15mm and 25mm, used for billing flow rates ranged between 1.5 m³/h and

2.5m³/h, respectively. Bulk water meters are used where the consumption is 3.5m³/h and above, with 50mm and above sizes.

Table (4-4): Types of Flow Meters in Water Distribution Network
(Source: EWA)

Meter Type	Measurement Mechanism	Category	Installation Position	Accuracy Range (R-Value)
Positive Displacement	Mechanical	Domestic	Vertical	160
Turbine	Mechanical	Domestic/ Bulk	Vertical/ Horizontal	160 250
Ultrasonic	Electronic	Domestic	All	400
Electromagnetic	Electronic	Domestic/ Bulk	All	800

Previously, EWA installed mechanical meters of volumetric (positive displacement) and vane (turbine) types. The meters were replaced by new mechanical meters after 5-7 years of operation. Unfortunately, though, many meter defect cases were reported regarding the accuracy, meter stop reading or blockage before 5 years. In addition, mechanical parts of the meter cause obstruction in the flow, and it can be easily damaged, increasing the heat losses. A recent study by WDD revealed that the average percentage error of tested mechanical water meters (of various brands) is more than the permissible error for measuring the minimum flow. This results in the misleading assessment of water losses; the minimum night flow results are not reliable as the customer could have minor leakage that flow cannot be measured by the meter.

Due to the repeated deficiencies of mechanical water meters, EWA has searched for other alternatives. In 2012, EWA installed 250 smart

ultrasonic meters (RF) of size 15mm, as a pilot project to test the smart meters in the field. After two years, the meter's performance was evaluated and found acceptable in accuracy and durability. Later, in 2015, two AMR stations (2 antennas and an RDC in each station) capture meters' data within the project area and send it to HES. Again, the project has shown satisfactory results. Thus, EWA has decided to replace mechanical meters all over the Kingdom of Bahrain with smart meters.

The first phase of the meter replacement program involved the installation of bulk water meters and disconnected meters. Table (4-5) introduces the number of smart water meters and the percentage of smart meters to a total number of meters in 2015-2020. As per statistics for the year 2020, about 23% (64,006) of water meters in the distribution network are yet to be replaced and planned to be completed in 2021.

Table (4-5): Number of Installed Smart Water Meters During 2015-2020 (Source: EWA Statistics Reports)

Year	2015	2016	2017	2018	2019	2020
No. of Smart Meters	7,639	13,178	40,679	95,505	128,666	210,880
% Smart Meters	4.0%	6.6%	19.5%	41.1%	51.3%	76.7%

4.3.2.2.2 AMI Deployment

Before the implementation of the AMI, EWA faced challenges in taking actual readings of all meters (taken manually) due to inaccessible meters, defected/ stopped meters, and a lack of human resources to cover all areas. Thus, meter readings were estimated based on customer seasonal consumption trends for several months until the actual meter reading was

obtained. Also, the meters' readings used to be recorded once per month at the end of the billing cycle. These issues have affected EWA's ability to earn revenues and contributed to an inaccurate assessment of NRW.

Further to the pilot project's success in Galali, the EWA has decided to deploy the AMI all over the Kingdom of Bahrain. Currently, where AMI is completed, the meter reading is pushed to the HES every three hours. This helps to eliminate estimated tasks and increases the certainty of customer consumption. Moreover, implementing AMI allows a significant amount of data for more accurate demand pattern analysis and minimum night flow. The progress of the meter replacement program and AMR installation for domestic meters is shown in Table (4-6). As reported, 14.5% of planned RDC stations are being constructed by 2020. In addition, EWA has published a tender for the design, installation, testing, and commissioning of AMR networks to cover all radio frequency meters in the network. As per EWA's strategic plan, the AMI will be entirely operational by the end of 2021. Figure (4-7) illustrates the status of the smart water metering project per governorate in the year 2020.

Table (4-6): Smart Water Meters and AMR Coverage per Governorate in 2020 (Source: EWA Statistics Reports)

Governorate	% Smart Meters	AMR			
		Planned RDCs	No. of RDCs	% Completion of RDC	No. of Wired Gateways
Muharraq	99.99%	58	58	100%	23
Southern	99.50%	152	33	21.7%	5
Capital	65.80%	187	0	0%	31
Northern	58.17%	244	2	0.8%	2
Total	76.72%	641	93	14.5%	61

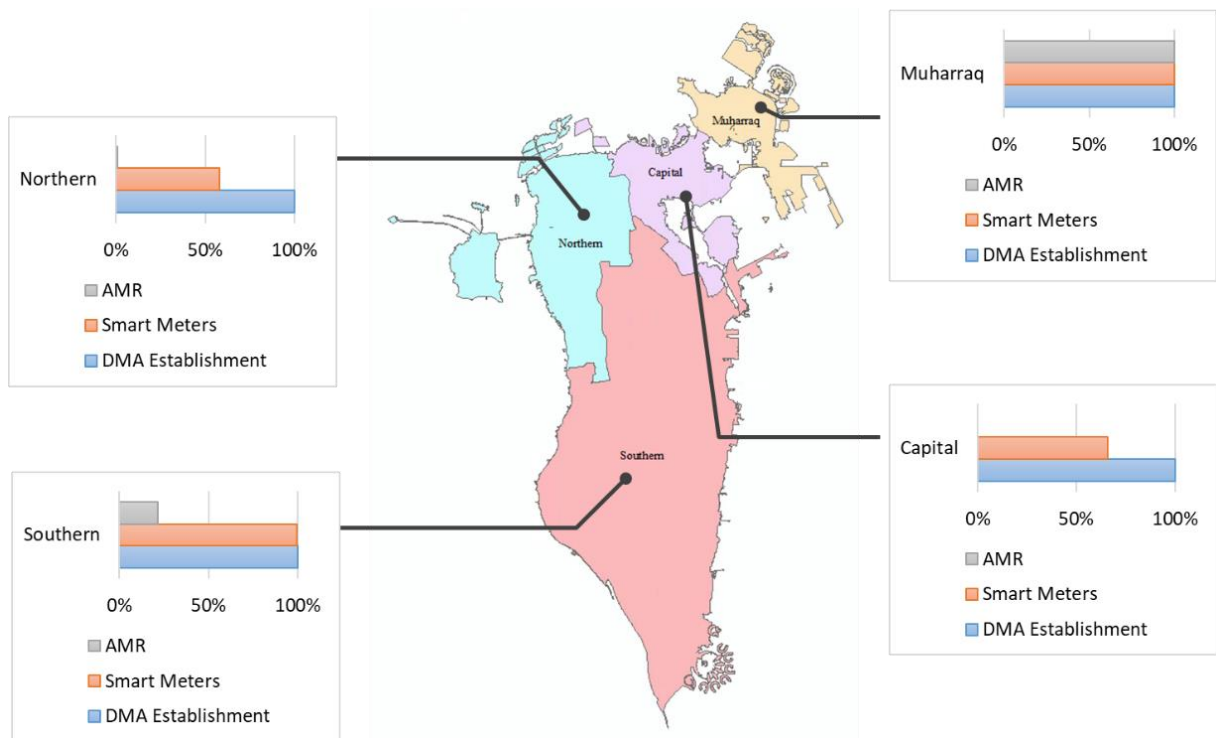


Figure (4-7): Smart Water Metering Status per Governorate in 2020
(Source: EWA Statistics Reports)

4.4 NRW Data Analysis

The Electricity & Water Authority (EWA) uses percentage Non-Revenue Water (NRW) as an indicator of NRW. First, it is calculated using the simple formula considering the system input volume and billed authorized volume. Figure (4-8) shows the data and software used to calculate the NRW. Next, the IWA estimates the breakdown elements of the water balance table according to the available incident data for the leak, unauthorized usage, and meter inaccuracy.

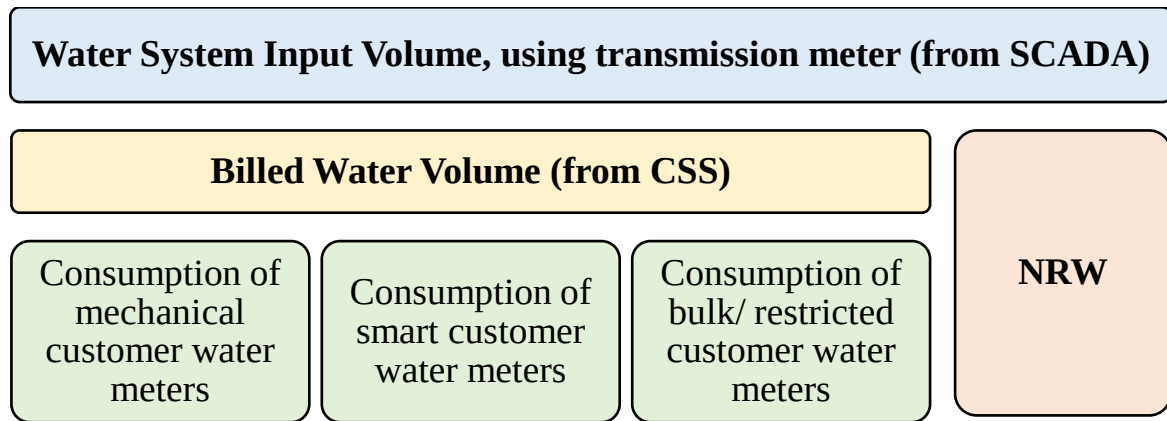


Figure (4-8): Software and Data for NRW

As mentioned in Chapter 1, water is supplied to the water distribution network through transmission pipelines, which end with a water meter to measure the **volume of water input** to the distribution system. The EWA is used to install turbine type mechanical water meters in the zonal water meter. All meters were replaced by smart electromagnetic water meters. Details of network zones will be introduced in part No. 4.3.1.1.

The authorized customers are usually supplied through a water meter that measures consumption. Customer water meters' measurements are collected by EWA, manually or through a smart metering head-end system, on a cycle of 28-30 days and entered into EWA's Customer Service System (CSS) from which the bills are issued. The total volume of billed water is the **billed authorized consumption**. The customer water meters used to be mechanical water meters which are being replaced with smart meters. The mechanical water meters are read manually monthly by meter readers, while the smart meters are read either manually or automatically through the automatic meter reading network. Details of the customer meters' type in the distribution network and reading methods will be discussed in part No. 4.3.2.2.

4.4.1 Descriptive Analysis of NRW

Figure (4-9) presents the official data for NRW in the Kingdom of Bahrain for the years 2010-2020 compared with the target NRW level. Before 2016, EWA had targeted reducing the NRW level to 25%, and they were able to meet the target by lowering the NRW to 14.1% (from 38.1% in the year 2010 to 24% in the year 2016). However, the target NRW was later reduced to 15%, not yet met.

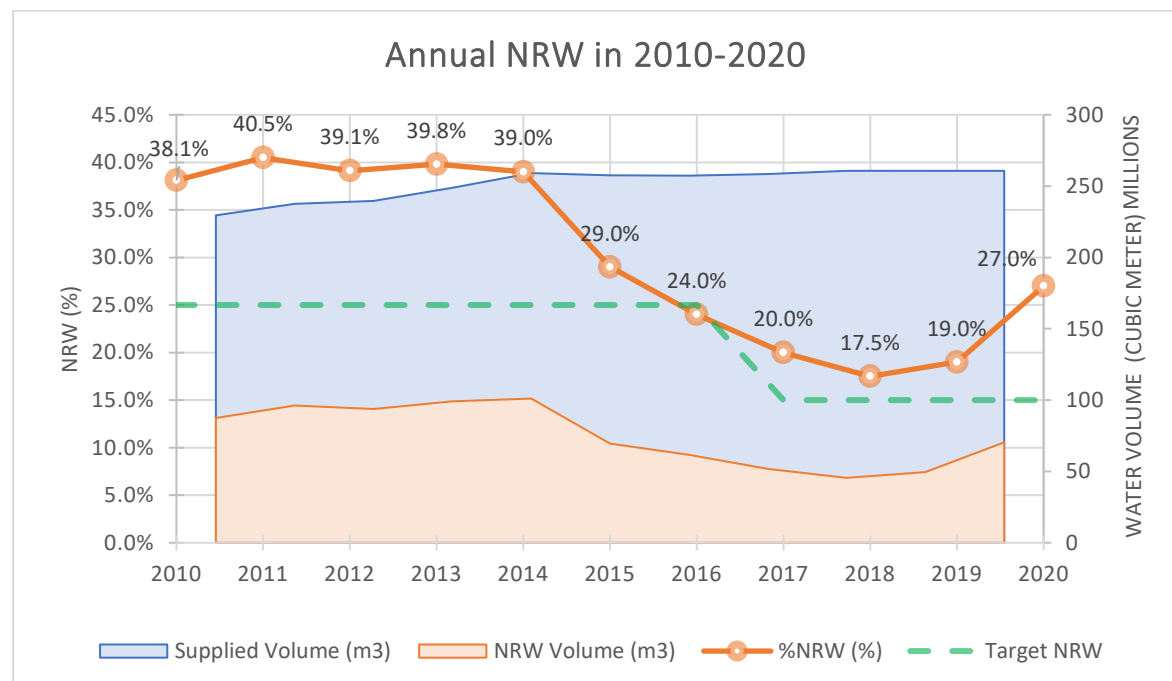


Figure (4-9): NRW in Kingdom of Bahrain for Years 2010-2020

(Source: EWA Statistics Reports)

From 2010 to 2014, the NRW varied from 38.1% to 40.5%. In 2011, the maximum increase was 2.4%. In 2015, a dramatic reduction (10%) was noticed in the NRW level, decreasing until reaching its lowest in 2018 (17.5%). However, the level increased in the following two years, reaching about 19% in 2019 and 27% in 2020. The inclined NRW can be related to fully establishing and activating DMAs and intensifying active leak control

exercises. Also, it can be referred to as the increase in network pressure during the COVID pandemic to cater to the raised customers' requirements. Subsequently, the amount of leaking water increased, resulting in a jump in the invisible leaks in these two years compared to visible leaks and higher NRW.

To better understand the variation in annual NRW during 2010 and 2020, the following part will discuss the changes noticed in water balance elements for 2010 and 2018. The researcher has chosen these specific years as 2010 is the beginning of the ten years, and 2018 had the lowest NRW recorded. However, for 2019 and 2020, the water balance values are not available. Thus, the depth analysis will be done using documented cases of water losses.

In her thesis, Al Maskati (2011) presented the water balance table for the Kingdom of Bahrain for the year 2010, as shown in Table (4-7). The volume input into the system was 229.6 Mm³ per year which about 38% was not paid (including 32% water losses). In terms of water losses, 5% were estimated to be apparent losses (divided into 1% unauthorized consumption and 4% meter inaccuracies), with the remainder (27%) being real losses. In year 2018, the distribution of NRW parameters changed in addition to the noticeable reduction in percentage NRW, as shown in Table (4-8). The NRW was calculated as 17.5% distributed into 0.3% unbilled authorized consumption and 17.2% water losses (2% unauthorized consumption, 7.2% apparent losses and 8% real losses).

**Table (4-7): IWA Standard Water Balance for Kingdom of Bahrain,
Year 2010 (Source: Al Maskati, 2011)**

	Authorized consumption	Billed authorized consumption	Billed metered Consumption	Revenue Water 142,107,517 [62%]
			Billed un-metered Consumption	
System Input Volume 229,612,636 [100%]	155,884,275 [68%]	unbilled authorized consumption	Unbilled Metered/ un-metered consumption 13,776,758 [6%]	Non-Revenue Water 87,505,119 [38%]
	Water Losses 73,728,361 [32%]	Apparent Losses	Unauthorized Consumption 2,296,126 [1%]	
			Customer Meter Inaccuracies 8,526,451 [4%]	
		Real Losses	Leakage from Distribution mains 62,905,784 [27%]	

**Table (4-8): IWA Standard Water Balance for Kingdom of Bahrain,
Year 2018 (Source: EWA Statistics Reports)**

	Authorized consumption	Billed authorized consumption	Billed metered Consumption	Revenue Water 215,229,111 [82.5%]
			Billed un-metered Consumption	
System Input Volume (m ³) 260,744,515 [100%]	216,011,341 [82.8%]	unbilled authorized consumption	Unbilled Metered/ un-metered consumption 782,230 [0.3%]	Non-Revenue Water 45,515,404 [17.5%]
	Water Losses 44,733,174 [17.2%]	Apparent Losses	Unauthorized Consumption 5,201,532 [2%]	
			Customer Meter Inaccuracies 18,725,515 [7.2%]	
		Real Losses	Leakage from Distribution mains 20,806,127 [8%]	

Figure (4-10) shows a comparison between the NRW components of both years. The unbilled authorized consumption and leakage in the water distribution system have radically dropped by 5.7% (in 2010) and 19% (in 2018), respectively. Conversely, the components related to apparent losses, meter inaccuracies, and unauthorised consumption have risen by 3.2% and 1%, respectively, compared to 2010. That means EWA decreased the percentage of NRW from 2010 to 2018 by reducing the unbilled authorized consumption and real losses.

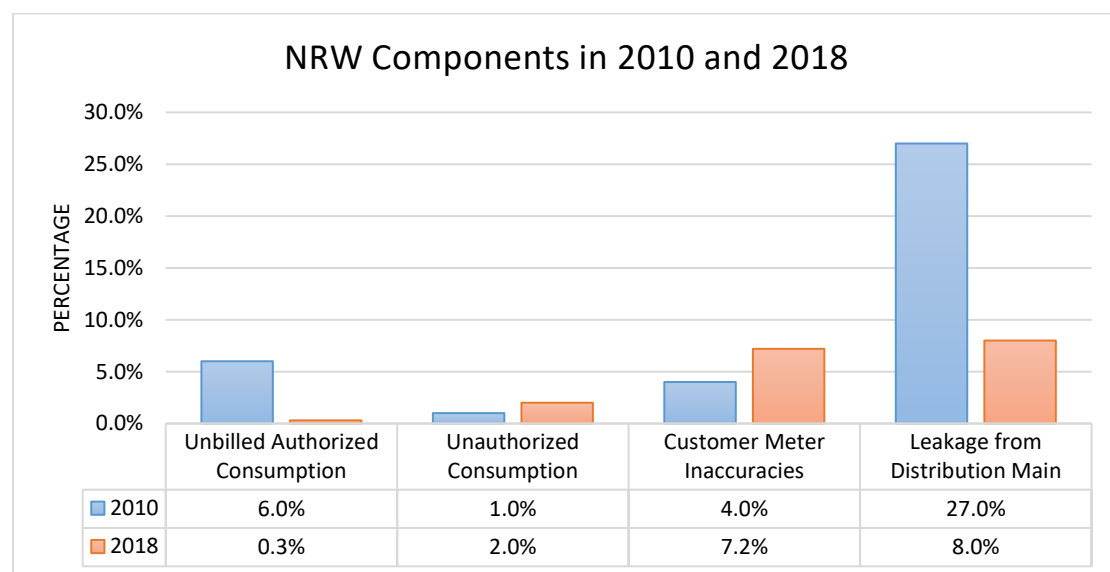


Figure (4-10): NRW Components in 2010 and 2018 (Source: Al Maskati, 2011; EWA Statistics Reports)

Table (4-9) presents reported leak cases during 2015-2020. Figure (4-11) illustrates the trend of recorded leak incidents of different categories: visible leak, invisible leak, and customer meter leak during 2015-2020. The documented visible leak cases were far lower compared to the other classes over the period. On the other hand, the reported customer meter leaks were higher than the invisible leak during 2015-2018, whereas the hidden leak incidents were higher in the following two years. Overall, the number of

reported leak incidents has fluctuated during the six years but has declined compared to cases in 2015.

Table (4-9): Number of Reported Leak Incidents During 2015-2020
(Source: EWA Statistics Reports)

Period	Year					
	2015	2016	2017	2018	2019	2020
Visible Network Leak	176	98	127	136	52	82
Customer Meter Leak	1,752	911	1,178	655	445	367
Invisible Leak	607	403	473	552	500	893
Total No. of Leaks	2,535	1,412	1,778	1,343	997	1,342

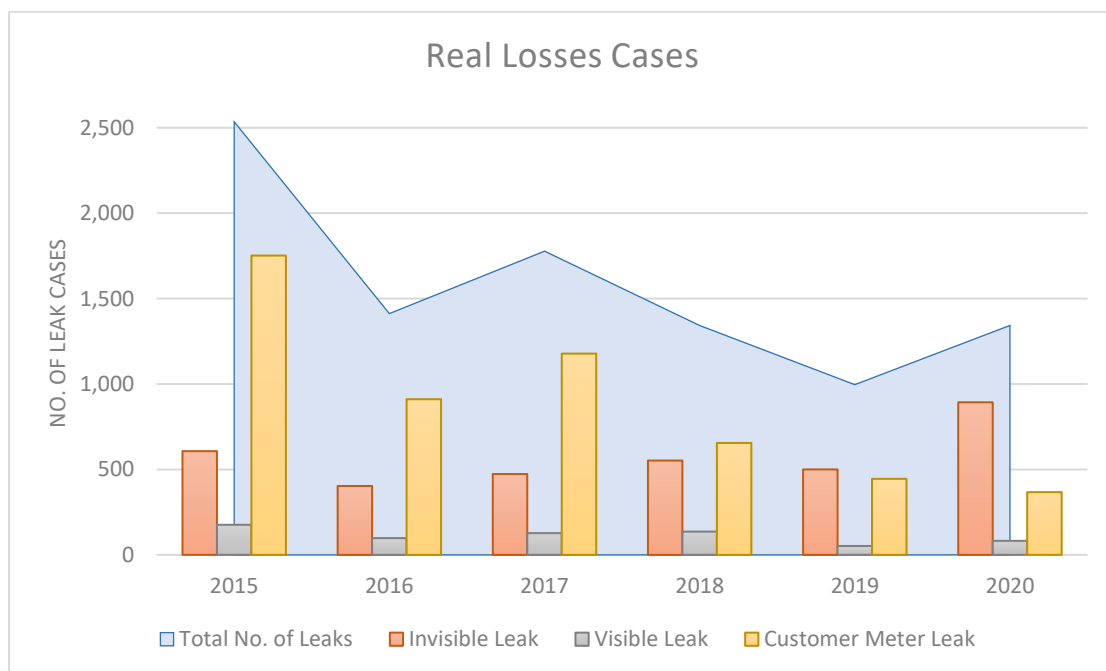


Figure (4-11): Reported Real Loss Cases During 2015-2020 (Source: EWA Statistics Reports)

Table (4-10) and Figure (4-12) illustrate the trend of reported apparent losses of different categories, namely: customer meter defect and illegal connections during the years 2015-2020. The customer meter defects were

the highest cases of apparent losses in 2015-2018, but the situation changed in the following years. On the other hand, the illegal connections showed a slight decrease in 2015-2019 and increased again in 2020 to be the same as number of recorded cases in 2018, approximately. As sum, the number of registered apparent losses showed a massive decline from 370 cases in 2015 to 42 cases in 2019. However, it increased in 2020 (95 cases) due to registered illegal connections.

Table (4-10): Apparent Loss Cases During 2015-2020 (Source: EWA Statistics Reports)

Period	Year					
	2015	2016	2017	2018	2019	2020
Customer Meter Defects	230	139	215	127	8	10
Illegal Connections	140	138	121	89	34	85
Total Apparent Losses Cases	370	277	336	216	42	95

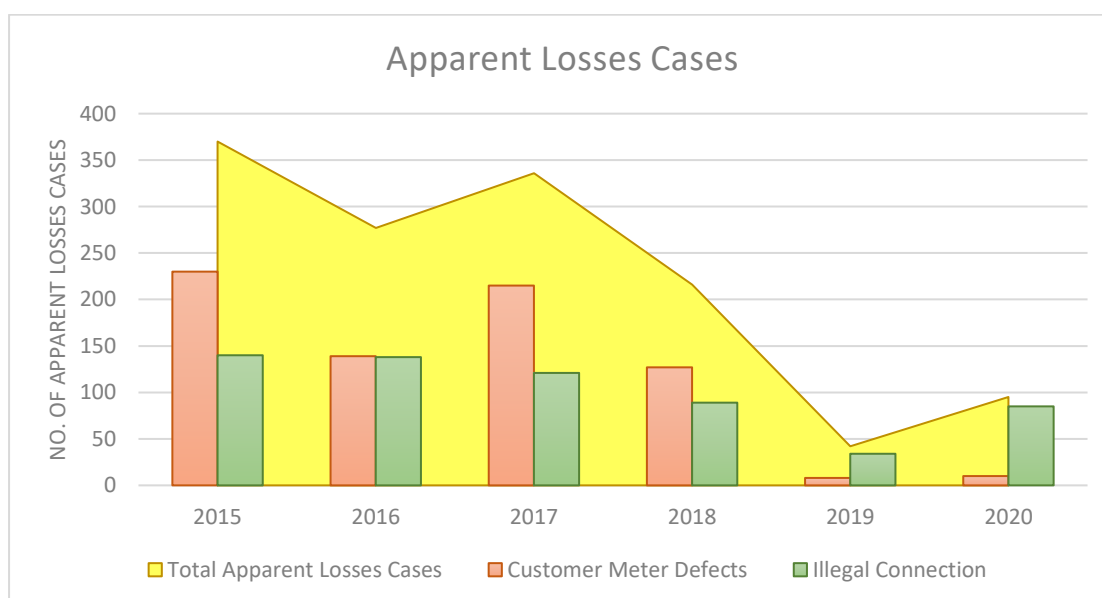


Figure (4-12): Apparent Loss Cases During 2015-2020 (Source: EWA Statistics Reports)

Another NRW indicator used by EWA is the Linear Leakage Index (LLI), which relates to actual losses. The LLI measure is used to monitor the performance of the distribution network considering the expansion in length. EWA targets to be below 10 m³/km/day, following the recommendation of the IWA task force, as reported by EWA. As illustrated in Figure (4-13), EWA has recorded LLI below the targeted level over the past five years.

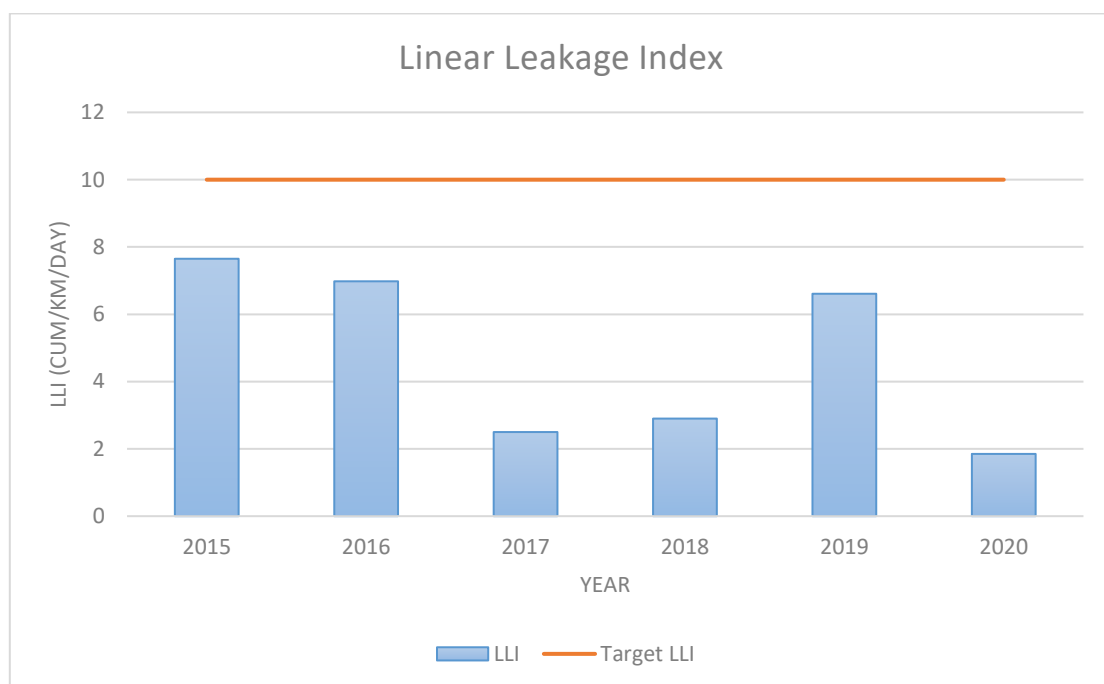


Figure (4-13): LLI for 2015-2020 (Source: EWA Statistics Reports)

Since July 2020, EWA has started to calculate the NRW% per DMA in addition to the entire network every month. This exercise aims to identify DMAs with high water losses for analysis, detect the losses type, and promptly take corrective action. Figure (4-14) shows the work flow of the latest procedure to reduce the water losses.

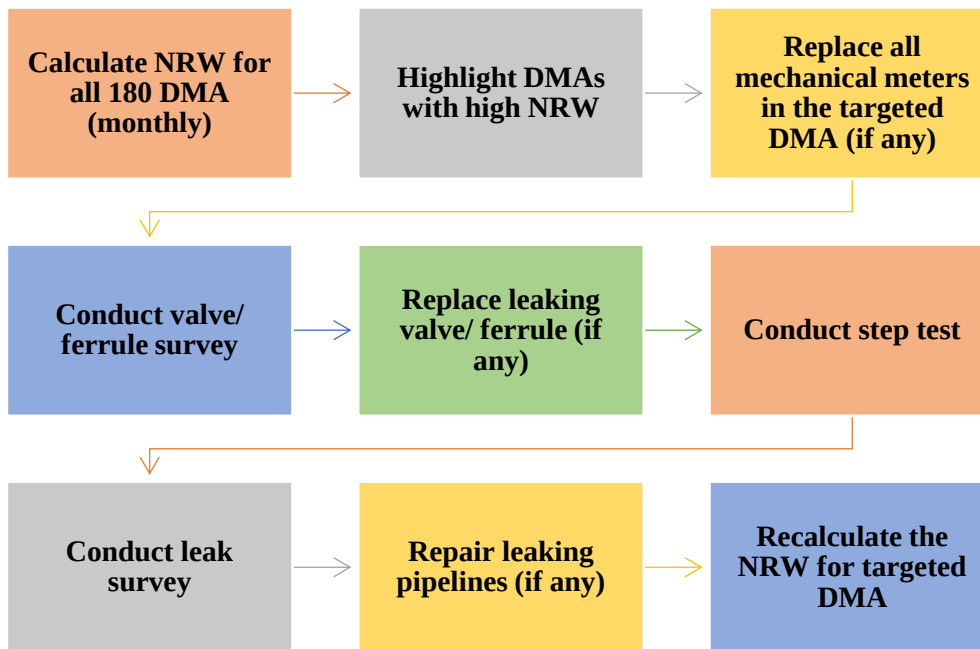


Figure (4-14): New Procedure to Control NRW within DMAs

The following part will discuss the results of applying the new procedure to 32 DMAs in the year 2020. As the NRW of the DMAs was above 15%, focused study and actions were taken as per the procedure described in Figure (4-14). Details of the 32 DMAs are in Table (4-11). The average number of customers in these DMA is 1130 with an average NRW of 187,538 (38% approximately).

Table (4-11): Number of Customers and Initial NRW in the 32 DMAs
(Source: EWA Statistics Reports)

DMA Sr.	No. of Customers	Initial NRW (m ³)
1	397	297,677
2	720	103,324
3	654	162,495
4	319	59,025
5	1,317	503,179
6	653	180,697
7	1,542	109,003

DMA Sr.	No. of Customers	Initial NRW (m³)
8	888	183,278
9	1,217	171,736
10	4,015	493,401
11	759	222,383
12	682	217,865
13	490	128,427
14	756	127,787
15	220	87,736
16	469	26,396
17	931	128,569
18	3,272	448,358
19	3,796	135,006
20	1,558	125,680
21	1,022	116,612
22	1,364	206,369
23	748	243,771
24	1,027	243,418
25	506	216,566
26	316	35,498
27	1,553	154,703
28	1,751	213,860
29	1,093	97,453
30	180	90,943
31	1,173	315,388
32	760	154,601
Total	36,148	6,001,204
Average	1,130	187,538
Median	824	158,599

Figure (4-15) displays the percentage of calculated NRW before and after replacing mechanical meters with smart meters. The maximum calculated NRW% was 65%, and the mean was 40%. After mechanical water meter replacement, the maximum recognized reduction was 23% (see the blue

dots), while in some DMAs, the NRW did not change at all. The average NRW reduction in the DMAs was 8%.

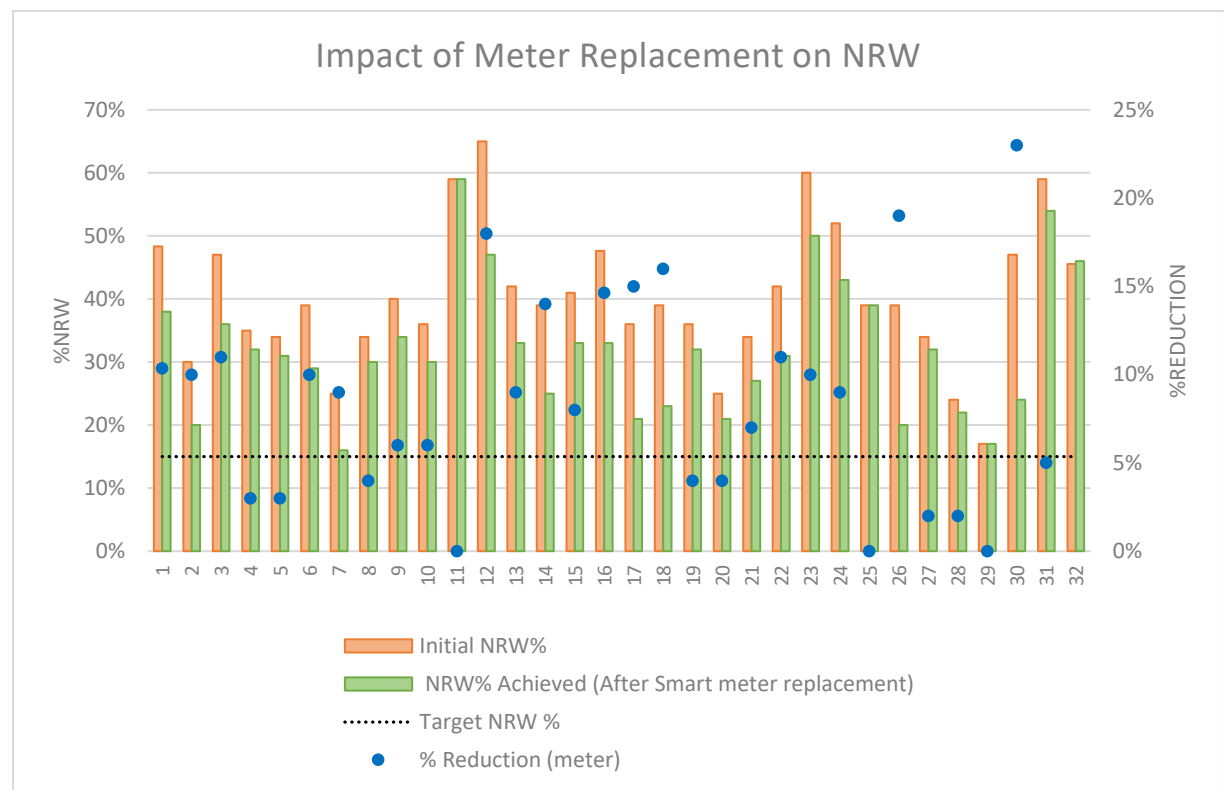


Figure (4-15): Impact of Meter Replacement in 32 DMAs (Source: EWA Statistics Reports)

The DMAs were subjected to a leak survey. In addition, exercises on valves, ferrules and pipelines were conducted. Figure (4-16) displays the percentage of calculated NRW before and after repairing leakages. The maximum recorded reduction was 32% (see the purple dots), while in some DMAs, the NRW did not change at all. The average NRW reduction in the DMAs was 5%.

Among the 32 DMAs, NRW in only one DMA was not changed during the exercise (17%), and only one DMA met the target NRW (15%).

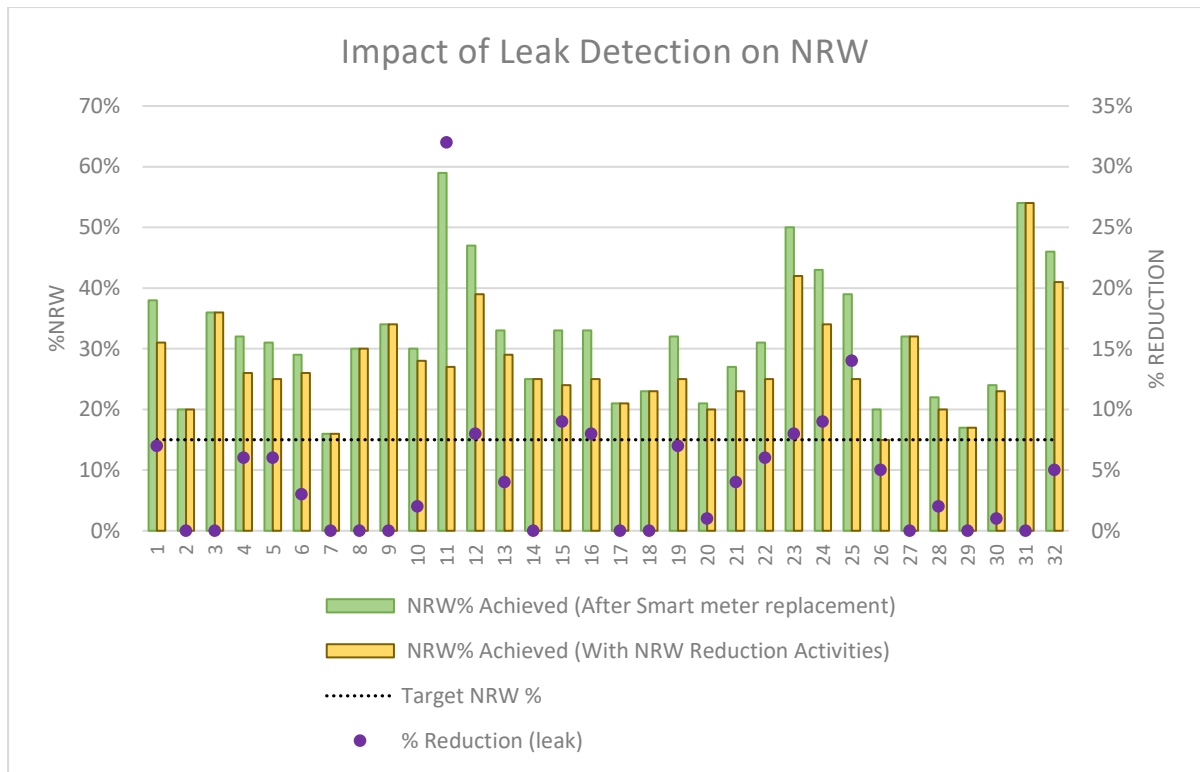


Figure (4-16): Impact of Leakage Repair in 32 DMAs (Source: EWA Statistics Reports)

4.4.2 Statistical Analysis of NRW

Various statistical techniques were utilized to investigate the relationship between smart meters and water loss cases.

4.4.2.1 Correlation Analysis

Bivariate correlation analysis is a technique to measure the nature and strength of the relationship between variables. There are three types of correlations: Pearson correlation, Kendall rank, and Spearman correlation. For example, the Pearson (product-moment) correlation describes the relationship between interval and ratio data variables. In contrast, the Kendall rank and the Spearman correlation are used for ordinal data.

Using Pearson's correlation, the relationship strength is determined via the correlation coefficient (r), which ranges between -1 and +1. The r ranges

between -1 to 1, and the sign indicates a positive or negative association. The r -value of 0 indicates no relationship between the variables, 1 indicates a perfect positive correlation, and -1 shows a perfect negative correlation. (Cooper & Schindler, 2014) The Pearson correlation measures the best fit between the data of various variables and their r -value. As the r -value is closer to 1, the relationship between the variables is stronger. It is calculated using the following equation.

$$r = \frac{\sum_i^n (x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_i^n (x_i - \bar{x})^2 \sum_i^n (y_i - \bar{y})^2}}$$

Where r is the correlation coefficient. Table (4-12) is the guideline for interpolating the strength of correlation. (Kumar et al., 2012)

Table (4-12): Guideline of Correlation Strength (Source: Kumar et al., 2012)

Coefficient value, r	Strength of Correlation
0 to 0.3	Weak
0.31 to 0.6	Moderate
0.61 to 1.0	Strong

The correlation analysis was applied between the percentage of smart meters in the network, NRW and water losses cases (real losses, illegal connections and customer meter defects) to test the research hypotheses. Collected data from 2015-2020 was analysed using Pearson's correlation. The significance level of all correlation coefficients was set at 0.05 (2-tailed). The findings of the correlation Pearson coefficient (r) is presented in Table (4-13).

Table (4-13): Pearson Correlation Analysis Results

		Correlations				
		% Smart Meters	NRW (%)	Customer Meter Defects Cases	Illegal Connections Cases	Leaks Cases
% Smart Meters	Pearson Correlation	1.000	-0.172	-.858**	-0.219	-.515*
	Sig. (2-tailed)	0.000	0.423	0.000	0.304	0.010
	N	24	24	15	24	24
NRW (%)	Pearson Correlation	-0.172	1.000	0.435	0.397	0.336
	Sig. (2-tailed)	0.423	0.000	0.105	0.054	0.108
	N	24	24	15	24	24
Customer Meter Defects Cases	Pearson Correlation	-.858**	0.435	1.000	.921**	.585*
	Sig. (2-tailed)	0.000	0.105	0.000	0.000	0.022
	N	15	15	15	15	15
Illegal Connections Cases	Pearson Correlation	-0.219	0.397	.921**	1.000	0.155
	Sig. (2-tailed)	0.304	0.054	0.000	0.000	0.468
	N	24	24	15	24	24
Leaks Cases	Pearson Correlation	-.515*	0.336	.585*	0.155	1.000
	Sig. (2-tailed)	0.010	0.108	0.022	0.468	0.000
	N	24	24	15	24	24
**. Correlation is significant at the 0.01 level (2-tailed).						
*. Correlation is significant at the 0.05 level (2-tailed).						

4.4.2.1.1 Percentage NRW

The Pearson correlation coefficient (*r*-value) was computed to test the following hypotheses, concerning the relationship between %smart meters and %NRW:

- H_0 : there is no significant relationship between % Smart Meters and %NRW.

- H_1 : there is a significant relationship between % Smart Meters and %NRW.

Table (4-14): Person Correlation for %NRW

Correlations		%NRW	% Smart Meters
%NRW	Pearson Correlation	1.000	-0.172
	Sig. (2-tailed)	0.000	0.423
	N	24	24
% Smart Meters	Pearson Correlation	-0.172	1.000
	Sig. (2-tailed)	0.423	0.000
	N	24	24

Table (4-14) shows the Pearson correlation analysis for 24 populations in SPSS. The Pearson coefficient (r) is -0.172, and the standard alpha (p) is 0.423 (>0.05). The results indicate no statistically significant linear relationship between %Smart Meters and %NRW. Therefore, the null hypothesis was accepted since it failed to be rejected.

4.4.2.1.2 Meter Inaccuracies Cases Recorded

The Pearson correlation coefficient (r -value) was computed to test the following hypotheses, concerning the relationship between %smart meters and customer meter defect cases:

- H_0 : there is no significant relationship between % Smart Meters and customer meter defect cases.
- H_1 : there is a significant relationship between % Smart Meters and customer meter defect cases.

Table (4-15): Person Correlation for Meter Inaccuracies Cases

Correlations			
		% Smart Meters	Customer Meter Defects Cases
% Smart Meters	Pearson Correlation	1.000	-0.858**
	Sig. (2-tailed)	0.000	0.000
	N	15	15
Customer Meter Defects Cases	Pearson Correlation	-0.858**	1.000
	Sig. (2-tailed)	0.000	0.000
	N	15	15
**. Correlation is significant at the 0.01 level (2-tailed).			

Table (4-15) shows the Pearson correlation analysis for 24 populations in SPSS. The Pearson coefficient (r) is -0.858, and the standard alpha (ρ) is 0.000 (<0.01). The results reveal a strong negative statically significant linear relationship between %Smart Meters and meter inaccuracies Cases. Hence, the alternate hypothesis is accepted the null hypothesis is rejected.

4.4.2.1.3 Unauthorized Usage Cases Recorded

The Pearson correlation coefficient (r -value) was computed to test the following hypotheses, concerning the relationship between %smart meters and illegal connection cases detected:

- H_0 : there is no significant relationship between % Smart Meters and illegal connections cases.
- H_1 : there is a significant relationship between % Smart Meters and illegal connections cases.

Table (4-16): Person Correlation for Unauthorized Usage Cases

Correlations			
		% Smart Meters	Illegal Connections Cases
% Smart Meters	Pearson Correlation	1.000	-0.219
	Sig. (2-tailed)	0.000	0.304
	N	24	24
Illegal Connections Cases	Pearson Correlation	-0.219	1.000
	Sig. (2-tailed)	0.304	0.000
	N	24	24

Table (4-16) shows the Pearson correlation analysis for 24 populations in SPSS. The Pearson coefficient (r) is -0.219, and the standard alpha (ρ) is 0.304 (>0.05). The results indicate no statically significant linear relationship between %Smart Meters and Unauthorized Usage Cases. Hence, the alternate hypothesis was rejected, and the null hypothesis is failed to be rejected.

4.4.2.1.4 Meter Leaks Cases Recorded

The Pearson correlation coefficient (r -value) was computed to test the following hypotheses, concerning the relationship between %smart meters and leak cases detected:

- H_0 : there is no significant relationship between % Smart Meters and leaks cases.
- H_1 : there is a significant relationship between % Smart Meters and leaks cases.

Table (4-17): Person Correlation for Leaks Cases

Correlations			
		% Smart Meters	Leaks Cases
% Smart Meters	Pearson Correlation	1.000	-.515*
	Sig. (2-tailed)	0.000	0.010
	N	15	24
Leaks Cases	Pearson Correlation	-.515*	1.000
	Sig. (2-tailed)	0.010	0.000
	N	24	15
*. Correlation is significant at the 0.05 level (2-tailed).			

Table (4-17) shows the Pearson correlation analysis for 24 populations in SPSS. The Pearson coefficient (r) is -0.515, and the standard alpha (p) is 0.010 (<0.05). The results reveal a moderate negative statistically significant linear relationship between %Smart Meters and meter inaccuracies Cases. Hence, the alternate hypothesis is accepted, and the null hypothesis is rejected.

Overall, two of hypotheses developed were accepted and two were rejected. Table (4-18) provides a summary of the hypothesis test results.

Table (4-18): Results of Hypotheses Testing

Hypothesis	Type of Association	Hypothesis Results
H1. There is a significant relationship between % Smart Meters and %NRW	Not Statically Significant	Rejected
H2. There is a significant relationship between % Smart Meters and customer meter defect cases	Strong Negative	Accepted

H3. There is a significant relationship between % Smart Meters and illegal connections cases.	Not Statically Significant	Rejected
H4. There is a significant relationship between % Smart Meters and leaks cases	Moderate Negative	Accepted

4.4.2.2 Multivariate Regression Analysis

Regression analysis is a commonly known statistical technique used to evaluate and explain the change in a dependent variable by the mean of one or more independent variables. It involves developing a model of the relationship and estimating parameter values to develop the regression equation. The regression equation can be used for forecasting future values as well. There are two types of regression analysis, simple linear and multiple regression. The difference between the two is that the simple liner regression is applied when the test is done for a single continuous dependent variable and a single continuous independent variable. Multiple regression is an extension of simple linear regression, used where the relationship between a group of independent variables and a dependent variable is under question. It determines the overall fit model and the contribution of each independent variable to the total variance in the dependent variable value. The multiple regression model is expressed through the following equation:

$$y = \beta_0 + \beta_1x_1 + \beta_2x_2 + \cdots + \beta_ix_i$$

Where y is dependent variable, x is the independent variable, β_0 is the regression intercept point and β is the regression coefficient of the independent variable x .

In the last part, the correlation results revealed an association between the smart meters and the incidents of apparent losses (meter inaccuracies) and real losses (leaks). Therefore, the study will use multiple regression analysis to examine the influence of apparent and real losses on the NRW. The dependent variable will reduce NRW, while the independent variables will reduce apparent and real losses. The findings of linear regression analysis are presented in Table (4-19), Table (4-20) and Table (4-21).

Table (4-19): Model Summary of Multiple Regression Analysis

Model Summary				
Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.600 ^a	.360	.316	6.25750%
a. Predictors: (Constant), %Reduction in Real Losses, %Reduction in Apparent Losses				

Table (4-19)) summarises the well fit of data in the developed model. The well fit of the model is described via four parameters, R, R-square, adjusted R-square and standard error of the estimation. The correlation coefficient, R, is the correlation factor between the data points and the predicted values by the model, and the square of this value, R-square, indicates how much the independent variables describe the variance in the dependent variable. For example, the developed model in this study has a data correlation level of 0.6. In contrast, the independent variables (reduction in apparent losses, by mean of meter replacement to smart, and reduction in real losses) represent only 36% of the variability in the dependent variable (%NRW).

Table (4-20): ANOVA Test Results of Multiple Regression Analysis

ANOVA ^a						
	Model	Sum of Squares	df	Mean Square	F	Sig.
1	Regression	638.405	2	319.203	8.152	.002 ^b
	Residual	1135.533	29	39.156		
	Total	1773.938	31			

a. Dependent Variable: %Reduction in NRW
b. Predictors: (Constant), %Reduction in Real Losses, %Reduction in Apparent Losses

The F-ratio in Table (4-20) tests whether the developed regression model is a good fit for the data, in other words tests the model significance. The ANOVA results show that F value is F=8.152 with significance level, p (0.002) < 0.05. This indicates that the model is statically significant.

Table (4-21): Coefficient Results of Multiple Regression Analysis

Coefficients*								
Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.	95.0% Confidence Interval for B	
		B	Std. Error				Beta	Lower Bound
1	(Constant)	6.066	4.369		1.389	.176	-2.869	15.001
	%Reduction in Apparent Losses	.755	.188	.602	4.021	.000	.371	1.140
	%Reduction in Real Losses	.019	.136	.021	.143	.887	-.259	.298
a. Dependent Variable: %Reduction in NRW								

From Table (4-21) of the multiple regression analysis results, the reduction in apparent losses (resulted by smart meters installation) and the reduction in real losses (resulted by leak repair) have affected the %NRW by 0.755 and 0.019, respectively. As a result, the regression equation of %NRW is defined as follows:

$$\%NRW = 6.066 + 0.755 (\%Apparent Losses) + 0.019 (\%Real Losses)$$

Though the overall model is statically significant, the independent variable (% reduction in real losses) is not significant, which can be related to the small size of the used data in compare to values variety.

4.5 Financial Impact of Reducing NRW

The smart meters have resulted in a decrease in the NRW of an average of 8% in the DMAs under the study. Therefore, using the NRW volume presented in Table (4-11), 8% of the total supplied volume (15,533,982 m³) to these DMA is 1,242,719 m³, which is equivalent to a revenue of BD 932,039.250.

Considering the system input in year 2019 (260,677,823 m³), 1% reduction in NRW equals 2,606,778 cubic meter. Based on the supply cost of 750 fils per m³, % of NRW is equivalent to a revenue loss of about 1,955,084 BD/year or 5,356 BD/day.

4.6 Summary

The chapter discussed the results of data analysis which targets finding answers for the research questions and test the research hypotheses quantitatively. Combination methods were used for the analysis; descriptive and statistical techniques.

Chapter 4 reports the strategies considered by the Electricity & Water Authority of the Kingdom of Bahrain to manage and reduce Non-Revenue Water. Also, it covered the progress of the initiatives implemented to reduce water losses. Furthermore, it presented the historical data of Non-Revenue Water (NRW) and the IWA components and descriptively analysed the change in the values of these parameters. The analysis revealed that the NRW and IWA components cases had undergone significant changes over the years. Also, data of NRW for 32 DMAs before and after using smart meters and leak repair were analysed to explore the effect of smart meter usage.

The relationships in the conceptual framework and research hypotheses were statistically examined using correlation and multiple regression analyses to support the descriptive analysis findings. Table (4-22) summarises the descriptive and statistical analysis findings. The analysis revealed that the smart meters influenced an average of 8% of NRW in the DMAs under the study. That influence was statically verified by quantitatively testing the study hypotheses. A significant relationship was found between the installation of smart meters and the reported meter inaccuracies and leak incidents. Moreover, the impact of smart meters on NRW was modelled in a combination of the leaks. The effect of meter replacement and leak repair explains 36% of the change in NRW with a contribution of 0.755 and 0.019, respectively.

Table (4-22): Results of Quantitative Data Analysis

Analysis Type	Objective	Results
Descriptive	To describe overall changes in NRW and IWA components	• NRW has reached the lowest level (17.5%) in the testing period (2010-2020) in 2018, where 91% of DMAs were established and 41% of customer meters were smart. • The IWA's data also showed that water losses due to meter inaccuracies have increased from 4% in 2010 to 7.2% in 2018.
	To understand the trend of recorded water losses cases	• The reported real losses showed a decrease in the number of cases in 2019 but a sudden increase in 2020, caused by an increase in the invisible leaks. • The apparent losses reported indicated a histrionic decline in the

Analysis Type	Objective	Results
		number of cases in 2019. However, it slightly increased again in 2020, caused by an increase in illegal connections.
	Reduction in NRW after replacement of meters and leak detection	• Customer meters' replacement to smart has resulted in reduction of average 8% in the DMAs in the study and maximum of 23%. • The leakage detection and repair exercises have resulted in a 5% - 32% reduction in the number of DMAs in the study.
Pearson's Correlation	To test the relationship significance between % Smart meter in the network, %NRW and losses cases	• There is negative association between smart meters, and meters inaccuracies and leaks. • There is no statically significance between smart meters and NRW and unauthorized usage.
Multivariate regression	To explore to what extent variables (x, apparent and real losses) can be used as a predictor of variable (y, NRW).	• The developed model is statically significant and explains 36% of the variance in NRW. • The impact of smart meters on NRW is 0.775 compared to leak repair is 0.019.

Chapter Five: Discussion, Conclusion and Recommendation

5.1 Introduction

This chapter discusses the key findings of the analysis carried out in this study, and presented in Chapter 4. The findings will be discussed based on literature reviews (Chapter 3) and the policies and strategies in the Kingdom of Bahrain (Chapter 4). The scope of this chapter includes addressing the key issues and limitations of the study results and recommendations for application and further investigation.

5.2 Discussion

The primary purposes of this research study are to (a) review the water losses situation and strategic plans to manage the NRW in the Kingdom of Bahrain (b) study the impact of implementing the smart metering system on *water losses* in the Kingdom of Bahrain (c) investigate and assess the true impact of smart metering on *water supply revenue* in the Kingdom of Bahrain. The four research questions that are discussed in this section will help the participants in reaching their goals:

5.2.1 What are the strategies implemented by the Kingdom of Bahrain's government to manage the NRW?

From the reports survey about the Electricity and Water Authority' strategies for well manage and control the NRW illustrated in Chapter 4, it was found that EWA implemented comprehensive solutions to control and reduce the value of NRW to 15%.

To reduce the real losses, EWA has divided the water distribution network into isolated 180 DMAs across the Kingdom of Bahrain which are monitored through smart water meters (electromagnetic meters). The DMAs facilitate active leak detection, which results in the rapid

localization and repair of the leaks. EWA has set measures to quickly attend to the reported leak complaints through many advanced techniques, such as using satellite images.

Also, the Pressure Reducing Valves are used to control valves at the DMA level and control the volume of leaking water. As a result, the supply is optimized to meet the actual water demand of the DMA by applying sufficient pressure. On top of that, EWA has managed to perform planned preventive maintenance on the network's valves through surveys and exercises to ensure their workability. Besides that, the old water pipelines are being replaced in the predicted leak segments.

To reduce the apparent losses, the Kingdom of Bahrain has upgraded the policy and procedure for handling unauthorized water usage. It carries out random and planned field surveys to detect illegal use. According to the policy, the consumed water is quantified, and the customer is charged. Additionally, EWA has implemented the Advanced Metering Infrastructure (AMI) to enhance automatic customer meter reading. Conventional or mechanical water meters are being replaced with smart water meters of different types (ultrasonic and electromagnetic).

About 76.7% of the water meters in the water network are smart electronic water meters. Electronic meters are more accurate than mechanical ones due to their dependence on electronic measurement methods. Moreover, their accuracy is sustained along the meter's lifetime, as it does not contain mechanical measurement parts. Also, the smart meters are facilitated with a communication mode to communicate with the Automatic Meter Reading (AMR) network. Various AMR methods are adapted by EWA based on the installation condition and the location of the meters, namely: (a) Radio Frequency (RF) fixed network through RDCs (b) wired fixed

network through wired gateways for multi-storey buildings (c) walk-by and drive-by for RF meters. Regarding RF fixed network, about 14.5% of planned RDC stations and 61 wired gateways will be activated in 2020.

Comparing the Kingdom of Bahrain's practice for NRW control with those implemented around the world reviewed in Chapter 2, Bahrain has applied the experienced strategies in United Arab Emirates, Denmark, Sweden and Romania.

5.2.2 What is the water losses situation in the Kingdom of Bahrain?

As highlighted by the literature reviewed in Chapter 2, NRW can be expressed in percentage or volume (m^3 per km of pipe per day or m^3 per connection litres per day). However, as stated in Chapter 4, EWA has adapted percentage expression, which is not recommended by Pedersen & Kristensen (2016) and Dalton, J. (2019). Therefore, EWA uses the ILI performance indicator in addition to the %NRW.

EWA reduced the percentage of NRW to 17.5% in 2018, which increased again to reach 27% in 2020. Due to increasing illegal consumption and meter inaccuracies, the contribution of unbilled water balance values in the NRW declined significantly during 2010 and 2018. Considering the massive progress of customer water meters' replacement to smart in 2019-2020, the NRW was expected to further decrease by below 17.5%. However, EWA recorded an increasing value, which the researcher reasoned was due to intense leak detection and rapid repair activities and a fluctuation in the pressure during the COVID pandemic in these two years.

5.2.3 What is the impact of the smart metering system on water losses in the Kingdom of Bahrain?

In Chapter 4, the impact of smart metering was tested using different data related to water loss incidents recorded in 2015-2020 and a case study of 32 DMA. The data was statistically analysed using descriptive, correlation, and regression techniques.

The water loss incidents were presented in tables and charts to understand the trend. The reported real losses showed a decrease in the number of cases in 2019 but a sudden increase in 2020, caused by growth in the invisible leaks. Regarding the reported apparent losses, the recorded cases indicated a histrionic decline in the number of cases in 2019. However, it slightly increased again in 2020, caused by illegal connections. These results support the researcher's view about the rise of percentage NRW in 2020 but do not justify the increase in NRW in 2019. That is because several cases do not reflect the volume of water lost.

The same data were subjected to Pearson correlation analysis to check the associated water loss parameters with smart metering. It was found that smart water metering has a strong relationship with the customer meter inaccuracies cases and a moderate relationship with the leak cases. Yet, the relationships with %NRW and unauthorized users are not statically significant. This result can be referred to that the size of data was small.

The other sort of data related to the case of 32 DMAs, were analysed using tables, charts and descriptive techniques to explore the extent to which smart metering and leak repair affect the NRW reduction. The study also noted that replacing customer meters with smart ones has resulted in a decrease of about 5% in the number of affected meters. Although the NRW level did not decrease in some DMAs, the exercises did not reduce the

NRW in others. The NRW can be caused by illegal usage or meter data recording error to be studied further.

In addition to that, the DMA data were analysed using multiple linear regression to verify the findings. The multiple regression analysis revealed that the analysed parameters do not fully express the change in NRW; the meter inaccuracies and leaks explain only 36% of the NRW. Although that can be justified according to the IWA water balance, the apparent losses are not only about the meter inaccuracies. It also covers data handling and illegal consumption, which were not considered due to missing data. Nevertheless, the impact of smart meters on NRW is 0.775 compared to leak repair is 0.019.

Overall, smart metering has contributed to reducing the water losses in the Kingdom of Bahrain, especially the apparent losses.

5.2.4 How many increases in revenue did smart metering achieved in the Kingdom of Bahrain? How much is the saving if NRW is reduced by 1%?

As calculated in Chapter 4, the smart meters have increased the revenue by BD 932,039.250 in the study DMAs. In general, reducing 1% in the NRW can save BD1,955,084 per year, considering the supplied water volume in 2019.

5.3 Conclusion

This research aims to review the strategies applied for limiting water losses and investigate the impact of smart metering on water losses in the Kingdom of Bahrain.

The study's conceptual framework was developed based on the IWA breakdown of Non-Revenue Water (NRW), and the recorded cases on water losses incidents. A secondary data collected from the Government archive and literatures was used to investigate the water management practices, and test the relationships and power of influence between the variables. The used data was of various types and formats: longitudinal, cross-sectional, percentages and volumes.

The study found that the Kingdom of Bahrain has implemented various strategies for better managing the water distribution network. The strategies target all the water loss components and cope with the latest practices in the world and the Gulf Cooperation Council countries. One of the most critical steps taken is implementing the smart metering system. As argued by the researchers and proven in this study, smart meters significantly reduce water losses in the Kingdom of Bahrain. The study has explored and quantified the impact of smart meters on the NRW by developing a model for estimating the NRW percentage based on leaks and meter inaccuracies.

The smart metering system offers many advantages to water utilities. The most apparent benefit is the ability of the system to reduce and control the Non-Revenue Water. The smart metering system provides timely, accurate meter data reading through the automated reading capabilities that will support the water audit. In addition to their role in smart data

transformation, the smart meters provide benefits to customers such as, help them monitor and proactively control their consumption.

5.4 Recommendation

This part links the contribution of the thesis the existing knowledge, limitation of the research and suggests areas for further research.

5.4.1 Implications for Research and Practice

The critical contributions of the research findings to decision-makers and researchers are the following:

- f) During the initial stage of this study, many research papers found discussing the topic of water management and smart metering, relationship between smart meters' accuracy and apparent losses, and influence of smart meters on controlling the real losses in the DMAs. This study investigates the impact of smart meters on different water loss elements in case of the Kingdom of Bahrain.
- g) The study findings serve as a reference for NRW reduction strategies and historical NRW levels at the Kingdom of Bahrain.
- h) The study found that smart meters influence the control of NRW in terms of network monitoring and water audit. Thus, due to the complexity of the meters, it is recommended that they be replaced as soon as possible.
- i) It helps assess the justification of the meter's replacement program and the utility revenue increase. It gives an indication on the return of the huge investments on the smart metering in the GCC countries and supports fund providers' decisions.

- j) It assists decision-makers in quantifying the predicted impact of NRW factors and developing programs that focus on these factors.

5.4.2 Research Limitations

The researcher has acknowledged some limitations in the research results.

Firstly, the study was conducted using the available data obtained from the water utility in the Kingdom of Bahrain. The types of data were frequencies and percentages; utilizing volumes of water will provide more credibility to the study.

Secondly, the NRW in Bahrain is expressed in percentage, limiting the understanding and research of the real impact of the smart water meters as the DMAs have different sizes and numbers of customers.

Thirdly, the researcher only found the quantity of water balance components for two years. The study findings would improve if the exact details for the remaining years were available.

Fourthly, through regression analysis, the developed model found 36% of NRW, which means other predictors need to be considered, such as authorised billed consumption, illegal consumption, and data handling errors.

Notwithstanding the listed limitations, the research findings remain trustworthy and do not detract from the value of this research. On the contrary, they provide a platform for further future research ideas.

5.4.3 Recommendations for Further Research

Following are some recommendations for developing NRW strategies.

- a) This study looked at the widespread impact of smart water metering on water losses. Further study is to be done on the effect of smart meters on reading accuracy and data handling reliability.
- b) There is a need for further studies on the various components of the water balance system of IWA to identify effective ways to limit water losses.
- c) After ultimately deploying the smart metering infrastructure, a study on the return on smart metering investment is required.

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ملخص الرسالة

نفذت مملكة البحرين مشروع لإنشاء بنية تحتية لنظام العدادات الذكية، حيث تهدف من خلاله إلى تقليص الفجوة بين كميات المياه المنتجة و المياه المفوترة، يعمل النظام على توفير قراءات أكثر دقة (من العدادات التقليدية) ، وقراءات تلقائية للعدادات بشكل مستمر وعلى فترات محددة من اليوم، وتقليل الخسائر الظاهرية والحقيقية في الشبكة. تهدف الدراسة إلى بحث شامل للاستراتيجيات التي وضعتها مملكة البحرين للحد من فاقد المياه، ودراسة تأثير العدادات الذكية على خفض الفاقد، وبالإضافة إلى تحديد الأثر المالي الفعلي للعدادات الذكية والنتائج من تقليل الفاقد. تم استخدام البيانات المتاحة لاختبار فروض البحث والإجابة على أسئلة البحث إحصائياً، تضمنت الدراسة بيانات نوعية تم جمعها حول استراتيجيات التحكم في المياه التي تتبناها مملكة البحرين، وعمل اختبارات إحصائية للبيانات التاريخية التي تم تجميعها، كما تضمنت الدراسة على تحليل بيانات الفاقد من المياه في ٣٢ DMA's، للتحقيق في التأثير الحقيقي للعدادات الذكية. وكشفت الدراسة أن العدادات الذكية تؤثر إيجابياً على زيادة عائدات المياه وتتساهم في الحد من فاقد المياه في البحرين. كما تم تطوير نموذج للتنبؤ بنسبة الفاقد من المياه. يمكن استخدام نتائج الدراسة من قبل صانعي القرار لتقدير التأثير المتوقع لعوامل المياه المفقودة وتطوير البرامج التي تركز على هذه العوامل. بالإضافة إلى ذلك، تؤكد نتائج الدراسة وتوصي بالاستمرار في برنامج استبدال العدادات الذكية.



جامعة البحرين
كلية إدارة الأعمال
قسم الإدارة والتسويق

تأثير العدادات الذكية على الحد من فاقد المياه: دراسة حالة مملكة البحرين

أطروحة مقدمة كجزء من متطلبات الحصول على درجة الماجستير في إدارة الأعمال

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مريم كاظم مدن
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