Assessing the Resilience of Water Supply Systems in Oman

A thesis submitted for the degree of
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by

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I certify that this is the true and accurate copy of the thesis approved by the examiners

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Abstract

Water systems in the Sultanate of Oman are inevitably exposed to varied threats and hazards due to both natural and man-made hazards. Natural disasters, especially tropical cyclone Gonu in 2007, cause immense damage to water supply systems in Oman. At the same time water loss from leaks is a major operational problem. This research developed an integrated approach to identify and rank the risks to the water sources, transmission pipelines and distribution networks in Oman and suggests appropriate mitigation measures. The system resilience was evaluated and an emergency response plan for the water supplies developed.

The methodology involved mining the data held by the water supply utility for risk and resilience determination and operational data to support calculations of non-revenue water. Risk factors were identified, ranked and scored at a stakeholder workshop and the operational information required was principally gathered from interviews. Finally, an emergency response plan was developed by evaluating the risk and resilience factors.

The risk analysis and assessment used a Coarse Risk Analysis (CRA) approach and risk scores were generated using a simple risk matrix based on WHO recommendations. The likelihoods and consequences of a wide range of hazardous events were identified through a key workshop and subsequent questionnaires. The thesis proposes a method of translating the detailed risk evaluations into resilience scores through a methodology used in transportation networks.

A water audit indicated that the percentage of NRW in Oman is greater than 35% which is similar to other Gulf countries but high internationally. The principal strategy for managing NRW used in the research was the AWWA water audit method which includes free to use software and was found to be easy to apply in Oman. The research showed that risks to the main desalination processes can be controlled but the risk due to feed water quality might remain high even after implementing mitigation measures because the intake is close to an oil port with a significant risk of oil contamination and algal blooms. The most severe risks to transmission mains were found to be associated with pipe rather than pump failure. The systems in Oman were found to be moderately resilient, the resilience of desalination plants reasonably high but the transmission mains and pumping stations are very vulnerable.

The integrated strategy developed in this study has a wide applicability, particularly in the Gulf area, which may have risks from exceptional events and will be experiencing NRW. Other developing countries may also experience such risks but with different magnitudes and the risk evaluation tables could provide a useful format for further work.

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List of Abbreviations

ALARP	As Low As Reasonably Practicable
AWWA	American Water Works Association
CARRI	The Community and Regional Resilience Institute
CAVLAR	Criticality Analysis Valve Locations And Reliability software
CCC	Centralized Control Centre
CECC	Corporate Emergency Control Centre
COCIS	Cabinet Oversight Committee on Internal Security
CRA	Coarse Risk Analysis
DEMA	Danish Emergency Management Agency
DGW	Directorate General of Water
DMA	District Metered Area
DPRM	Disaster Preparedness and Risk Mitigation
EMNIC	Emergency Management Norfolk Island Committee
ERP	Emergency Response Plan
FEMA	Federal Emergency Management Agency
FMEA/FMECA	Failure Mode and Effect (Critical) Analysis
FI	Financial Indicator
GCC	Gulf Cooperation Council
GIS	Geographic Information System
GPDC	Ghubrah Power and Desalination Company
HAZOP	Hazard & Operability Analysis
HDPE	High Density Polyethylene
IEC	International Electro-technical Commission
ILI	Infrastructure Leakage Index
IWA	International Water Association
IWP	Independent Water Project
IWPP	Independent Water and Power Projects
JHA	Job Hazard Analysis
JRA	Job Risk Assessment
MECA	Ministry of Environment and Climate Affairs
MRMWR	Ministry of Regional Municipalities and Water Resources

MOD	Ministry of Defense
MSF	Multistage Flash
MUSS	Metropolitan Waterworks and Sewerage System
NCCD	National Committee on Civil Defense
NCND	National Committee for Natural Disasters
NEMP	National Emergency Management Plan
NRW	Non Revenue Water
OIFC	Oman Investment & Finance Company
O&M	Operation and maintenance
ONEIC	Oman National Engineer & Investment Company
OP	Operational Indicators
PAEW	Public Authority for Electricity and Water
PHA	Preliminary Hazard Analysis
PIs	performance indicators
PCRAFI	Pacific Catastrophe Risk Assessment and Financing Initiative
PRVs	Pressure Reducing Valves
RAECo	Rural Areas Electricity Company
RAMCAP	Risk Analysis and Management for Critical Asset Protection
RO	Reverse Osmosis
ROP	Royal Oman Police
RVA	Risk and Vulnerability Analysis
SCADA	Supervisory Control and Data Acquisition
SST	Sea Surface Temperatures
SWIFT	Failure Mode and effect (Critical) Analysis
TFS	Tanker Filling Station
UFW	Unaccounted for Water
UARL	Unavoidable Annual Real Losses
WDs	Water Districts
WHO	World Health Organization
WSP	Water Safety Plan

Chapter 1 Introduction

1.1 General Background

Water is the most important and valuable resource not only for human life but also for all living things. Both the access to and the quality of drinking water affects public health, economic development and national well-being (IWA, 2004).

Water supply utilities are required to fulfill water requirements both quantitatively and qualitatively, and in developing countries are, along with many utilities, operated by government organizations. In Oman for example, the Public Authority for Electricity and Water (PAEW) is a wholly public undertaking. Since water systems include several subsystems - sources, treatment plants, transmission, distribution networks, together with electricity and telecoms installations - there are many areas where undesired events may occur and cause harm (Beuken et al., 2008b). Consequently, there is a need to evaluate the urban water supply utilities in Oman, and assess and improve the resilience of drinking water supplies as part of long-term strategy to ensure service failures are close to zero and the service meets customers' expectations.

The impact of natural disasters on infrastructure including water supply systems can be considerable. In addition to natural hazards, the loss of a water service due to operational practices is a major concern with levels of losses in Oman estimated at more than 40%, which is high by international standards (UNEP-IETC, 1999; Word Bank 2007; PAEW, 2010). High levels of water loss or Non Revenue Water (NRW) reflect the significant volumes of water lost through leaks and water not invoiced to customers. Such losses seriously affect the finances of the water utility through lost revenues and increased operational costs (McKenzie and Seago, 2005).

High NRW levels normally indicate a poorly run water utility which lacks good governance, autonomy, accountability, and the technical and managerial skills necessary to provide a reliable service to its customers. The waste of resources resulting from high NRW levels in developing countries is considerable (Kingdom, et al. 2006) and at times of emergency or disaster, efficient water operators are imperative for the rapid return to normalcy.

A natural disaster can cause contamination of water, breaks in pipelines, damage to structures, water shortages, and in extreme events, the collapse of the entire system (Beuken *et al.*, 2008a; Nadebaum *et al.,* 2004). Depending on the level of preparedness that the water operator has adopted, repairs to systems can take days, weeks, or even months. The risk of damage to water systems increases dramatically with factors such as uncontrolled growth of urban areas, deficiencies in infrastructure, and, above all, the location of system components in areas that are vulnerable to natural hazards (Kwabena Sarpong and Mensah, 2006).

A holistic risk assessment and risk management approach, one which includes the entire drinking water system, from source to tap, is the most effective way to ensure a safe drinking water supply (WHO, 2008).There are strong parallels between risk assessment and management and the concept of resilience. As Blackmore et al. (2008) notes there are intuitive similarities between risk assessment and resilience concepts and it is therefore important to evaluate and assess the resilience of a system. The concept of resilience links strongly with risk management, but it is “a lesser function within the risk framework” (White, 2010) when defined as the ability of system to undergo change, while retaining functionality (Amarasinghe, 2014).The degree of resilience, which a system might require, also depends on risk and risk appetite (Howard, 2013).

If such a system’s functions are compromised due to a change in circumstances, it may not be sufficiently resilient to cope with whatever change has caused the failure (Rance and Wade 2013; Johansen et. al. 2014). Consequently, understanding the resilience of infrastructure or a service, requires an investigation of the systems required for its delivery and the risks associated with these systems (EPA, 2015).

1.2 Risk Evaluation and Emergency Planning

A risk assessment provides information so that well-informed decisions can be made. Water utilities must know the risk level to decide if risk-reduction measures are required or not (Aven and Korte, 2003). Risks are first analyzed and evaluated, and decisions are made in a subsequent step followed by risk-reduction measures and monitoring of the effects (IEC, 1995; Reekie, 2010; IPWEA, 2011). Risk analysis may be either qualitative or quantitative, depending on its purpose and the risk. Risk management priorities are determined by evaluating and comparing levels of risk against predetermined standards, target risk levels or other criteria (Almoussawi and Christian, 2005). If it is to be acceptable, it may be enough to control the risk instead of reducing it. However, if the risk is unacceptable, different risk reduction options have to be analyzed and compared so that the best can be identified (Rosen, *et al.,* 2007).

Improving the resilience of a water supply system requires understanding and planning for risks and increasing overall adaptability so that unforeseen changes can be dealt with (Carayannis, 2000). Examples of specific resilience-improving actions include preparing management or emergency plans, securing backup supplies, protecting water sources, improving infrastructure, and leakage management (Raouf, 2009). Emergency response management is another area where there is a clear overlap, particularly with the response element of resilience. Some sections of the literature focus entirely on this response element and how it can be assessed and improved in a complex system (for example Knott and Fox, 2010). Research in this field has been used to improve resilience by increasing the effectiveness of a system's response to hazards (EPA, 2015; Scottish Water, 2013; Tanali and Harrald, 2006; White, 2010).

This research tests and evaluates the effect of two particular stress factors on operating water supply systems in Oman; Non Revenue Water and, as an example of extreme event, a tropical cyclone. It further considers how the water service company might improve the resilience of drinking water supplies to extreme natural events and manmade hazards. The research involves identifying, understanding, managing, monitoring and communicating threats. The proposed emergency response to these threats is evaluated with regard to the risks to the water supply utilities in Oman and in the context of the financial resources available.

1.3 Problem Statement

The water utilities in the study area (the Sultanate of Oman) face a number of problems, among which are; low coverage of water supply to households, low service levels, high non revenue water, frequent pipeline bursts, problems with billing / revenue collection, and stopped or faulty water meters. Oman is located on the northern Indian Ocean in a tropical cyclone zone and suffers from natural storms and cyclones that can cause major damage to structures and infrastructure such as water utilities.

In June, 2007 a severe category four cyclone, 'Gonu', hit coastal Oman, with 213-232 km/h winds and heavy rainfall. High surface runoff, which in some areas exceeded three meters in depth, caused extensive flooding and substantial damage to critical infrastructure. Particularly severe damage was caused to the water distribution networks and water facilities.

The hurricane left thousands without a water service or with low water pressure for almost a month (Al Hattaly & Al-Kindy, 2008).

Water loss is an extremely challenging problem in Oman which is a desert country. This is aggravated by the fact that there is a lack of technological expertise and equipment to deal with water loss in most water systems. Taking all challenges into account, better management of water resources in the country is extremely important and research is required to understand and to properly manage distribution systems (Thornton 2002). There is a lack of relevant literature and studies about Non-Revenue Water in desert countries and in particular Oman, and about the impacts of cyclones on drinking water facilities (Kingdom, et al. 2006).

The emergency response to natural disasters should be appropriate, and problems associated with water lost through water distribution networks should be managed at an acceptable level (EPA, 2010). The PAEW's current emergency response regime is principally on resolving the causes of problems as quickly as possible and it does not take a long-term view. Equally, important aspects such as public information, alternative water supplies, contingency options for further reconfiguration of the network and rapid repair during extreme events are not given appropriate emphasis (James and Pavani, 2007; Tanali, and Harrald, 2006).

To summarize, water supply systems in Oman are exposed to a range of risks, both natural and man-made. There are risks to water supplies arising from operational practices, perhaps currently the most important being the leakage problem. However, new risk factors are certain to arise from for example, climate change, societal development and the emergence of new contaminants (UNESCO, 2012). To tackle these challenges, risks must be assessed and the results incorporated into a decision framework. This research identifies the problems and risk factors and recommends methods of analysis and assessment to improve the resilience of water supply systems in Oman and other desert countries.

1.4 Research Aim and Objectives

The aim of this research is to bring an understanding of how resilience to various hazards (natural and manmade) in water supply systems can be developed in the Sultanate of Oman. The research developed an integrated approach to identifying the risks and assessing their impact on the source, transmission and distribution of water in Oman. To achieve the above aim a number of objectives were set:

1) To identify and evaluate the financial impact posed by Non Revenue Water (NRW) and how this impact may be reduced, thus ensuring a more cost effective delivery of the water service.

2) To identify and estimate the risks associated with natural and manmade hazards to water supply utilities in Oman including desalination plants, transmission pipelines and water distribution network.

3) To Identify and evaluate the risk factors on potable water facilities arising from natural events using tropical cyclone Gonu as a case study.

4) To understand the level of risks to which the water infrastructure and hence wider society, is exposed and to determine how these risks may be reduced through effective measures of mitigation with the aim of improving the resilience of drinking water supplies.

5) To develop a justified response plan for water related emergencies including the options available to improve PAEW's response to managing emergencies.

1.5 Structure of the Thesis

This thesis is structured in accordance with the objectives and scope of work. There are eight chapters.

Chapter One outlines the problem statement, research aim and objectives, scope of work, and structure of the thesis. ***Chapter Two*** deals with the theory and current practice of resilience of critical infrastructure, potential hazards to water systems and their impact, tropical cyclones in the Arabian Sea, losses from water systems, risk assessment, risks to water facilities, and the emergency response plan.

Chapter Three presents the research approach, research techniques, and the risk assessment methodology. ***Chapter Four*** presents basic data about the study area (Oman), the impact of the cyclone Gonu, a water audit of a part of the water distribution system (Al Seeb Wilayat) and information about wider regional water supply systems.

Chapter Five is devoted to water audits and the background of the AWWA water audit tool, losses in the Al Seeb water supply system, results of a questionnaire survey and the strategy for reducing water losses. ***Chapter Six*** summarises and analyses risks and addresses potential mitigating measures, together with system resilience.

Chapter Seven proposes a new emergency response plan which has been evaluated against the responses to cyclone Gonu and compares this new plan with the existing. ***Chapter Eight*** concludes on the three main threads of the work; resilience to risks, the financial impacts of Non Revenue Water, and the proposed new Emergency Response Plan.

Chapter 2 Literature Review

The underpinning literature on the research reported in this thesis is reviewed in this chapter. There are three main threads to the work, Losses from Water Systems and Non-Revenue Water; Water System Risk and Resilience; and Emergency Planning. A general introduction to the research is followed by sections on each of the three threads. The relevant later chapters (Chapters 5, 6 and 7) include additional consideration of further specific research texts.

2.1 General Background

Severe social, economic and ecological impacts may result when societies are unable to predict, adapt to, or respond to disruptions in the supply of water. WHO (2008) concludes that the most effective way to ensure safe drinking water supply is by means of a comprehensive risk assessment and risk management approach. Water demand for domestic, agricultural, commercial and industrial uses is significantly increasing worldwide and arid regions in particular have great challenges (Raouf, 2009). Securing water supplies and infrastructure is becoming of vital importance especially in areas with inadequate water supplies such as Oman (Raouf, 2009). In addition to being a desert country, Oman is exposed to cyclones that cause damage to infrastructure and disruption of public services including water networks and there is concern that with climate change these problems will increase in frequency and severity. At the same time, during routine operations, there are often service interruptions due to equipment failure and breaks in pipelines, which can cause severe disruption. The starting point of the research is a study of the losses in water network operations in an arid country and the stress factors influencing the resilience of the system to overcome such losses.

2.2 Losses from Water Systems

2.2.1 Overview

Water lost from potable water distribution systems remains one of the key problem issues facing not only developing but also developed countries (McKenzie and Seago, 2005). The resource required for the development of infrastructure is lacking in most developing countries. This is aggravated by a lack of technological expertise and equipment to deal adequately with water loss in most water utilities, which further reduces the availability of adequate good quality water to consumers (Thornton, 2002; Michel et al, 2012).

Water loss rates in most cities in developing countries are in the range 40-60% of the total water supply (Butler & Memon, 2006; UNEP-IETC, 1999; Word Bank 2007). While it is commonly accepted that no water network can avoid losing water throughout its path, it is of high priority to ensure that these level of losses are known and controlled and that they do not exceed the pragmatic level that is technically and economically manageable on given infrastructures. This is particularly true where the production cost of water is high (as is the case in Oman through the necessity of using desalination plants), where there is the requirement of transporting water over long distances, where there is water scarcity, and where there are low income customers (PAEW, 2009; WHO, 2001).

2.2.2 Definition of Non Revenue Water

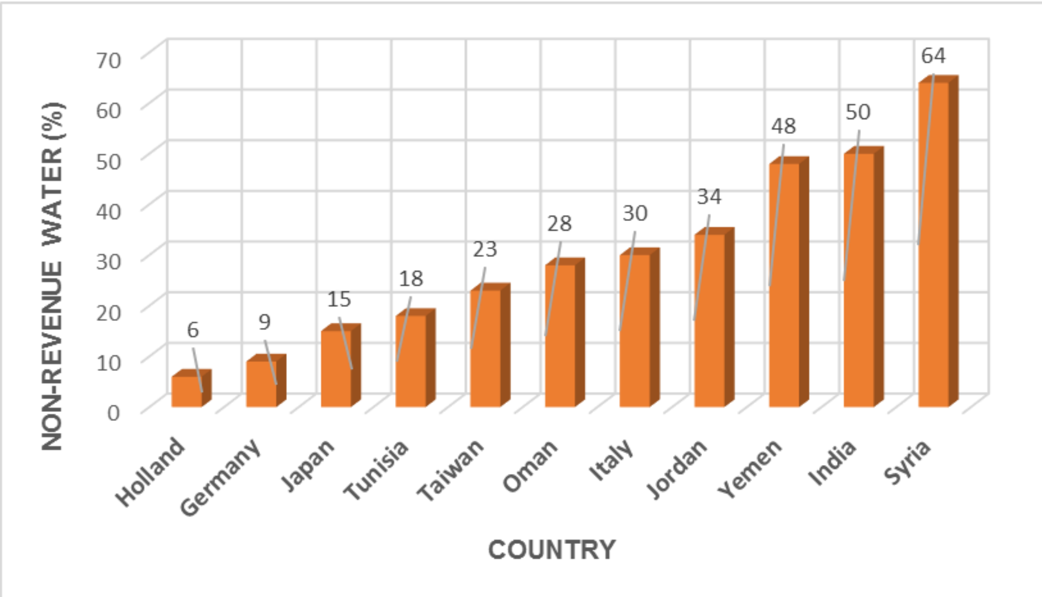
Non Revenue Water (NRW) is the difference between the volume of water input to a water distribution system and the volume that is billed to customers (IWA, 2004) and can be expressed in different ways:

- The percentage of the water produced from the raw water source, which is not accounted for (MWAC, 1999).
- The difference between water delivered to the distribution system and water sold (IWA, 2014).
- An accumulated range of losses by a Water Utility when comparing the demand of a hydraulic water network with the quantity of water acknowledged as consumed by consumers (UNEP, 2000).
- Lambert & Hirner (2000), go further, and define non revenue water, as the difference between the system input volume and billed authorized consumption.

Although the above definitions seem to have differences, all have in common that they have taken the water produced and distributed to the system as an input and the water consumed or exported from the distribution system as output. In the local context, NRW is defined as the difference between the amounts of treated water produced and supplied and the total amount of water billed and collected (IWA, 2014).

Non-revenue water rates in different countries including Oman are summarized in Figure 2.1. It will be noted that, while the NRW rates in Oman are high, several other countries and cities have higher rates.

Figure 2.1: Percentage of Non-Revenue Water



Source: **(**IWSA,1991 Word Bank, 1997)

2.2.3 Components of NRW and Water Losses

IWA have developed a methodology (Mcintosh, 2003) for determining NRW in which all water that enters and leaves the distribution system can be classified as belonging to one of the categories in the water balance table shown in Figure 2.2. The three components are: physical (or real) losses; commercial (or apparent) losses, and; unbilled authorized consumption. Each of these terms is defined below (Adu Yeboah, 2008).

Figure 2.2: The IWA Best Practice Standard Water Balance

System Input Volume	Authorized Consumption	Billed Authorized Consumption	Billed Metered Consumption (including water exported)	Revenue Water
			Billed Non-metered Consumption	
		Unbilled Authorized Consumption	Unbilled Metered Consumption	Non-Revenue Water
			Unbilled Non-metered Consumption	
	Water Losses	Apparent Losses	Unauthorized Consumption	
			Metering Inaccuracies	
		Real Losses	Leakage on Transmission and/or Distribution Mains	
			Leakage and Overflows at Utility's Storage Tanks	
			Leakage on Service Connections up to Customers' Meters	

Source: **(**Mcintosh, 2003)

- **Physical (or real) losses** occur as a result of poor operations maintenance, the lack of active leakage control, and poor quality of underground assets and are "any leakage downstream of a production source and upstream of the consumer meter" (UNEP/IETC, 1999).
- **Commercial (or apparent Losses)** are caused by customers' meters recording low, data-handling errors, and theft of water;
- **Unbilled authorized consumption** includes water used by the utility for operational purposes, for firefighting, and water provided for free to certain consumer groups.

The first two components constitute Water Loss (IWA, 2004, 2014). Normally the water loss indicators reflect the level of efficiency of management of the water supply system (Butler & Mamon, 2006). To be able effectively to reduce water loss, issues of technical, operational, institutional, planning, financial and administrative issues need to be coherently addressed (WHO, 2000 as cited in Butler and Mamon, 2006).

2.2.4 IWA System of Performance Indicators

Water supply systems are important and expensive core public assets and the primary objective of a water utility is to operate assets at their maximum possible efficiency with minimum cost. Performance indicators (PI) are useful when evaluating the efficiency (resilience) of all the components of the water supply system (Haider, et al. 2013). Various agencies and organizations worldwide have developed detailed performance evaluation frameworks including several indicators to cover all water system aspects including physical assets, staffing, operational, customer satisfaction, economic value (Alegre, et al, 2006).

The IWA Performance Indicators System for water services is now recognized as a worldwide standard. Since it first appearance in 2000, the system has been widely quoted, adapted and used in a large number of projects both for internal performance assessment and metric benchmarking. It has proven to be adaptable and can be used in any organization regardless of its size, nature or degree of complexity and development (Alegre, et al, 2006). The IWA PIs are grouped as follows:

- Water resources (Wr)
- Personnel (Pe)
- Physical (Ph)
- Operational (Op)
- Quality of Service (QS)
- Financial (Fi)

Although the indicators, data and context information in the IWA system have been chosen to represent universal concepts that may be applied almost anywhere in the world, the system may be insufficient, incomplete or inappropriate in certain particular situations. However, it is possible to define a starting point as broad and general as possible that will enable users to develop their own compatible systems (Alegre, et al, 2006). In this research, some of the Operation (Op) and Finance (Fi) indicators are calculated as presented in chapter 5.

2.2.5 Benefits of Reducing NRW

NRW reduction and control is one area of demand management where the objective is to limit the demand for water services by users and continued water loss affects negatively on efforts to limit demand. In economic terms this can be translated as more efficient use of existing supplies which becomes an increasingly cost effective alternative to supply augmentation and management (Versteeg and Tolbom, 2003; Michel et al, 2012).

A programme for NRW reduction and control should significantly benefit the Authority both financially and operationally as the public see the efforts bearing fruit. Improved service, fewer leaks and extension of the distribution system are positive outcomes of reducing NRW. However, such a programme must be properly communicated so that the good work is not disruptive and is of long-term benefit (Motevallian et al, 2011).

2.2.6 Causes of Water losses

Leakage is usually the major component of water loss but this is not always the case in developing or partially developed countries, where illegal connections, meter error and accounting errors are often more significant (Farley & Trow, 2003; WHO, 2001)). The several causes of increased NRW are;

1) Leaks in Water Distribution Systems

The causes of leaks vary depending on the nature of the soil, the quality of construction, the materials used, the pressure levels and the operating and maintenance practices of the utility (AWWA, 1987). Leakage is often a significant source of NRW and is a result of either lack of maintenance or failure to renew ageing systems. Poor management of pressure zones, resulting in pipe or pipe-joint failure, may also cause it. Although some leakage may go unnoticed for a long time, detection of visible leakage requires good reporting which also needs public participation (Motevallian and Tabesh, 2011).

2) Pressure and leakage

Pressure in a pipe system on the one hand contributes to the increase of leakage, which increases with pressure, and on the other hand, low-pressure systems suffer from a shortage of water causing unequal distribution of water among consumers. Pressure variation in a distribution network is also caused by changes in the demand by users (Kamani et al, 2012). Pressure reducing valves (PRVs) which throttle automatically are installed where high downstream pressures could cause damage (Walski et al., 2003; Ranhill, 2011).

3) Age of pipes

Pipe age and material are important factors contributing to the burst probability of pipes that as a result cause much water loss. However, as this information is not readily available especially for older pipes, it is usually estimated using the history of the urban development. There is a general correlation between the age of a system and the amount of NRW. Newer systems may have as little as 5 percent leakages, while older systems may have 40 percent or higher (Walski et al., 2003).

4) Effects of corrosions

Corrosion occurs in mild steel and ductile iron pipelines where they are in continuous contact with water or moist soil where they must be protected by coatings with corrosive resistant materials (Morrison et al, 2011). The majority of breaks in mains occur at locations where the metal pipe wall has been weakened due to corrosion.

5) Meter error and water loss

Under-registration of customer meters also contributes to NRW as does the age of meters. Customer meter errors can be due to accounting procedures and under or over-registration of the metering units. Where customers are served by way of roof tanks, the probability of customer meter under-registration is increased because of the tendency for a greater part of the consumption to pass through the meter at rates less than the minimum flow for the meter (Lambert, 2003).

2.2.7 Strategies for Dealing with Water Losses

The starting point in addressing water losses in any water utility is to understand the network of the utility (Butler & Mamon 2006). These authors suggest that certain questions should be posed about the water utility; (i) how much water is being lost? (ii) where is it being lost from?, (iii) why is it being lost? This research addresses the first and last of these points. Two tools for water audits and network reviews respectively, enable priority areas to identified and tackled (Thornton 2002).

After decreasing the level of leakage to a satisfactory rate, a continuous monitoring system must be implemented that permanently assesses the performance of the system and identifies areas where problems are likely in future. Computer simulation of the hydraulic system, with related techniques and instrumentation, also helps significantly at this stage (Covas & Ramos, 2000).

2.2.8 Assessment of Water Losses (Water Audit)

2.2.8.1 The Importance of a Water Audit

The objective of a water audit (Ganorkar et al., 2013) is to determine the amount of water lost from a system due to pipe leakage, overflows, losses due to metering errors, un-authorized connections and free water supplied at public standpipes. Water audits provide a rational, scientific framework that categorizes all water used in the system. It is a most effective tool for water management and with its help the water utility can identify and quantify what steps can be taken to reduce water use and losses (MDE, 2013). In the context of the prevailing problem in Oman, the water audit becomes an inevitable activity. Thus, it is a tool to identify the wastage of public money due to the water loss and un-authorized connections (Ganorkar et al, 2013) based on measurements or estimations of water produced, imported, exported, used and lost.

2.2.8.2 Water Audit Methodology and Software

A number of different approaches to water audits have been developed, several by the American Water Works Association (AWWA) (IWA, 2000; Adu Yeboah, 2008; Butler & Mamon, 2006). All fall short by categorizing a portion of the supply as unaccounted for water. Not only is this term inconsistently defined, it has frequently fallen prey to manipulation, with many utilities arbitrarily quoting an “unaccounted for percentage” without the means to validate the source of data.

It is found that AWWA methodology and software (AWWA, 2010) is the most appropriate approach that are used in many places in the world (Puusta et. al. 2010; Mutikanga et. al. 2011) and it was selected as the most applicable for application for this research since;

- It is based on a standard water balance
- It is capable of analyzing the different categories of losses, revenue and non-revenue water and other parameters.
- The software runs under excel Microsoft office with number of work sheets.

2.3 Resilience of Critical Infrastructure

This section addresses the issue of resilience. It might be considered premature to cover this topic prior to considering the more detailed aspects of risk and its determination since definitions of risk are covered in section 2.4 However, the concept of resilience covers broad issues including organization and governance and is addressed first.

2.3.1 Overview

Drinking water security is the ability to access an adequate amount of good quality water to support human health, the economy and the environment. It also means protecting drinking water from a wide variety of hazards including natural disasters, climate change, terrorist attacks and other manmade hazards (EPA, 2015).

The delivery of clean, reliable and secure water services relies on there being enough treatment capacity to satisfy consumer requirement. It also relies on the assets, such as treatment works, pumping stations and transmission and distribution pipes being maintained to a level that ensures services are not affected during normal, planned operation conductions (OFWAT, 2010). A water company should have to manage its system during and after extreme events such as cyclones, floods and droughts by providing appropriate levels of protection to consumers, this being termed resilience (OFWAT 2010).

The concept of resilience informs the ability of a system to undergo change, while retaining functionality (Amarasinghe, 2014). Furthermore, resilience as a concept highlights characteristics such as the ability of a system to absorb pressures or disturbances, and re-organize itself. Resilience is considered to be the ultimate objective of hazard mitigation, that is, ‘action taken to reduce or eliminate long-term risk to people and property from hazards and their effects’ (Godschalk, 2002). While there are numerous definitions for resilience in the literature, the most relevant to this study is; "resilience is the ability of assets, networks and systems to anticipate, absorb, adapt to and / or rapidly recover from a disruptive event" (Cabinet Office, 2011).

Since resilience is of particular concern to water utilities many have developed resilience criteria. These include Scottish Water (2013) which lists the following key resilience factors;

- Ensuring critical assets are secure;
- Achieving the necessary levels of duplication and reliability;
- Improved response to customers' needs;
- Improving drought resilience ;
- Managing demand through leakage management;
- Reducing the risk of failure of critical assets;
- Improving response to short term interruptions to supply;
- Ensuring customers have an adequate water pressure; and
- Developing response and recovery plans for extreme events;

Since the present research emphasizes the resilience of water supply systems in Oman as operated by the Public Authority for Electricity and Water (PAEW), the following section presents the components of infrastructure resilience, resilience of water supply systems, and the relation between resilience and risk management of particular interest to this research.

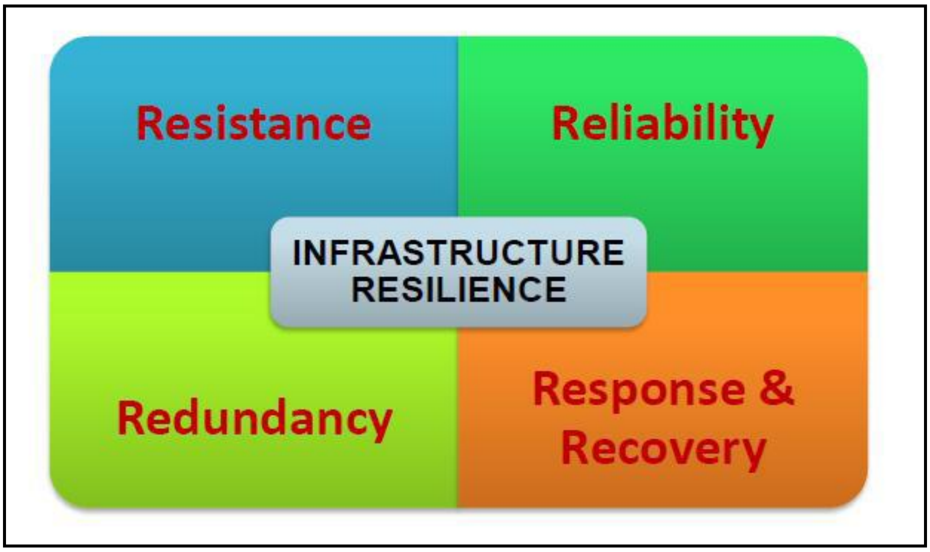
2.3.2 Resilience of Water Supply Systems

The resilience of water supply systems to natural disasters and other hazards implies a continuous cycle of planning and preparedness activities (Blackmore 2009), response and recovery actions following an adverse event (Rance and Wade 2013), adapting (Johansen et. al. 2014) and changing to be better prepared for future events based on lessons learned (EPA, 2015). Much has been written about the resilience of drinking water systems to natural disasters (Copeland 2006; Béné et. al. 2012), terrorist attacks (Little 2004) and other emergencies (ASCE, 2008; ANSI, 2010; USEPA, 2011 and 2012) providing useful information on preparedness, response and recovery, case studies and lessons learned, and water sector specific tools.

One of the challenges to using the concept of resilience is determining how it may be quantified. With limited resources, water utilities must make decisions about which preparedness and adaptation activities will most improve their resilience (EPA, 2015). Measures of resilience would help in prioritizing such decision-making; however, satisfactory measures or indicators of resilience are not currently available. As described in McAllister (2013), resilience performance goals and quantitative metrics are needed that can be used to support risk-based decision-making for water systems.

The Cabinet Office explains that resilience is the sum of four main system characteristics shown in Figure 2.3: resistance, reliability, redundancy and response (Cabinet Office, 2011). Resistance is specific protection such as floodwalls, redundancy consists of spare capacity such as backup systems, and reliability consists of designing system components such that they can operate in a wide range of circumstances. Response activity consists of emergency plans, and ensuring the right corporate culture and skills exist to be able to react in the event of a hazard.

Figure 2.3: The Components of Infrastructure Resilience



Source: Cabinet Office (2011)

In building resilience, the contribution made by each of these four components is considered since each can be utilized or adapted to different levels. Given the range of risks, organizations should select combinations of responses from all four components to develop a strategy that will deliver the most cost effective and proportionate risk management response to hazards and threats (Cabinet Office, 2011).

Hence the resilience of infrastructure is provided through (a) good design of the network and systems to ensure it has the necessary resistance, reliability and redundancy (spare capacity), and (b) by establishing good organizational resilience to provide the ability, capacity and capability to respond and recover from disruptive events. The latter is gained through business operations and appropriate support for business continuity management as shown in Figure 2.4 (Cabinet Office, 2011).

Figure 2.4: Continuous Cycle of Building Resilience to Hazards

Source: EPA, (2015).

2.3.3 Enhancing the Resilience of Water Systems

Preparedness involves anticipating risks and planning mitigation strategies. The Recovery Practices Primer for Natural Disasters (ASCE, 2008) and Welter (2009) provide guidance on preparedness and hazard-specific guidance for natural disasters. Le Chevalier and Chelius (2014) suggest resiliency planning should include: renewing aging infrastructure, planning for operational continuity, combining new operational solutions with capital improvements, and practicing emergency response plans. Several authors have a joint focus on building resilience of the water and energy sectors (Johnson Foundation, 2013; Ajami and Truelove, 2014).

Several authors provide guidance for water utilities on enhancing preparedness to different hazards (ASCE, 2008, and Welter, 2009). The CIPAC Workgroup (2009) helps to build resilience of water utilities by identifying specific actions that will mitigate the consequences of hazardous events by grouping the potential consequences of hazardous events into categories: loss of power, loss of communication, loss of supervisory control and data acquisition, service disruption, reduced workforce, contamination incidents, and economic disruptions. For each of these consequences, specific preparedness and response and recovery actions are identified.

For a complex water system, Chang and Shinozuka (2004) noted that robustness, redundancy, resourcefulness, and rapidity enhance the resilience of a system. They identify different actions that can be taken in order to enhance systemic resilience including: increase of storage, strengthening the capacity of water treatment plants to treat lower quality water, providing alternative sources, and building an efficient management strategy. These actions have been included in the mitigation measures and solutions that have been considered in this study to mitigate risks and enhance resilience of water systems in Oman.

2.3.4 Water System Resilience Tools

A number of tools have been developed to help water utilities improve their resilience. The CBWR tool (USEPA, 2011) provides over 400 targeted resources to help local communities plan for and respond to drinking water emergencies and includes a resiliency self-assessment tool which evaluates a water utility's resilience in terms of outreach to interdependent sectors, dedication of resources, security enhancements, vulnerability assessments and emergency response plans. It addresses contaminant detection, incident command system training, mutual aid assistance agreements, participation in local emergency response planning, and long-term climate change planning.

Another EPA resilience tool is The Risk Analysis and Management for Critical Asset Protection (RAMCAP) standard for risk and resilience management of drinking water and wastewater Systems (ANSI, 2010). Different strategies may be classified as countermeasures (ones that can reduce vulnerability or threat) or consequence mitigating actions (ones that reduce consequences). The strategies can then be ranked by the amount that they reduce risk for the water utility, summed up across all threat-asset pairs.

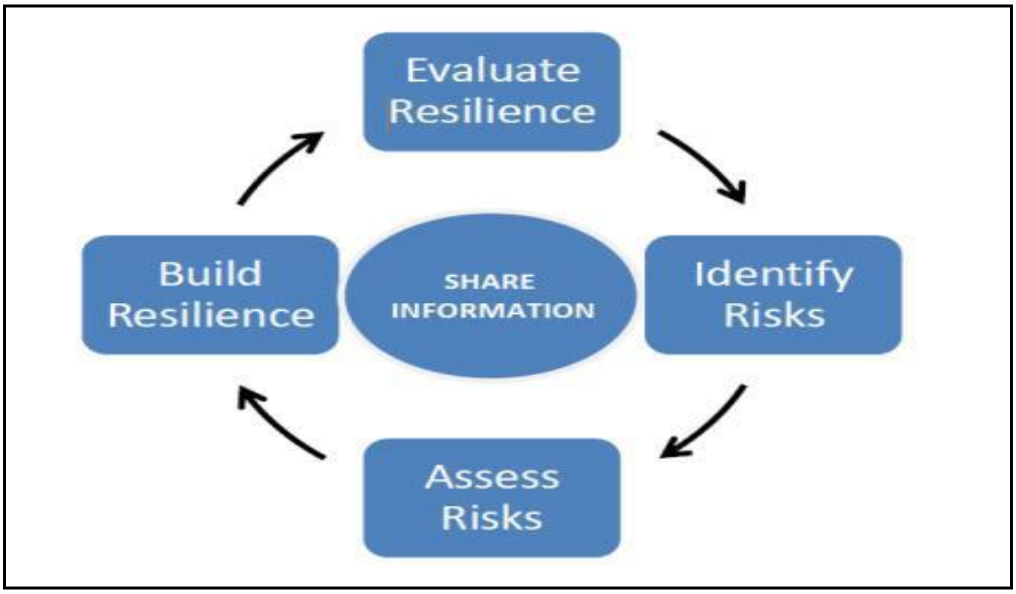
The Argonne National Laboratory Resilience Index (Fisher, 2010) measures the resilience of critical infrastructure including drinking water and wastewater systems. It combines more than 1,500 variables into a composite index that measures robustness, recovery and resourcefulness and produces an overall score from 0 (low resilience) to 100 (high resilience). In contrast to the RAMCAP tool, this index is designed for national authorities, the single index allowing national comparison of water systems to help prioritize funding and assistance.

The three tools outlined above were evaluated and it was decided (5) to use an approach similar to the CBWR and RAMCAP tools which concentrate on natural disasters and traditional utility challenges such as loses due to pipe breaks, and poor water quality. This is in contrast with many tools which focus on climate change scenarios while the others concentrate in threats from different issues and the factors that affecting community and environmental health (USEPA, 2011). It is considered that the CBWR / RAMCAP approach is best because of the amount of support resource material available and its relative ease of use and its match with the available data.

2.3.5 Hazards, Risks and Resilience

Risk management is a process of identifying, understanding, managing, controlling, monitoring and communicating risk while resilience is very closely related to the fields of risk assessment of management (Cabinet Office, 2011). Effective risk management is the key to facilitating and building resilience and the effectiveness of the four components of resilience (Resistance, Reliability, Redundancy and Response/ Recovery) can be assessed using the Resilience Cycle shown in Figure 2.5. Key to building resilience is the governance of, and attitudes to, risk and resilience within an organization. The resilience cycle emphasizes the need for continuous re-evaluation of resilience in the face of changing risks and the importance of sharing information between stakeholders. This is particularly important when assessing climate change risks and adaptation options, since knowledge of climate predictions, and hence climate risk to service, will change over time (Cabinet Office, 2011).

Figure 2.5: Resilience Cycle for Infrastructure



Source: Cabinet Office (2011).

Anticipating and managing risk is one-step towards increasing resilience to hazards. Disaster risk is “the potential for adverse effects from the occurrence of a particular hazardous event, which is derived from the combination of physical hazards, exposures, and vulnerabilities” (NAS, 2012). Risk is normally calculated as the product of the likelihood of a specific hazard and the consequences of that hazard and is addressed in more detail in section 2.4. Sometimes, the likelihood is expressed as the product of the vulnerability and the threat. Understanding risk enables informed decision making about how to reduce risk (either the likelihood or consequences) and increase resilience (EPA, 2015).

Building on the work of Klein (2003) and others, resilience can be defined as a measure of the ability of a system to absorb changes whilst performing its intended functions. If such a system's functions are compromised due to a change in circumstances, it may be deemed not resilient enough to cope with whatever the change was that caused the failure. The concept of resilience links strongly with risk management, but that it is "a lesser function within the risk framework" (White, 2010).

The degree of resilience which a system might require depends on risk and risk appetite (Howard, 2013). To investigate the resilience of a service therefore requires an investigation of the systems required for the delivery of that service and the risks associated with these systems including the infrastructure networks themselves, practices and procedures of the operators, critical external dependencies and institutional arrangements.

The Community and Regional Resilience Institute's (CARRI) definition of resilience helps to pull all of these concepts together: resilience means the ability of a system to anticipate risk; limit affects, and bounce back rapidly (CARRI, 2014). Anticipating risk means identifying and understanding the risks of potential hazards to a system. Limiting impacts means enhancing preparedness, implementing risk management strategies, and reducing vulnerabilities. Bouncing back rapidly means ensuring the ability to respond and recover rapidly through training, planning, and building flexibility and adaptability into the organization.

2.3.6 A Methodology for using Risk Scores to Understand Resilience in Water Systems

Definitions of risks are covered in section 2.4 of this thesis. Several approaches to converting risk scores into estimates of resilience were investigated (Hughes and Healy, 2014; Perry, 2013; FAO, 2013) but none were found to be specific to the problem being considered and the procedure developed by Hughes and Healy (2014) for application in transportation infrastructure was adapted for this purpose. To investigate the resilience of a service therefore requires an investigation of the systems required for the delivery of that service and the risks associated with these systems. Understanding risk enables informed decision making about how to reduce risk and increase resilience (EPA, 2015).

Logically, assessing resilience requires a comprehensive risk assessment relating to the system under discussion to be undertaken by developing an understanding of what the threats to that system are and what mitigates should be exist which help deal with those risks. A comprehensive risk assessment should therefore be a ‘resilience approach’ as Blackmore et al. (2008) define it. Consequently, the output of the risk assessment would determine the ‘desired’ level of resilience.

Based on the results of a risk assessment, the resilience of a system can be evaluated and the resultant risk score is translated to a level of resilience. Hughes and Healy (2014) used a simple scoring method to generate a resilience score from descriptions of the risks in a transportation system. Their procedure converts the risk into a four scale resilience score;

1 Low resilience: The risks to the system are significant or extreme.
2 Moderate resilience: The risks to the system are major.
3 High resilience: The risks to the system are acceptable.
4 Very high resilience: The risks to the system are very low.

The information presented here is applied to the water networks in Chapter 6 of this thesis.

2.3.7 Potential Hazards to Water Systems and Their Impacts

This section overviews the impacts of natural events on drinking water facilities and the ongoing efforts required to assess damages and the needs to repair and reconstruct damaged systems. Drinking water systems are subject, to a greater or lesser degree, to both natural and manmade hazards that are common in the Gulf Coast region of the USA (Gleick, 1996; Annerberg, 2009). It is a priority for such services to operate optimally, since a significant degradation of their quality can affect most of the population (WHO, 2005).

Even during routine operations, there may be service interruptions due to equipment failure, breaks in pipelines, and rationing due to lack of water. Factors such as uncontrolled growth in urban areas, deficiencies in infrastructure, and, most importantly, the location of system components in areas that are vulnerable to natural hazards all increase the risk of damage to water systems in disasters. Operation and maintenance organizations are required to have strategies directed at reducing the vulnerability of the systems and providing the best possible response once an emergency arises (WSDH, 2003; Michel et al, 2012). The emergency plan (considered in detail in Chapter 7 of this thesis) should establish the necessary procedures to mobilize existing resources quickly and effectively, and, if necessary, request outside assistance in order best to react to the effects of hazards.

2.3.8 Types of Disasters and their Effects

Disasters are mostly caused by natural phenomena, even if many of their consequences are attributable to human actions or negligence. Natural disasters can be of two types: sudden onset, as in the case of earthquakes and gradual onset, as in the case of drought (PAHO, 2002).

2.3.8.1 Earthquakes

Earthquakes are one of the most serious hazards, given their enormous destructive potential, the extent of areas affected, and the impossibility of forecasting their occurrence. The significance and type of damage relate to the magnitude of the earthquake and the area covered, the degree to which buildings and infrastructure are seismic resistant, and the quality of soil where structures are located (Robert et. al. 1997). Although Oman is in a low risk earthquake zone, the possibility of one’s occurrence is real and earthquakes are considered here so that extreme possibilities are seen to be considered. The types of damages that an earthquake can inflict on water supply systems as given by; (Shi and O'Rourke, 2008; Javanbarg and Takada, 2010) are;

- Total or partial destruction of intake, transmission, treatment, and / or distribution systems;
- Rupture of transmission and distribution pipes and damage to joints between pipes or tanks, with consequent loss of water;
- Interruption of electric power, communications, and access;
- Deterioration of quality due to landslides and other phenomena;
- Reduction in yields from groundwater sources and flow in surface water sources;
- Changes in the exit point of groundwater or in the phreatic level;
- In coastal areas, inland flood damage due to the impact of tsunamis. Introduction of salt water into coastal aquifers.

2.3.8.2 Hurricanes

Depending on wind speeds, hurricanes (known locally as cyclones) are tropical depressions (winds up to 63 km/h accompanied by changes in atmospheric pressure), tropical storms (winds between 64 and 119 km/h accompanied by intense rainfall), or hurricanes (wind speeds of 120 km/h or higher, accompanied by heavy rainfall and significant changes in atmospheric pressure) (PAHO, 1998, 2002). The Saffir-Simpson scale includes five categories, as shown in Table 2.1 (Simpson, 1974).

Table 2.1: Saffir-Simpson Scale

Saffir-Simpson Category	Maximum Sustained Wind Speed		Height of Waves	Potential Damage
	(m/s)	(km/h)	(m)	
1	32.7- 42.6	118- 153	1.0 to 1.7	Minimal
2	42.7- 49.5	154- 178	1.8 to 2.6	Moderate
3	49.6- 58.5	179- 210	2.7 to 3.8	Extensive
4	58.6- 69.4	211- 250	3.9 to 5.6	Extreme
5	≥69.5	≥251	≥5.7	Catastrophic

Source: (Simpson, 1974)

Hurricanes can cause major damage to structures and infrastructure exposed to flooding and high winds. The potential damage is directly related to wind speed, height of waves, rainfall and exposure including damage to power lines and infrastructure located near waterways; damage to homes and an increase in precipitation that may give rise to severe flooding.

In general, drinking water facilities are badly affected by the Hurricanes (PAHO, 2002; Copeland, 2006; Malam, 2010). The most common effects of hurricanes on drinking water systems include:

- Partial or total destruction of buildings, broken windows, roof damage, flooding;
- Ruptures of pipelines in exposed crossings over rivers and streams;

- Breaks of pipes in mountainous terrain as a result of landslides and water erosion;
- Damage to elevated and ground-level tanks;
- Contamination of water in tanks and pipes;
- Breaks in pipelines and structural failure because of settling earth;
- Damage to electrical transmission and distribution systems resulting in the interruption in operation of equipment, instruments, and communication.

Hurricane Katrina in 2005 is well researched and documented and is used here to illustrate the risks associated with tropical storms. Hurricane Katrina was the costliest and one of the top five most deadly hurricanes in the history of the United States (National Hurricane Center 2006; Knabb et al, 2006). It was the deadliest Hurricane since 1928 with hundreds missing and causing at least 1,836 lives to be lost in the hurricane and subsequent floods In addition, 450,000 were displaced and over 200,000 never returned to their city (Seed, et al, 2006).

Much of the water system of Greater New Orleans area was completely wiped out, and in the entire area affected by the hurricane, over 1,200 water systems and 200 wastewater systems were affected. About 40% of these systems were up and running again within two weeks but a full month after the storm only 85% of water systems were fully operational, many of which were still operating on boil water notices (Copeland, 2005).

In addition to the damage to city systems, in the state of Louisiana, 23% of drinking water and 29% of waste-water facilities were inoperable after the storm, all of which were located within 100 kilometer of the coastline (Muthuramalingam, 2005). Direct physical damage and extended power outages affected both the ability to treat and distribution of water throughout the area (Ram et al, 2007).

The two largest drinking water plants serving New Orleans were completely underwater for at least two weeks after the storm and even after they were repaired to allow for flow for fire-fighting, toilet flushing, and showers, they did not provide potable water for over a month. For a population used to the comfort of a faucet in their own home, this sudden termination of water treatment can be very dangerous to health. Where the population has little concept of the dangers of unsanitary water or knowledge of alternative methods of sanitation, these deficits will inevitably lead to increased negative health effects and possibly outbreaks of waterborne infectious disease notices (Copeland, 2005).

2.3.8.3 Floods

Floods are the result of excessive rainfall resulting from hurricanes, unusually high sea levels or the rupture of dams and dikes (PAHO, 1998, 2002; Haraguchi and Lall, 2013). Increasingly, floods result from human activity causing environmental degradation, deforestation, and inappropriate land use. On the other hand, some floods are the result of the geomorphology and climatology of water catchment areas. The magnitude of the effects of floods is principally related to the level reached by the water, its speed, and the geographical area covered.

The most common impacts of floods are (PAHO, 1998, 2002):

- Damage or destruction of housing built close to waterways;
- The flooding of urban areas, even entire cities, built in low−lying areas, affecting the economy and the provision of services;
- Accumulation of water in low−lying areas, creating breeding opportunities for disease carrying insects.

The main impact of flood on drinking water and sewerage systems can be summarized as follows (Attari and Rashidi, 2009; Fritz et al, 2007):

- Total or partial destruction of intakes located in rivers or ravines;
- Sedimentation, resulting in silting up of intakes and reservoirs;
- Loss of intakes because of changes in the course of rivers;
- Breaks where exposed pipe crosses ravines and/or rivers;
- Contamination of the watershed;
- Damage to pumping equipment;
- Indirect effects such as interruption of electricity and communications, and road blockages.

2.3.9 Man-made Hazards

Man-made hazards are defined as conditions of potential danger or risk to life and health or property resulting from acts of man and use of technology. They arise from deliberate human actions (e.g., war, terrorism, emergencies, etc.) that are usually predictable and preventable and from the unforeseen or unexpected consequences of human development and technology, for example, nuclear weapons, industrial accidents, etc. (Carayannis, 2000). Disasters in water utility operations may also occur due to neglect and/or failure to properly institute and adhere to maintenance procedures and manmade hazards may result in multiple impacts to water systems (EPA, 2015).

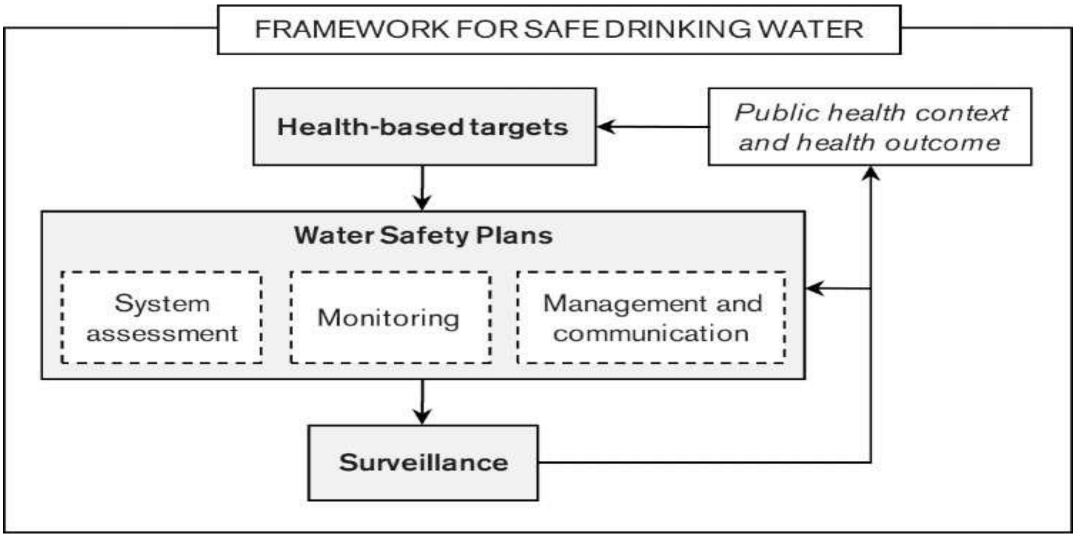
2.4 Risk Assessment and Management

2.4.1 Water Safety Plans

The World Health Organization (WHO, 2008), concluded that a holistic risk assessment and risk management approach which including the entire drinking water system, from source to tap, is the most effective way to ensure a safe drinking water supply. Methods and tools available today, and possible future methods and tools, provide better means than previously for assessing risk and providing useful decision support regarding risk issues (Andreas, 2010). The purpose a Water Safety Plan (WSP) is to assess the entire water system, identify possible hazards and plan how to monitor and operate the system so that risks are controlled.

The WSP approach is a risk management strategy that aims consistently to ensure the safety and acceptability of a drinking water supply (Bartram *et al.*, 2009). These authors have suggested that WSP is used to determine whether the drinking water system is capable of delivering water that meets the health-based target and should include system assessment, monitoring and management plans as shown in Figure 2.6.

Figure 2.6: The Framework for Safe Drinking Water



Source: (WHO, 2008)

The purpose of the WSP is to assess the entire drinking water system in a given area to identify possible hazards and set up plan how to monitor and operate the water system so that the risks are controlled (WHO, 2008). The assessment should include the complete system (from source to tap) and interactions between all elements in the system. The monitoring processes allows the assessment of control measures for better assurance that the system is functioning properly. However, management plans should be adopted to document and communicate relevant information of the water system. WHO (2008) suggests that risk ranking should be a part of WSPs (Bartram *et al.,* 2009).

2.4.2 Risk Definition

In the methodology adopted (MHLS, 2010), the probabilities of occurrence of a particular event are typically defined as small, medium, large or very large. Similarly, the consequences of the same occurrence are described as small, medium, large and very large and the risk is expressed as a combination of the probability and consequence of each hazard (event):

$$\text{Risk} = \text{Likelihood} \times \text{Consequence} \qquad (2.1)$$

The Likelihood is the chance that a hazard will actually compromise drinking water quality or quantity and pose a public health threat while the consequence is the combination of the severity, nature, and duration of an event, the proportion of the population affected, and type of health consequences. The results are normally arranged in a risk matrix. (MHLS, 2010).

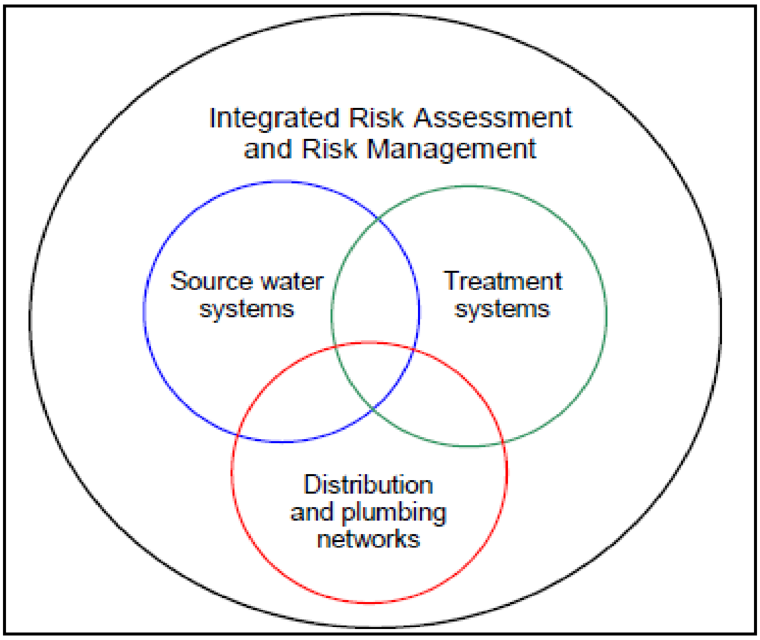
2.4.3 Risk Assessment

A risk assessment provides information so that well-informed decisions can be made (Aven and Korte, 2003). Water utilities are interested in knowing the risk level to decide if risk-reduction measures are required or not. If the risk level is unacceptable, possible measures need to be evaluated to determine what alternative is most suitable. Hence, risk assessments are initiated by an underlying decision problem. Since it is not possible to eliminate all risks, an acceptable risk level must be obtained by balancing risks, benefits and cost. Risk assessment is thus closely linked to decision-making and it is common to combine risk assessment and decision analysis.

Risks are first analyzed and evaluated, and decisions are made in a subsequent step followed by risk-reduction measures and monitoring of the effects (IEC, 1995; Reekie, 2010, IPWEA, 2011). Risk management is an iterative process which means that the work should be continuously updated and that there are no strict boundaries between the steps. Furthermore, risk and related aspects need to be communicated between decision-makers, scientists, the general public and other stakeholders since risk management aims to protect humans and what is considered of value to humans.

TECHNEAU (2005) promotes the integration of risk assessments of the separate parts in drinking water supplies into a comprehensive decision support framework for cost-efficient risk management in safe and sustainable drinking water supply as illustrated in Figure 2.7.

Figure 2.7: Integrated Risk Assessment and Risk Management of a Water Supply System



Source: (Rosen, *et al.,* 2007)

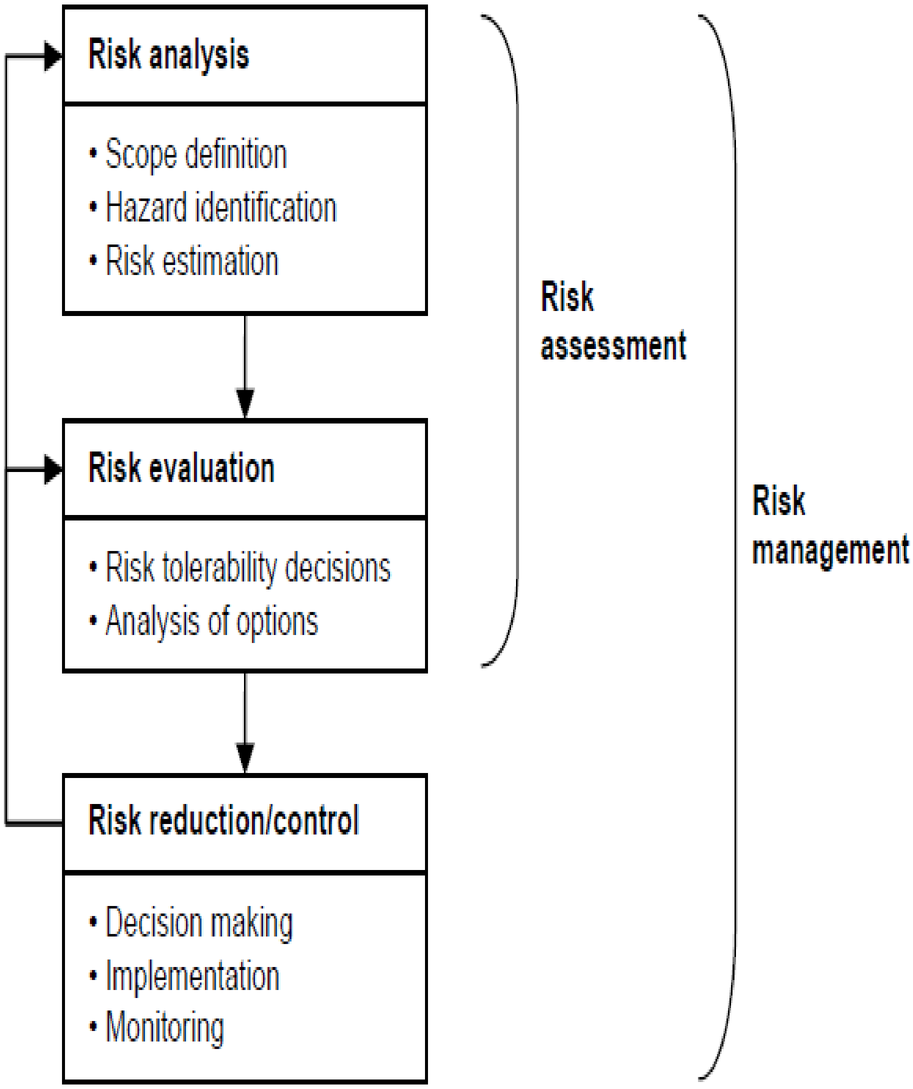
2.4.4 Risk Management Process

2.4.4.1 Introduction

Although some differences can be found in the literature regarding the presentation and outline of the process, there is a strong consensus regarding the major topics in risk management. The outline shown in Figure 2.8 is commonly used and is often quoted (EPA, 2008).

Risk management also includes risk monitoring and follow up during operations. It is an iterative process of continuous updating as new information becomes available and as the preconditions change. Successful risk management also requires communication of risks between the various involved stakeholders (IRR, 1996).

Figure 2.8: The Risk Management Process



Source: (IEC,1995)

2.4.4.2 Assessment of Risk

The risk associated with each hazard may be described by identifying the likelihood of occurrence (e.g. 'certain', 'possible', 'rare') and evaluating the severity of consequences if the hazard occurred (e.g. 'insignificant', major', 'catastrophic'). The potential impact on public health is the most important consideration, but other factors such as aesthetic effects, continuity, adequacy of supplies, and the reputation of the utility should also considered (WHO, 2009).

2.4.4.3 Risk Analysis

Risk analysis is a major part of risk assessment and management and may be either qualitative or quantitative, depending on its purpose and the risk. The analysis may also be semi-quantitative, which is something between a quantitative and qualitative analysis (Rosen, *et al.,* 2007). When analyzing risks it is important to choose which endpoints or consequences to include and also to decide which measures to use since that the choice of one measure or another can make a technology look more or less risky Slovic (2001),

A simplified qualitative approach (Table 2.2) relies on the expert judgment of the water safety plan team. A small water supply may only require a team decision, whereas a more complex system may benefit from a semi-quantitative risk prioritization approach. The ranking table developed by WHO (WHO, 2009) takes into account the quantitative and semi-quantitative approach and provides estimation of likelihood/ frequency and severity/consequence of an event as shown in Table 2.3.

Table 2.2: Semi-quantitative Risk Matrix Approach

Likelihood or Frequency	Vulnerability					
	Rating	Insignificant or no impact	Minor complian ce impact	Moderate aesthetic impact	Major regulatory impact	Catastrophic public health impact
		(1)	(2)	(3)	(4)	(5)
Almost certain / Once a day	(5)	5	10	15	20	25
Likely / Once a week	(4)	4	8	12	16	20
Moderate / Once a month	(3)	3	6	9	12	15
Unlikely / Once a year	(2)	2	4	6	8	10
Rare / Once every 5 years	(1)	1	2	3	4	5
Risk Score			< 6	6-9	10-15	> 15
Risk Rating			Low	Medium	High	Very high

(from Deere et al., 2001)

According to WHO (2009) a 5x5 risk matrix is satisfactory for scoring and prioritizing risks with variable scoring ratios to separate high, medium and low risks. The use of a basic non-scoring 3x3 risk matrix (high, medium and low) is not helpful because most risks end up in the medium category and have to be reprioritized. An example is shown in Table 2.3, although each system must be considered on a case-by-case basis.

Table 2.3: Risk Table Developed by WHO (2009)

High Risk ≥ 20 **Medium Risk 10-19** **Low Risk < 10**				**Consequence**				
				Wholesome Water	Short term or locallised, not health related non compliance or aesthetic	Widespread aesthetic issues or no long term non compliance not health related	Potential long term health effects	Potential illness
				Insignificant	**Minor**	**Moderate**	**Major**	**Catastrophic**
				1	**2**	**4**	**8**	**16**
Likelihood	Has not happan in the past and it is highly inmprobable that it will happan in the future	**Most Unlikely**	**1**	1	2	4	8	16
	Is possible and cannot be ruled out completely	**Unlikely**	**2**	2	4	8	16	32
	Is possible and under certain circumstance could happan	**Forseeable**	**3**	3	6	12	24	48
	Has occurred in the past and hasthe potential to happan again	**Very Likely**	**4**	4	8	16	32	64
	Has occurred in the past and could happen again	**Almost Certain**	**5**	5	10	20	40	80

2.4.4.4 Risk Evaluation

Risk evaluation decides whether or not a risk is tolerable. Risk management priorities are determined by evaluating and comparing levels of risk against predetermined standards, target risk levels or other criteria (Almoussawi, and Christian, 2005). If it is to be acceptable, it may be enough to control the risk instead of reducing it. However, if the risk is unacceptable, different risk reduction options have to be analyzed and compared so that the best can be identified (Rosen, et al., 2007).

A further principle widely used to evaluate a risk is termed the As Low As Reasonable Practicable (ALARP) principle (Melchers, 2001). ALARP can be explained as follow:

- Unacceptable risk: this type of risk must be reduced or eliminated;
- Acceptable risk: can be left without further action;
- or between acceptable and unacceptable: *may* be accepted if it is economically and/or technically unreasonable to be reduced.

2.4.4.5 Risk Reduction/Control

If the risk is not acceptable, it is mandatory that it should be addressed or treated Rosness, (1988) and an action plans for risk prevention/ mitigation might include (AS/NZS 4360, 2004):

- Planned actions;
- Existing/required resources;
- Involved responsibilities;

- Duration; and
- Action tracking and controlling measures.

These actions, when systematically applied, will evaluate, and control risk.

2.5 Methods of Risk Analysis and Assessment

2.5.1 Risk assessment methods.

Risk assessments (Hokstad et al, 2009, WHO, 2009), can be carried out with a range of methods that can be broadly classified:

1. **Qualitative methods:** result in qualitative descriptions of risk in terms of high, moderate, and low. These are used when the hazard cannot be expressed in quantitative terms and/or when the vulnerability cannot be expressed quantitatively.

2. **Semi-quantitative methods:** Semi-quantitative techniques express risk in terms of risk indices. These are numerical values, normally ranging between 0 and 1 which do not have a direct meaning for expected losses but are merely relative indications of risk. Also, in this case risk, is expressed in a relative sense.

3. **Quantitative methods**: express the risk either as probabilities, or as expected losses. The methods can be deterministic / scenario-based or probabilistic (taking into account the effect of all possible scenarios). Some of main risk analysis methods, mostly in the stage of risk estimation are reviewed by TECHNEAU (Rosen et al., 2007) as

presented in Table 2.4 which shows the most popular methods. In this research, the preliminary hazard analysis (PHA) using Coarse Risk Analysis (CRA) method was applied as discussed in the following section.

Table 2.4: Overview of Main Risk Analysis Methods

No.	Name of Method	Stage in Risk	Type (Qualitative/ Quantitative)	Data Require-ments
1.	Hazard Identification (HAZID)	Hazard identification	Qualitative	Low
2.	Hazard and Operability Studies (HAZOP)	Hazard identification	Qualitative	Medium
3.	Preliminary Hazard Analysis (PHA) - Coarse Risk Analysis (CRA) method - Risk and Vulnerability Analysis (RVA) method	Hazard identification Risk estimation	Qualitative	High
4.	Failure Mode, Effect & Criticality Analysis (FMECA)	Hazard identification Risk estimation	Qualitative/ Quantitative	High
5.	Fault Tree Analysis (FTA)	Risk estimation	Qualitative/ Quantitative	High
6.	Reliability Block Diagram (RBD)	Risk estimation	Qualitative/ Quantitative	High
7.	Event Tree Analysis (ETA)	Risk estimation	Qualitative/ Quantitative	High
8.	Human Reliability Analysis (HRA)	Risk estimation	Qualitative/ Quantitative	High
9.	Physical models (e.g., EPANET, CARE-W)	Risk estimation	Quantitative	High
10.	Health Risk Assess./Quantitative Chemical Risk Assessment (QCRA)	Risk estimation	Quantitative	High
11.	Quantitative Microbial Risk Assessment (QMRA)	Risk estimation	Quantitative	High
12.	Barriers and Bow- Tie diagram	Risk estimation	Qualitative/ Quantitative	Low

Source: (Adapted from Rosen et al., 2007)

2.5.2 Approach to Risk Assessment for Water Supply Systems

When deciding what method to apply it is important to consider what information the risk assessment provides and what resources are available. A logical approach is to first perform a qualitative risk assessment covering the entire system, from source to tap, and later use a quantitative method for a more detailed assessment. However, if the overall risk situation is well known and documented, quantitative risk assessments can assess the entire system or specific parts directly. The most common semi-quantitative risk assessment approach which is used widely by different water supply operators is the Coarse Risk Analysis (CRA) method (TECHNEAU, 2010). Several case studies on risk assessment from different world locations were reviewed, some using qualitative methods and others using semi quantitative or quantitative methods.

1. **Breznice,Czech Republic:** The risk analysis of the drinking water system in Breznice, the Czech Republic covered the system from source to service connection and was focused on identification of all hazardous events which may influence the quality of distributed water (Kozisek et al, 2008). The study applied the CRA method for risk identification and estimation process since in this case study it seemed to be a suitable tool for risk identification and estimation in small water supplies.

2. **Bergen, Norway:** The drinking water system in Bergen, Norway, was analyzed using CRA (Rostum and Eikebrokk, 2009).The hazards were identified and assigned probabilities and consequences based on scales presented in a risk matrix. Three different types of consequences were considered: (1) water quality effects, (2) water

quantity effects and, (3) consequences to the reputation and economy of the water utility. All elements of the supply system, i.e. from source to tap, were included in the analysis. Based on the analysis possible new risk reducing measures were identified for all elements in the water supply system.

3. **Upper Mnyameni, Eastern Cape, South Africa:** This risk analysis used CRA (Tornqvist et al., 2009). The objective of this study was to identify hazards in the drinking water supply system (from “source-to-tap”), estimate and evaluate the risks to humans and the development of the society, and evaluate the risk assessment methods that were used. The risk reduction options proposed were found to reduce risks significantly.

Quantitative risk assessment methods are often used when qualitative methods are not considered detailed enough. Quantitative methods provide an estimate of the risk level in absolute terms (e.g. as the expected consequence) which facilitates comparison with other risks and acceptable levels of risk. Furthermore, by using a quantitative method it may be possible to quantitatively estimate the efficiency of different risk reduction options.

Further case studies on risk assessment of the drinking water systems using at least one quantitative method were reviewed. As an example, the

Goteborg, Sweden system was analyzed using a Fault Tree method conducted by Chalmers and Goteborg Water (Lindhe et al., 2008). KWR and Waternet (Beuken et al., 2008a) assessed the risks to the water supply for the city of Amsterdam, Netherlands using the CAVLAR method. A risk assessment of the system in Freiburg, Germany (Sturm et al., 2008) used a Geographical Information System (GIS) to assist the risk analysis.

These case studies show that both qualitative and quantitative methods provide different kinds of results but they are both useful. The case studies where semi-quantitative (CRA) was used show that this kind of assessment typically requires a medium level of expertise, time and level of data detail. The assessments enabled the identified risks to be prioritized and guide the water utility where risk-reduction measures are most important. CRA is also useful in providing an overview of the risks in all parts of the system and can be used to identify what further more detailed assessments are required. The quantitative methods used in the case studies required a medium or high level of expertise, time and data details. At the same time, the results were more detailed compared to the qualitative or semi-quantitative methods and could more easily be compared to acceptable risk level, system requirements and similar measures (TECHNEAU, 2010).

2.5.3 Risk Assessment Approach Selected

From the above discussion, it was decided that the Coarse Risk Analysis (CRA) method was the most appropriate for the research. The basic ideas of this method along with how it is applied are discussed in the following section.

2.5.4 Coarse Risk Analysis (CRA)

The main objective of the CRA is to identify hazardous events, the cause(s) of the event, and to make a coarse evaluation of likelihoods and consequences of these events. The basis for the CRA is a description of the water supply system and a list of undesired events that may occur in the system. For each event, the likelihood of occurrence and the consequence are assessed using a scale of 5 categories in order to estimate the risk. The objectives of the analysis are to identify undesired events, to rank the undesired events with respect to risk and to assess the need for risk reducing measures. The scope of an overall CRA – including risk evaluation and risk control - typically consists of (Hokstad, et al, 2009):

1. Identify hazardous events related either to the total water supply system, or to a specific part (or in general to some category of undesired events).
2. Risk estimation, i.e. estimate the probability and consequence for each hazardous event. Present these risks in risk matrices, and possibly compare to risk acceptance criteria.

3. Rank the hazardous events with respect to their risk.
4. Assess the need for risk reduction options or more detailed analyses.

The risk estimation in a CRA is usually restricted to presenting categories of probability and consequence. The probability categories are denoted e.g. rare, unlikely, possible, likely, and almost certain, and similarly consequence categories, e.g. negligible, minor, moderate major, and severe. The combined likelihood-consequence categories could then be inserted in a risk matrix.

Several combinations of scale are possible. Table 2.5 shows an example of a CRA semi-quantitative risk matrix where the likelihoods and consequences have been assigned numbered levels that have been multiplied to generate a numeric description of risk ratings.

Table 2.5: Example of Basic Semi-Quantitative Risk Rating Matrix

Likelihood	Consequences					
	Score	Negligible	Minor	Moderate	Major	Severe
		(1)	(2)	(3)	(4)	(5)
Rare	(1)	1	2	3	4	5
Unlikely	(2)	2	4	6	8	10
Possible	(3)	3	6	9	12	15
Likely	(4)	4	8	12	16	20
Almost Certain	(5)	5	10	15	20	25
Risk Score		< 6	6-9	10-15	> 15	
Risk rating		Low	Medium	High	Very high/extreme	

The values that have been assigned to the likelihoods and consequences are not related to their actual magnitudes, but the numeric values that are derived for risk can be grouped to generate the indicated risk ratings. In this example, extreme risk events have risk ratings greater than 15, high risks are between 10 and 15, medium risk are between 6 and 9 and low risk are less than 6 (Australian Government, 2008). Critical to evaluating and comparing risks is good estimation of the scores which, in this research, were addressed in the workshop detailed in Chapter 3.

2.6 Risks to Water Facilities

2.6.1 Introduction

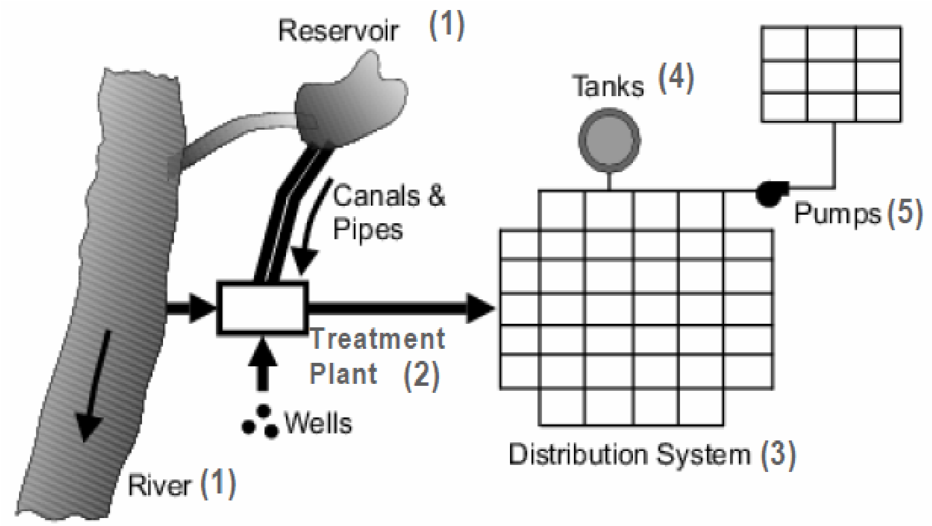
Water supply systems are usually designed, constructed, operated, and managed in an open environment, thus they are inevitably exposed to varied uncertain threats and hazards (Karamouz et al., 2010).

The components and subsystems of water networks give many opportunities for both natural and human-related influences because most components are spatially diverse and accessible. Potentially the most vulnerable areas in water delivery systems are (see Figure 2.9) (Karamouz et al., 2010):

1. Water sources (e.g., river, reservoir, and wells);
2. Water treatment plants that remove impurities and harmful agents and makes water suitable for domestic consumption and other uses;

3. Distribution pipelines that deliver clean water on demand to homes, commercial establishments, and industries;
4. Storages (tanks); and
5. Other facilities (transmission pipes, channels, pumps, valves, etc.).

Figure 2.9: Elements and Vulnerable Points in a General Water Supply System

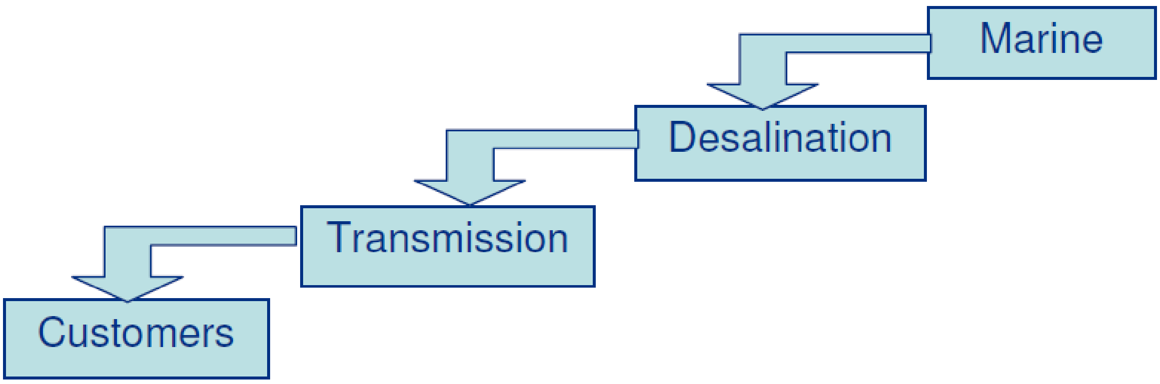


Source: (Karamouz et al., 2010)

With respect to the security of the water supply the actual risk to the water supply is only realized as a consequence by the customer. Risks from the marine environment are generally mitigated in the treatment process but if overwhelmed, the consequence is on production. Small changes in production are mitigated by storage of treated water at the desalination plant and within the transmission system but when this is exhausted; the customer suffers a loss of water supply.

Figure 2.10 illustrates the sequence of risks from sea to the customer if the measures in place are inadequate to mitigate the risks. The concept of this change of location of the risk is important to the consideration of solutions as problems resolved at the highest level have the greatest impact on the overall risk profile, although they may be more challenging to implement.

Figure 2.10: The Sequence of Risk Location from Sea to the Customer



Source: (Karamouz et al., 2010)

2.6.2 Major Desalination Plant Threats

In the late 1990s, nearly half of the world's desalinated water originated in the Arabian Gulf region (Wangnick 1999, cited in Latteman and Höpner, 2003). The Sultanate of Oman has been using desalinated water since 1976 when the Al-Ghubrah power and seawater desalination plant was first commissioned. The threats from the marine environment that affects desalination plants in the Gulf Region are characterized by:

1. Close proximity to busy national and international shipping lanes (potential for accidental and incidental pollution of the marine environment);
2. Warm and deep coastal waters (ideal conditions for blooms of jellyfish and algae which block intake screens (Al Hasni, 2012); and
3. Exposed coastline (risks from occasional extreme weather conditions).

2.6.3 Major Network Threats

1) Pipeline Failure

Long single pipelines are at risk from failure due to a variety of causes (PAEW, 2011):

1. Ageing/ deteriorating pipes.
2. Corrosion and growth of iron consuming bacteria resulting in pipe pitting.
3. Lack of proper maintenance, leading to failures of air valves, fittings.
4. Poor quality of installation and use of inappropriate materials.
5. External damage, either accidental or deliberate vandalism.
6. Rapid valve closure causing high surge pressures.
7. Failures of joints in pipes and fittings.
8. Natural disasters e.g. floods breaking pipelines at wadi crossings.

An overall level of risk is normally assessed from failure records for pipes of different diameters and different materials. The average risk of failure can then be applied to all pipelines. If certain sections prove to have higher failure rates, then the reasons for this can be examined and, where appropriate, action taken to reduce the risk (PAEW, 2011):

2) Pumping Stations and Control Systems

The risks to pumping stations may be grouped under three headings:

1. Breakdowns of pumps and motors.
2. Loss of incoming power supply.
3. Failures of control systems

3) Service reservoirs

Service reservoirs are at risk from:

- Pollution
- Structural failure

2.6.4 Extreme Weather Events

Several of the failure mechanisms described above may be due to adverse weather. In extreme weather conditions, it is likely that many failures will occur at the same time and they may be spread over a wide area. Furthermore, communications may be disrupted, creating difficulties in ascertaining where failures have occurred and reaching sites to undertake repairs (Brekke et. al., 2009).

2.7 Emergency Response Plan

2.7.1 The Requirements for an Emergency Response Plan

The emergency plan should comprise tools, measures and approaches aimed at overcoming the identified constraints to effective water supply and sanitation. The plan, if well implemented should achieve some expected outputs. First, the strategies and mechanisms for effective water supply and sanitation will be achieved. Further, when all relevant institutions work together, implementation of the plan will not be hampered and harmonizing monitoring and evaluation practices of the programs ensures that they are well implemented to the letter. Lastly, members of the public will be fully aware of issues during an emergency ensuring coordination and facilitation towards any emerging issue in the supply of water within the state (WHO, 2011; WSDH, 2003).

2.7.2 Mission statement

The mission statement for an emergency response plan is to plan and manage water supply and sanitation effectively by ensuring that members of the general population are effectively and adequately provided with consistent water supply and sanitation and health is well maintained during an emergency, (Reaves, Termini & Burkle, 2014). Having a mission statement and goal facilitates fast tracking of measures that will later ensure that the goals are realized. In addition, the response plan should establish a framework for effective planning and management of the water supply and sanitation and ensure that water supply and sanitation is achieved at all times.

2.7.3 International Practice of Emergency Response Plans for Water Supply

To counter the risks associated with disasters, each country tends to have its own unique way of handling cases of disasters.

2.7.3.1 Status of Disaster Preparedness and Risk Mitigation in the USA

As a developed country, the USA has a well-structured program with institutions tasked with disaster preparedness and risk mitigation (DPRM). The Us Federal Public Health Security and Bioterrorism Preparedness Act of June 2002 require that all systems must conduct a vulnerability assessment to gauge the level of preparedness in time of disasters. The department of Homeland Security under presidential directive should ensure that water supplies are free from any form of attacks by terrorists (Whybark, 2015).

2.7.3.2 Status of DPRM in the Philippines

In the Philippines, many agencies are involved in ensuring that DPRM is effectively executed. Overall, the Cabinet Oversight Committee on Internal Security (COC-IS) is in charge of national crisis management. The National Peace and Order Council is tasked with handling any form of crisis situation that poses a threat to peace and order (Lum and Margesson, 2014). The National Disaster Coordinating Council is tasked with strengthening disaster control and ensuring general preparedness in times of crisis. Through this body, all information relating to National Disaster preparedness are relayed to the President for management plans to facilitate the release of the National Calamity funds as required.

The Metropolitan Waterworks and Sewerage System (MWSS) in Manila has a plan, which is monitored and evaluated periodically by the MWSS regulatory office. Manila has the group called Risk, Crisis and Asset Management Cluster (RCAMC), which prepares for any emergency that may affect service delivery and includes risk, crisis, and asset management (McEntire, 2014). In smaller cities, for example Urdaneta, also have backup from the Army (Abdullah et. al., 2015).

2.7.3.3 State of DPRM in Tanzania

Tanzania, a sub Saharan suffered from catastrophic floods in January 2010 but had no proper disaster preparedness plan in place (McEntire, 2014). A first emergency appeal was launched on the 20th January 2010 which highlighted the vulnerabilities caused by the collapse of the water and sanitation infrastructure. Support came from internationally recognized institutions like the Red Cross, which provided 10 WatSan-Kits, which included social safety nets and provision of insurance cover. The main advantage of these kits was that people could cope with small-scale emergencies without requiring any external assistance. Tanzania opted to use satellite navigation to preposition emergency equipment. However, the use of satellite navigation is not enough as a counter measure for disaster preparedness since it does not address all issues and it is concluded that the use of the satellites should be combined with existing measures on site for capacity assessment (Almarez, Peòaroya, and Rubio, 2015).

2.7.3.4 Summary of Findings on International Practice

This review shows that the country showing the best example of disaster preparedness is the Philippines, which, in comparison with the USA and Tanzania has many departments tasked with ensuring that they combat any form of disaster that may occur. In Oman, the National Committee for Civil Defense (NCCD) is in charge of emergency preparedness within the regions of Oman. It works jointly with the Gulf Cooperation Countries (GCC) Regional Crisis Centre in Kuwait to achieve prevention, mitigation, disaster preparedness and with the armed forces and other governmental ministries in cases of disasters. In comparison with other countries, particularly within the region, Oman well prepared for disasters and response due to the mandate given to the NCCD (PAEW, 2011).

2.8 Summary

Only a limited number of studies that could form the basis of research into assessing the risks to water system arising from both natural phenomena and water losses were found. There is little literature on the effect of exceptional events such as Cyclone Gonu and their adverse effects on water networks in arid countries such as Oman, and consequently little attention has been focused on this joint problem that might assist in improving responses to emergencies. Further, no comprehensive study was found which addresses the issue of non-revenue water when estimating the revenue lost.

This chapter has included a comprehensive review of the risks factors in the problems addressed and this knowledge informs the risk assessments in Chapters 5 and 6. The most appropriate risk assessment method which links exceptional events and manmade hazards to water supply systems has been shown to be the Coarse Risk Analysis (CRA), a method which commonly used in the management of water supply systems.

The research translates the risk score to a level of resilience, the resilience score being generated using a simple scoring method used in transportation analysis. The data and performance indicators obtained using the well-known AWWA methodology and software, and the risk and resilience scores, an emergency response plan is developed in Chapter 7 taking into consideration the research output and best international practice. Before the risks are determined and the resilience evaluated, the methods used are outlined (in Chapter 3) and the case study area described (in Chapter 4).

Chapter 3 Methodology and Data Collection

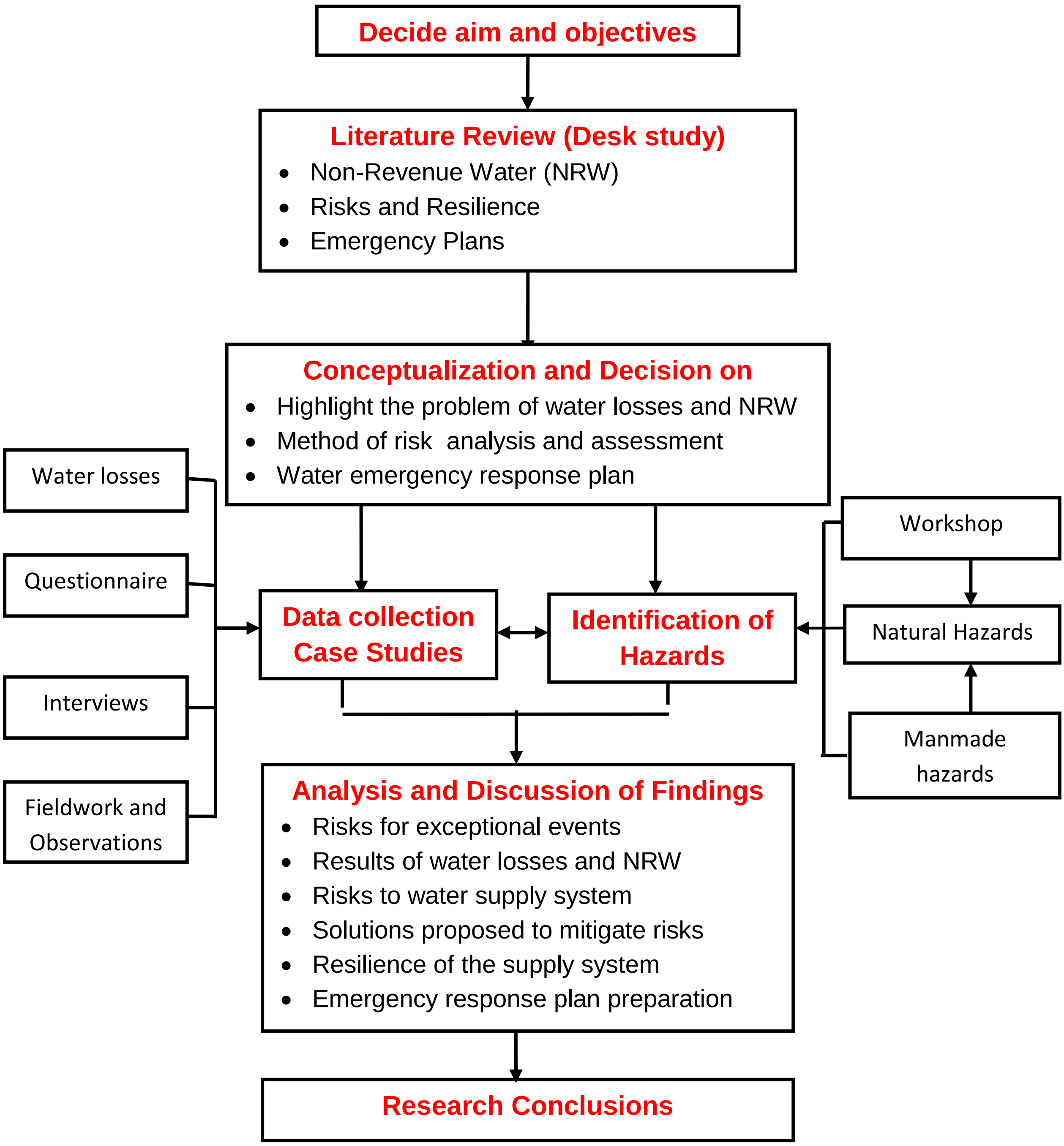
3.1 General Background

Both Quantitative and Qualitative data gathering (Blaxter et al. 2010) was undertaken in order to obtain and present relevant data and meet the aim and objectives of the research. After extensive reading of the literature on risk and resilience, records and data held by the water supply company were mined for system information. Risk factors were identified, ranked and scored at a workshop with key stakeholders. The data were mined a second time for the determination of NRW and the operational information required was principally gathered from interviews. Finally, the emergency response plan was developed through an evaluation of the above factors, which highlighted the deficiencies in the old plan, particularly following the experiences during tropical cyclone Gonu.

3.2 Research Approach

Blaxter et al. (2010) identified four basic approaches to the design of a research project; Action research, case studies, experiments and surveys. Apart from reviewing the literature, the two main research approaches adopted in this study were case studies and surveys. Case studies are usually used to illustrate problems or indicate good practices since they attempt to describe relationships that exist in reality, very often in a single organization. For this purpose, case study methodology was considered the most appropriate approach because it provides a systematic way to collect data related to water losses and risks to water supply systems, analyze information and report the results thus enabling an understanding of the particular problem in great depth. Figure (3.1) is a schematic representation of the framework of the research approach.

Figure 3.1: Research Approach



From the critical review of literature in chapter 2, the following tools are used in the subsequent chapters; the AWWA Water Audit Tool (see section 2.2.8); the CRA method for risk evaluation (section 2.5.4); a tool for resilience scoring developed by Hughes and Healy, 2014 (section 2.3.6), and; a risk scoring matrix (section 2.4.4.3). One questionnaire was also designed similar to the questionnaire developed by GTZ-VAG (2009).

3.2.1 Workshops and Interviews as Means of Gathering Data

Understanding of the operational and organizational practices of PAEW was gained through workshops (section 2.8). A workshop was held to undertake a comprehensive review of the security of water supply to consumers in Oman and for the development, optimization and presentation of detailed action plans for improving the security of supply.

In the case studies from WHO (2009) which were examined, the threats to water quality were identified by conducting workshops. In one example from Australia, two-day workshops were convened for each major water supply system involving a consultant, stakeholders and facilitators. In another example from the Caribbean, a two-day workshop was convened to identify hazards and assess risks. Hazards in the watershed, treatment process, water distribution system, and households were identified through brainstorming exercises and a review of water quality monitoring.

In this study, the author conducted surveys through questionnaires and interviews to determine the perceptions of staff of some factors regarding the topic. These surveys enabled the researcher to obtain data about practices, situations or views at one point in time. Quantitative analytical techniques were then used to draw inferences from these data (Scheyvens and Storey, 2003).

Laws, Harper and Marcus (2003) write that interviews can be conducted in a wide variety of situations and for different purposes:

- Knowledge is required about people's experiences or views in depth;
- Reliance is placed on information from small number of respondents;
- Issues may be sensitive and people may not speak in a group;
- Respondents may not be able to express themselves fully through a written questionnaire.

Daphne (2000), gives the main advantage of the interview over other forms of data collection as the ability for the interviewer to seek further clarification of the responses from the respondent by probing the initial responses giving richness to the data and allowing many individual differences in opinion and reasoning to be uncovered. This feature of the interview as a tool for data collection was an invaluable ingredient to the work of this research making the qualitative data collection more natural and also able to be used as a primary source of data.

According to (Scheyvens and Storey, 2003), in the work-place context of this research, highly structured interviews would not have allowed good qualitative data to be elicited and these authors are of the view that interviews as tools have inherent limitations:

- Recording of the responses is one of the weaknesses of interviewing. Writing while someone is speaking can put him/her off ;
- Tape recording and later transcribing is also time consuming; and
- Interviews can result in a one-way traffic of information from which only the researcher benefits.

3.3 Research Techniques

3.3.1 Introduction

As identified by Blaxter *et al.* (2010) there are four basic research techniques namely; the study of documents, observation, questionnaires, and interviews. The nature of this study and the aims it sought to achieve required the adoption of a variety of techniques of data collection and analysis. The present study obtained research data from documents analysis, observation, questionnaires, interviews and workshops. The data obtained from those data collection techniques were further analyzed to obtain the findings of the study. The interviews and workshops are the best ways of getting data compare to online surveys or telephone surveys as the responses of the people to gather more and deeper information can be explored. At the same time, the researcher can observe and witness certain things that are necessary for his research work.

The first phase was a review of relevant national and international literature in order to identify the need for such research, its context and furthermore to identify current trends and common themes. It was important to find out; the most appropriate methods of risk analysis; the assessment of exceptional events; the evaluation of manmade hazards to water supply systems, and; the determination of a reliable Non Revenue Water figure or equivalent performance indicators.

3.3.2 Field Work and Observation

Both quantitative and qualitative data collection result in precise measurements that are amenable to quantitative data analysis. The aim of collecting data in research “is the production of public knowledge (empirical and theoretical) about specific issues which can be used by others in a variety of ways”, and where it is used as the main research method, it can be used for the collection of descriptive quantitative data (Sapsford and Jupp, 1996). The researcher carried out field work with staff and fieldworkers of the host organization Public Authority for Electricity and Water (PAEW) and others to look for issues related to water loss and risks whilst he took accompanying notes.

3.3.3 Questionnaire and Interviews

A principal source of data was the interviews that were undertaken with the senior staff of PAEW who are involved in water losses and non-revenue water to determine their opinion on issues of water loss and risk assessment of the water supply system. Interviews allow the researcher to generate a rich and varied data set in a less formal setting (Kitchen and Tate, 2000).

Questionnaires generally produce quantitative data but can also capture qualitative information concerning the respondents opinion, attitude and perception. From the answers, the researcher generally creates quantitative data that he/she analyses to address the research problem (Neuman, 1997). One closed questionnaire was developed to gather information about NRW and this was followed up by semi-structured interviews on a one-to-one basis as discussed in section 3.5.

3.3.4 Workshop

Prior to the inception of this research, a two-day workshop had been held on 8th Sep. 2009, where the major risks were reviewed with PAEW stakeholders. A further one-day workshop held on 17 June 2013 at the Main Office of PAEW directly to inform this research as it undertook a comprehensive review of the security of water supply to consumers in Oman. The workshop also assisted in the development, optimization and presentation of detailed action plans for improving the security of supply. The objectives of the workshop (the results are in Chapter 6) were to:

1. Identify all risks to the security of supply.
2. Communicate the risk assessment process, and define the consequences and likelihood appropriate to PAEW.

3. Share some of the information on risks collected by the team of experts from PAEW and identify ideas to mitigate potential risks.

The researcher was the chairperson of that workshop, and experts in various fields relevant to PAEW attended. Among the participants, were Heads of the chemistry and microbiology departments due to the importance of the risks of water pollution and contamination. Three projects mangers attended because they have experience in the analysis and assessment of risk to water utilities during the construction projects. The design engineers are aware of how the water systems are designed against possible risks. The senior desalination plant engineer and senior water specialist participated as they have experience in the risks to desalination plants and the effects of mechanical and electrical failures of the water utility. Staffs from the operations department as the control engineers and operators were invited because of their knowledge on how the water systems is operated and the hazards expected. The operation and maintenance manager of Al Ghubrah desalination plant was invited because he is the responsible person for day-to-day work within the desalination. In total, 12 key personnel attended. However, an invitation was extended to the general manager of operation, a senior manager water quality, and maintenance planning manager but they could not attend due to work obligations. First there was an open discussion/ brainstorming within two groups and each group was asked to make list of risks. Later the two groups joined to agree on the final list of the key risks.

After the key risks had been identified they were tabulated and scored for likelihood and consequence to provide PAEW with a prioritized list of potential problems that may impact on the security of the water supply. Risk scores were generated using a simple risk matrix to assign the likelihood and consequence of an event occurring. PAEW then identified potential mitigation measures, with technical and economic justification. The workshop recommended that the risk tables are periodically updated (for more detail also see Appendix-A).

3.4 Methodology of the Water Audit

The standard water balance is a series of simple equations. A graphical presentation is presented in Figure 2.2 and this is the most common way to view the standard water balance developed by AWWA (BD9) (see section 2.2.8).

Ganorkar et al, (2013) gives a useful critique of the methodology, showing that the amount of water in a system can be broken down into; authorized use and water losses, where;

$$\text{Authorized Use} + \text{Water Losses} = \text{System input} \tag{3.1}$$

The following relationships are used in the standard water balance:-

$$\text{Water Losses} = \text{Apparent Losses} + \text{Real Losses} \tag{3.2}$$

Nonrevenue Water = Water Losses + Unbilled Authorized Use (3.3)

Apparent Losses = Metering Inaccuracies + Unauthorized Use (3.4)

These equations may be satisfied using the following the five step process (Ganorkar et al, 2013);

- **Source Evaluation:** A system may have multiple wells, springs or surface water intakes. The amount of water input to the balance is determined by metering at source.
- **Authorized Consumption**: Revenue Water is made up of Metered and Unmetered Consumption. Billed Metered Consumption includes residential, commercial and industrial customers. Billed Unmetered Consumption consists of any contracts the system has to provide unmetered water for a fee.
- **Evaluation of Apparent Losses:** Apparent Losses of water occur as inaccuracies in water flow measurement, errors in water accounting, and unauthorized usage. Apparent Losses are Unauthorized Use and Metering Inaccuracies and is theft.
- **Evaluation of Real Losses:** Real Losses are the physical escape of water from the distribution system, and include leakage and overflows prior to the point of end use. Real losses typically account for a greater volume of water lost by utilities in comparison to apparent losses.

The newest and most advanced real loss indicator (recommended by the IWA and AWWA Water Loss Committee) is the infrastructure leakage index (ILI) which is the ratio of the current annual real losses (real losses) to the unavoidable annual real losses (UARL) (Winarni, (2009). UARL is a theoretical reference value representing the lower limit of leakage that could be achieved if all of today's best technology could be successfully applied. The ILI is a highly effective performance indicator for comparing (benchmarking) the performance of the utilities in operational management of real losses (Delgado, 2008; Sharma, 2008).

- **Performance Measurement:** The final step in the water audit is the interpretation of the information collected. A straight percentage of water loss is a crude indicator unless several additional factors are taken into account, particularly variations in input or consumption. However, it is still a useful piece of information, particularly when there is little variability.

- **Financial Performance:** In addition to water losses values, the AWWA method also calculates the financial performance indicators as NRW and water losses as percent of volume and cost, and the operational efficiency indicators as in term of infrastructure leakage index (ILI).

On the basis of all of the above points, the AWWA method is considered the best tool for performance measuring for water supply systems.

3.5 Determination of Non-Revenue Water

3.5.1 Data Sheet

For the purpose of the present study and in order to estimate and audit the water losses in the water distribution networks of the study area (Al Seeb Wilayat, the data sheet in Table (4.9) was prepared. Data were collected from the engineers in charge of the water leakage detection program for input to the AWWA Water Audit Software.

The data sheet is divided into two sections. Respondents first have to fill basic utility and city information. Section two is the reporting work sheet which includes the data about water supplies, authorized consumption, apparent loss, system data, and cost data. The researcher collected all the data through face to face interviews with the engineers.

Table 3.9: Data Sheet for Water Loss Information

A- Basic Information

Name of City or Utility:		**Country:**			
Reporting Year:		**Start Date (MM/YYYY):**		**Start Date (MM/YYYY):**	
Name of Contact Person:		**E-mail:**			
Telephone:		**Fax:**		**Mobile:**	
Reporting Units for Water Volume:					

B- Reporting Work Sheet

1.	**Water Supplies**	**2008**	**2009**	**2010**	**2011**	**2012**
1.1	Volume from Own Sources					
1.2	Master Meter Error Adjustment					
1.3	Water Imported					
1.4	Water Exported					
2.	**Authorized Consumption**	**2008**	**2009**	**2010**	**2011**	**2012**
2.1	Billed Metered					
2.2	Billed Unmetered					
2.3	Unbilled Metered					
2.4	Unbilled Unmetered					
3.	**Apparent Losses**	**2008**	**2009**	**2010**	**2011**	**2012**
3.1	Unauthorized Consumption					
3.2	Customer Metering Inaccuracies					
3.3	Systematic Data Handling Errors					
4.	**System Data**	**2008**	**2009**	**2010**	**2011**	**2012**
4.1	Length of Mains					
4.2	Number of Active and Inactive Service Connections					
4.3	Average Length of Costumer Service Line					
4.4	Average Operating Pressure					
5.	**Cost Data**	**2008**	**2009**	**2010**	**2011**	**2012**
5.1	Total Annual Cost of Operating Water System					
5.2	Costumer Retail Unit Cost (Applied to Apparent Losses)					
5.3	Variable Production Cost (Applied to Real Losses					

3.5.2 Semi-Structured and Unstructured Interviews

Within the framework of the present research and in order to achieve one of the main objectives of this study, the researcher also prepared a questionnaire for PAEW staff. The aim of this questionnaire was to assess the views of stakeholder in PAEW on the current status of water losses in Oman from the technical and strategic point of view. It sought to discover from staff who are concerned with water losses, what their perceptions are about the official NRW figure, their understanding of the impact and main causes of water loss, and their opinions on PAEW's procedures and policy related to water loss reduction.

The questionnaire was based on the objectives of the study and by using similar questionnaires as a starting point (GTZ-VAG, 2009). The questionnaire is given in Appendix-B.

The quality of information obtained based on the quality of interaction between the respondents and interviewer and the quality of data depends on the experience, skills and dedication of the interviewer Kumar (1996). Since the researcher was known to all of the interviewees, a methodology suited to free flowing conversations and discussions was required. In addition to the semi-structured interviews, there was a follow-up with unstructured interviews with these staffs in order to obtain clearer answers on certain specific issues bordering on their schedules. These follow up meetings were particularly important because some respondents had difficulty in expressing themselves fully through a written questionnaire.

Although the interview questions were prepared in English, the questions were asked in the local language (Arabic). The responses and feedback were also translated back in English.

3.5.3 Interviewing Key PAEW Staff

Following pilot testing, thirty staff from the head office in Muscat and other Governorate offices of PAEW were interviewed face to face. The staff were mainly engineers who are concerned with water losses and some managers. The interviews gathered in-depth information of their knowledge, perceptions and experience with the current situation and future strategy of NRW. Further information on water losses and their understanding of the main causes of water loss was gathered and their opinions on PAEW's procedures and policy related to water loss reduction.

Twenty members of staff, both at senior and middle level from all departments were interviewed via semi-structured interviews. There were two exceptions, the leakage control manager and the general manager, operations and maintenance section head who were in addition to the semi-structured interviews. There was a follow-up unstructured interview to obtain clearer answers on certain specific issues. For example; why most PAEW efforts concentrate on apparent losses as against the other components of NRW reduction strategies, and; the issue of measurement of NRW in the system in the absence of comprehensive metering within in the system.

Information gathered from interviews and questionnaires was corroborated either with independent persons, or through available documentation. The data obtained were manipulated and presented using Microsoft Excel spreadsheet software. The results are analyzed and explained in chapter 5.

3.5.4 Reviewing Available Data within PAEW

Document review is another source of data collection used for qualitative analysis of existing data. Documents, apart from being a means by which data can be collected on a subject area, are also secondary sources of data in their own rights (Scheyvens and Storey, 2003). As mentioned earlier, the basic data and information related to thesis subjects were collected from Public Authority for electricity and Water (PAEW) archive.

3.6 Risk Assessment Methodology

3.6.1 Introduction

Risk assessment and analysis provide useful tools for the management and control of the variety of hazards and hazardous events caused by human or natural disasters to water utility infrastructure. The discussion of risk assessment in Chapter 2 mentions that both qualitative and the quantitative methods can provide useful results, qualitative methods requiring less input data and other resources than quantitative methods which, on the other hand, have been shown to provide more detailed results. The present research, used a semi quantitative approach that requires less information, numerical data and resources necessary than a statistically significant quantitative approach.

The objective was to distinguish between less and more significant risks and avoid being overly subjective. The most common way of carrying this out being to draw up a simple table to systematically record all potential hazardous events and associated hazards together with an estimate of the magnitude of each (PSC, 2012; PAEW, 2012; WHO,2009; Deere et al., 2001; Nadebaum et al, 2004; Australian Government, 2008).

When starting the risk assessment process, detailed definitions of what is meant by ‘possible’, ‘rare’, ‘insignificant’, ‘major’, etc. had to be drawn up by the utility. Of crucial importance is the need to define in advance the definition of risk matrix score that identifies ‘significant’ risk. The information to inform the risk assessment will come from the experience, knowledge and judgment of the utility and individual team members, industry good practice and technical literature and this was a function of the workshop (WHO, 2009).

Due to the lack of adequate information and data, the present risk assessment of water supply systems in Oman including the desalination plants and transmission pipelines used the semi-quantitative risk assessment approach, namely; Coarse Risk Analysis (CRA) which is the most common approach used for risk assessment and management of water supply systems (Kozisek et al, 2008; Rostum and Eikebrokk, 2009; Tornqvist et al., 2009.

3.6.2 Estimation of Risks: Coarse Risk Analysis

This section outlines how the risks and likelihoods of their occurrence in this study were assessed. The risk analysis covers the major desalination plants and the transmission mains taking water from the Al Ghubra desalination plant to Greater Muscat and to Ad Dakhliyah governorates respectively (see Chapter 4 for details). The study focused on the identification of all hazardous events, which might influence the quantity and quality of water distributed together with the risks to health.

The scope the CRA (see sections 2.5 and 2.5.4) including risk evaluation and risk control consisted of (Hokstad, et al, 2009):

1. Identifying hazardous events relating either to the total water supply system, or to a specific issue.
2. Estimating the risks (probability and consequence) for each hazardous event and presenting the results in risk matrices.
3. Ranking the hazardous events with respect to their risk.
4. Assessing the need for risk reduction options.

Risk were determined as the product of likelihood and consequence as:

$$\text{Risk} = \text{Likelihood} \times \text{Consequence} \quad (3.5)$$

Where, likelihood is the chance that a hazard will actually compromise drinking water quality or quantity, and pose a public health threat. Consequence is the combination of the severity, nature, and duration of an event, the proportion of the population affected, and type of health consequence (MHLS, 2010).

The risk estimation in a CRA is usually restricted to presenting categories of probability and consequence as rare, unlikely, possible, likely, and almost certain. In a similar way the consequence categories are negligible minor, moderate major, and severe. The combined likelihood-consequence categories are inserted in a risk matrix where several combinations of scale are possible through assigning numbered levels that are multiplied to generate a numeric description of risk ratings.

3.6.3 Likelihoods, Consequences and Risk Tables

The likelihoods and consequences of a wide range of hazardous events that could affect the security of the potable water supply were identified at the workshop in June 2013. Risks were evaluated on the basis of this information taking into account any control measures so that the effectiveness of the controls and further mitigation measures could be easily assessed. The return periods for likelihood, and consequence of hazard events for the desalination plant and transmission mains along with scores and the color-coding for scoring were developed during the workshop.

1) Likelihood: A likelihood score for each hazard event was assigned from the estimated probability of its occurrence within a time period as presented in Table 3.2. A time frame of a maximum of 100 years was agreed in the workshop since some hazardous events can be less frequent once in 50 years, particularly natural events such as cyclones.

Table 3.2: Qualitative Measures of Likelihood

Level	Description	Score
1	One in 50 to 100 years	1
2	One in 20 to 50 years	2
3	One in 5 to 20 years	3
4	One in 1 to 5 years	4
5	More than one per year	5

Source: Security of Supply Risk Workshop, See Appendix (A)

2) Desalination Consequence: Risks within desalination plants arise from multiple causes, including those arising from the sea but the result is always a loss of production and hence a loss of supply to customers. The consequence of a hazard event for desalination is presented using a separate table (Table 3.3). The duration of each severity was agreed in the workshop. A time period of seven days was used (Kozisek et al, 2008, Hokstad, et al, 2009).

Table 3.3: Consequence of Event Duration for Desalination

Severity	Definition	Score
A	< 12 hours partial reduction in treated water production (>34% of design output)	1
B	<12 hours loss of treated water production	2
C	12 – 48 hours loss of treated water Production	4
D	One sites affected for > 4 days 2 – 7 days loss of treated water production	8
E	>7 days loss of treated water production	16

Source: Security of Supply Risk Workshop, See Appendix (A)

Notes:

- Risk tables have been completed for each major desalination plant.
- Changes in water quality or taste/odour outside the Omani standards are assumed to result in plant shutdown and loss of production.

3) Transmission Consequence: The risks were identified earlier and the consequences (from the workshop) were assessed for transmission pipelines and are given in Table 3.4 (after Hokstad, et al, 2009). Multiple scenarios were selected to allow different events to be compared. For example, in severity B, 1,000 properties without water for 12 hours is made equivalent to 500 properties without water for 24 hours and also to one industrial customer. The industrial customer is assumed to have a greater need for water (equal to 1,000 properties) but the actual demand has not been considered.

Table 3.4: Consequence of Hazard Events for Transmission Mains

Severity	Definition	Score
A	<500 properties without water for 12 hours	1
B	<1,000 properties without water for 12 hours or one industrial customer <500 properties without water for 24 hours	2
C	<10,000 properties without water for 12 hours or two to ten industrial customers <1,000 properties without water for 24 hours or one industrial customer <500 properties without water for 48 hours	4
D	<50,000 properties without water for 12 hours or more than ten industrial customers <10,000 properties without water for 24 hours or two to ten industrial customers <1000 properties without water for 48 hours or one industrial customer <500 properties without water for 2-5 days	8
E	100,000 properties without water for 12 hours or more than one hundred industrial customers <50,000 properties without water for 24 hours or more than ten industrial customers <10,000 properties without water for 48 hours or two to ten industrial customers <1000 properties without water for 2-5 days or one industrial customer <500 properties without water for >5 days	16

Source: Security of Supply Risk Workshop, See Appendix (A)

Notes:

- Storage within a customer's premises has not been considered.
- Customers often have internal storage tanks that provide at least 12 hours supply.
- Many customers may have internal storage tanks with up to 3 days supply.
- Major industrial customers may be hospitals, schools, retail or industrial premises.

4) Risk Table (Matrix): Table 3.5 gives the resulting scoring system used in the risk tables (in Chapter 6).

Table 3.5: Consequence and Likelihood Categories to Generate Risk Scores

Likelihood	Consequences					
	Severity	A	B	C	D	E
Level	Score	(1)	(2)	(4)	(8)	(16)
1	(1)	1	2	4	8	16
2	(2)	2	4	8	16	32
3	(3)	3	6	12	24	48
4	(4)	4	8	16	32	64
5	(5)	5	10	20	40	80

Risk Score	< 6	6-16	> 16
Colour	Green	Amber	Red
Risk Rating	Minor	Major	Significant

Source: Security of Supply Risk Workshop, See Appendix (A)

Green scores < 6 represent minor risks that may not need any mitigation measures.

Amber scores 6 to 16 represent major risks that may need mitigation measures.

Red scores > 16 represent significant risks that certainly need mitigation measures.

In this methodology, the relative extent of the risk is illustrated by the scale of the number. The effectiveness of control measures can then be taken into account by revaluing the risk following the application of the risk mitigation measure. Control measures are considered not only for their long-term average performance but also for their potential to be ineffective over a short period. The outcomes of this work are reported in Chapter 6.

3.7 Development of a new Emergency Response Plan

The importance of component parts of the water utility (e.g. desalination plants, well field, transmission mains, and reservoirs) relies on two factors: (1) The impact of their potential loss; and (2) the probability of failure. A consistent and widely used method, the Coarse Risk Analysis (CRA – see section 2.5.4) has been used to identify hazards and generate risk scores. These scores are used to prioritise future investment in the water systems such as the provision of backup supplies, increased preventative maintenance as well as the creation of emergency response plan. Further the impact of water losses on water systems was also studied and the performance indicators help in preparing the emergency response plan.

The data obtained from the risk analysis process and water audit, the information obtained during the group discussion in the workshop and the system data obtained from PAEW were all used as basic inputs for developing options for the new emergency plan.

3.8 Conclusion

This chapter has outlined the philosophy, strategy and methodology used in conducting this research. Procedures used, research approaches and techniques and the methodology of risk assessment are all introduced. The methodologies are used in Chapters 5, 6 and 7 but first, the particular circumstances in Oman and the case study site are outlined in Chapter 4.

Chapter 4 Case study

4.1 General Background

The case study approach forms the backbone of this research both to illustrate the problems of providing a water supply in a desert country and to indicate good practices. The country of the Sultanate of Oman is the general case study of the present research work. A study of non-revenue water and water losses in the Al Seeb Wilayat water network of Muscat Governorate is used to highlight waster provision and delivery issues in Oman. The impact of tropical cyclone Gonu has been taken as a case study for the analysis and assessment of risks from exceptional events.

Risk analyses and assessments were carried out for major desalination plants taking as case study examples the Al Ghubrah Desalination plant located in Muscat, and for the main transmission pipelines, Muscat and Dakhliyah.

The case study was used to examine issues related to water supply in Oman within its particular context using empirical enquiry (Yin, 2012) in real world investigations where boundaries and contexts are not clearly evident. Blaxter *et al.* (2003) added that one of the advantages of case studies is that it can provide a data source from which further analysis can be made. They can, therefore, be archived for further research work.

4.2 The Study Area (Oman)

4.2.1 Introduction

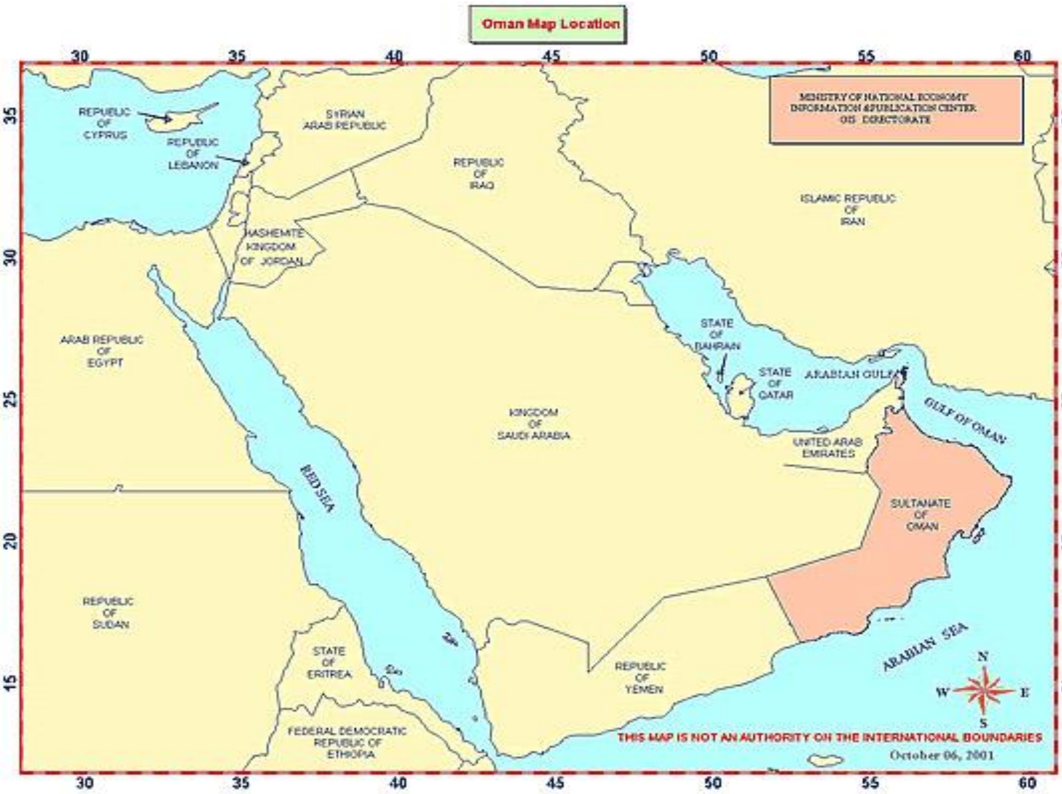
The Sultanate of Oman is a country in southwest Asia, on the southeast coast of the Arabian Peninsula. It borders the United Arab Emirates in the northwest, Saudi Arabia in the west and Yemen in the southwest. This section gives a brief overview of the basic data of Oman including geography (location and topography, and climate), population, and administrative units of Oman. In addition, it outlines water availability (resources), and gives an overview of the water supply system and of the main organization in the water sector.

4.2.2 The Geography of Oman

4.2.2.1 Location and Topography

The Sultanate of Oman is located in the south eastern corner of the Arabian Peninsula between Latitudes 16° 40` and 26° 20` North and longitudes 51° 40` and 59° 40` East as shown in Figure (4.1). Its coastal line extends 3,165 kilometers from the Strait of Hormuz in the North to the borders of the Republic of Yemen in the South. It overlooks three major bodies of water: the Arabian Gulf (Persian Gulf), the Gulf of Oman, and the Arabian Sea (Ministry of Economy, 2008).

Figure 4.1 Location Map for Sultanate Oman



Source: (PAEW, 2012)

The total area of the Sultanate is approximately 310,000 km^2 composed of varying topographic regions consisting of plains, dry river beds, and mountains. The most important area is the plain overlooking the Gulf of Oman and the Arabian Sea, with about 3% of the total area. This area is the most densely populated in the country, with rapid growth and industralization that creates a challenge for emergency management. The mountain ranges occupy almost 15% of the total land of Oman. The remaining area is mainly dry river beds and desert (about 82% of the total area) (Ministry of Economy, 2008).

4.2.2.2 Climate

The climate varies considerably throughout the year. There are two seasons, the hot, dry summer during the months of May to October and the cool winter months from November to April. During the summer, the weather is hot and humid, with temperatures up to 48°C, and relative humidity between 85% and 90%. The interior of the country is dry except at high altitudes in the northeast. The average sunshine is about 10 hours daily, with the exception of mountainous areas and the small region that experiences little sunshine between mid-June to mid-September.

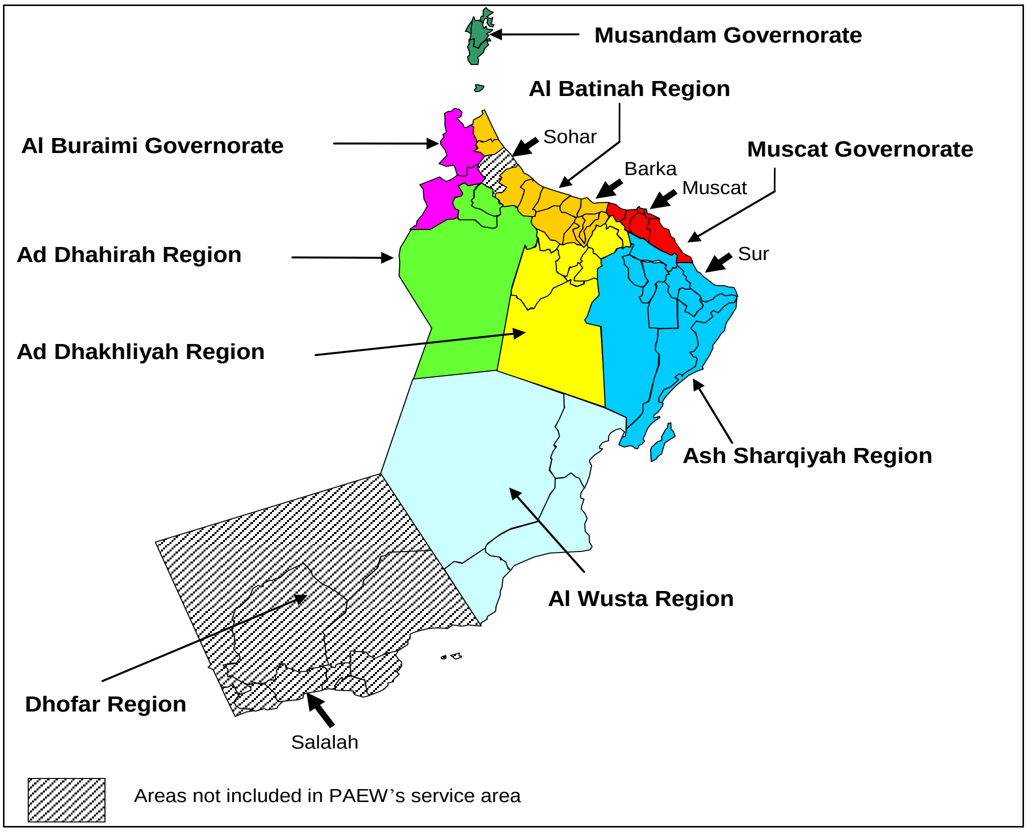
4.2.2.3 Population

Oman has a population of 2,967,700 (Census, 2010) and its geography allows habitation in only a small portion of the country. About 55% of the population lives in the Batinah coastal plain, where the nation's capital, Muscat, is located. About 215,000 people inhabit the Dhofar region, and about 30,000 live in the remote Musandam Peninsula on the Strait of Hormuz. Oman hosts some 660,000 expatriates, most of whom are guest workers from South Asia, Egypt, Jordan, and the Philippines.

4.2.2.4 Administrative Units

Oman is divided into eight main administrative Governorates as shown in Figure (4.2). These Governorates are further subdivided into 59 "wilayats". Information is given for the three governorates, which are of importance in this research:

Figure 4.2 Administrative Governorates of Sultanate of Oman



Source: (PAEW, 2012)

1. **Governorate of Muscat:** This is the central administrative area of the Sultanate and is characterized by a high population density. It comprises six wilayats.

2. **Al Batina Governorate:** The Al Batinah Region is located in the northeast of the Sultanate and is divided into two main areas. One is the coastal plain that occupies the frontier with UAE for a distance of 170 km southeast of Muscat. The other is the Western Hajar that runs parallel with and to the coast of the UAE in the north, and to the Wadi Al Maawil to the south.

3. **Ad Dakhliyah** Governorate**:** This area is bordered on the west by the Adh Dhahirah region and on the east by the Ash Sharqiyah region. It has a high population density. It comprises eight wilayats.

The remaining governorates are; Ash Sharqiyah; Adh Dhahirah; Al Wusta; Dhofar, and; Musandam.

4.2.2.5 Water Availability

In Oman water is a very scarce resource; Oman is situated in one of the most water-stressed regions of the world where there is no surface water to speak of, and as a result relies heavily on groundwater and desalination. The main sources of fresh water in Oman are groundwater, most of which is non-renewable, and a limited amount of renewable near-surface water. Non-conventional sources include desalinated seawater and wastewater treatment.

Water supplied to the customers by the PAEW is derived from several different source categories (PAEW, 2012):

1. Desalinated water from:
    - Independent Water and Power Projects (IWPP) plants at Ghubrah, Barka and Sohar;
    - An Independent Water Project (IWP) at Sur;
    - Plants owned and operated by the Rural Areas Electricity Company (RAECo), and

- Plants owned by the PAEW but operated by contractors, and

2. Community based fresh, groundwater wells.

The volumes into supply during 2014 are shown in Table (4.1). Not all water is supplied into a piped network. Some wells only feed into tanker filling stations (PAEW Archive).

Table 4.1: 2014 Water into Supply from Differing Sources

Water Source		Output as m^3/yr
Major desalination plants	Ghubrah	66,430,000
	Barka I and II	77,015,000
	Sohar	54,750,000
	Sur	33,580,000
Local RO (RAECO & PAEW) plants		4,1200,000
PAEW local wells including those in Muscat		51,214,000
Local wells with unclear status		4,580,323
Total Water into Supply		**291,168,323**

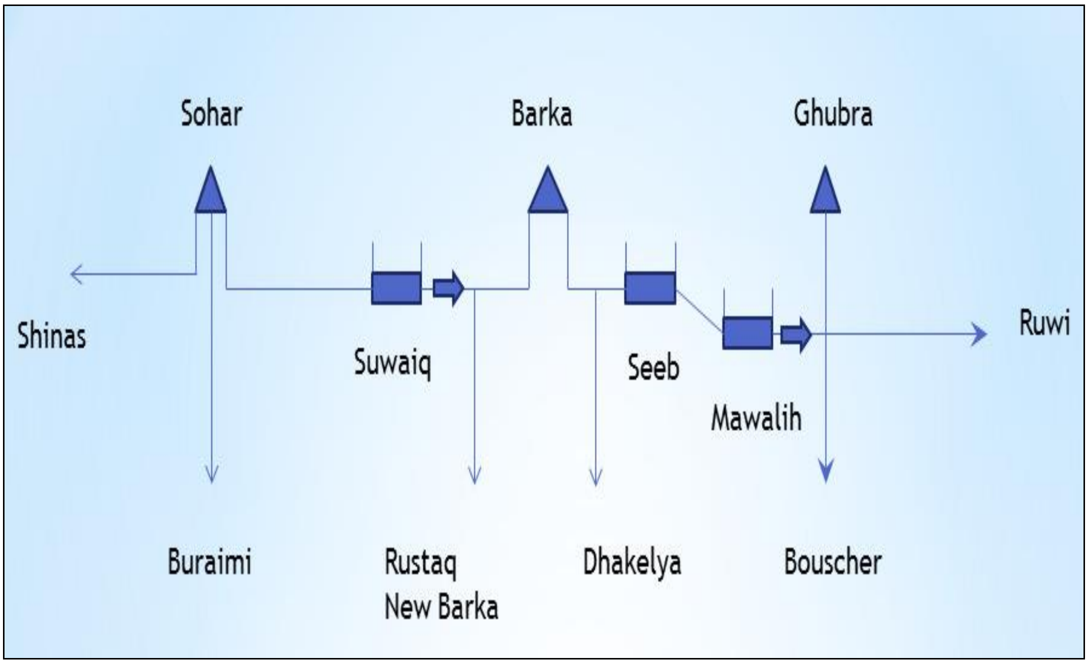
Source: (PAEW Archive)

4.2.3 Overview of Supply System

4.2.3.1 Transmission System

The Muscat, Batinah North, Batinah South, Buraimi and Dhakhliyah regions are all interlinked, allowing flexibility of operation and security of supply in the case of a failure at a major treatment work. This transmission system is fed by three major desalination plants at Sohar, Barka (both in Batinah region) and Ghubra (Muscat region) and some well fields mainly located in Muscat. A schematic layout of the interconnected network is illustrated in Figure (4.3) below (PAEW, 2012).

Figure 4.3: Schematic of Interconnected Network



Source: (PAEW, 2012)

4.2.3.2 Water Supply Network

Generally, water is pumped through the strategic transmission network to major distribution reservoirs sized to (1) ensure continuity of supplies in the event of a failure at a desalination plant or within the transmission network and, (2) to “smooth out” peak daily and weekly demands for which the desalination plants and strategic network are sized.

There are no consumer connections directly fed by the transmission system. All customers are fed via a service reservoir, which receives its flow from the transmission network. Table (4.2) summarises the transmission and distribution networks.

Table 4.2 : Network Lengths and Materials

Region	Network Length (km)									
	By Network		By Pipe Materials							Total
	Transmission	Distribution	DI	AC	HDPE	uPVC	MS	GI	Unknown	
Muscat	230	2106	230	527	1579					**2336**
Batinah	668	1249	560		824	212	321			**1917**
Dakhiyah	240	618	193	87	409		42	117		**858**
Buraymi	163	288	281	144			26			**451**
Dhahirah	389	454	389		431				23	**843**
Sharqiyah	324	139	198	131		8	94		32	**463**
Al Wusta	28	11	-		27		11		1	**39**
Masandam	33	165	46	115	37					**198**
Total	2075	5030	1897	1004	3307	220	504	117	56	**7105**
Percentage	29%	71%	27%	14%	46%	3%	7%	2%	1%	**100%**

Source: (PAEW, 2012)

4.2.3.3 Water Tankers

The PAEW uses water tankers to provide a supply to those who do not have a piped water supply. The tankers have access to the PAEW tanker filling stations (TFS), of which there are some 500. Many TFS are fed by a local on-site well and are not connected to the centralized pipe network.

Some but not all consumers without a connection are provided with a free supply of up to 20 gallons per person per day but, due to lack of good records, there is no clear picture of the volume of water supplied for domestic consumption by tankers, or of the number and coverage achieved through tanker supplies. The long-term policy of the PAEW is to reduce the amount of water distributed by tanker.

4.2.4 Main Organizations in the Water Sector

4.2.4.1 Ministry of Regional Municipalities and Water Resources (MRMWR)

The MRMWR plays a central coordinating role among the organizations involved in Oman's water sector with the task of managing and assessing water resources through the maintenance of the aflaj, excavation of the auxiliary wells, building dams, monitoring water status, implementing projects for the utilization of non-traditional water resources, and enhancing awareness on the importance of protecting water resources from depletion and deterioration (MRMWR, 2010)

4.2.4.2 Public Authority for Electricity and Water

The Public Authority for Electricity and Water (PAEW) was established in 2007, by the promulgation of Sultani Decree. While the MRMWR is responsible for water resources as a whole, the PAEW manages municipal water supplies. Its primary roles include:

1. Providing drinking water according to Omani standards and in response to urban expansion;
2. Activating and strengthening government policy to develop the water sector, and;
3. Encouraging the private sector to invest in the water sector.

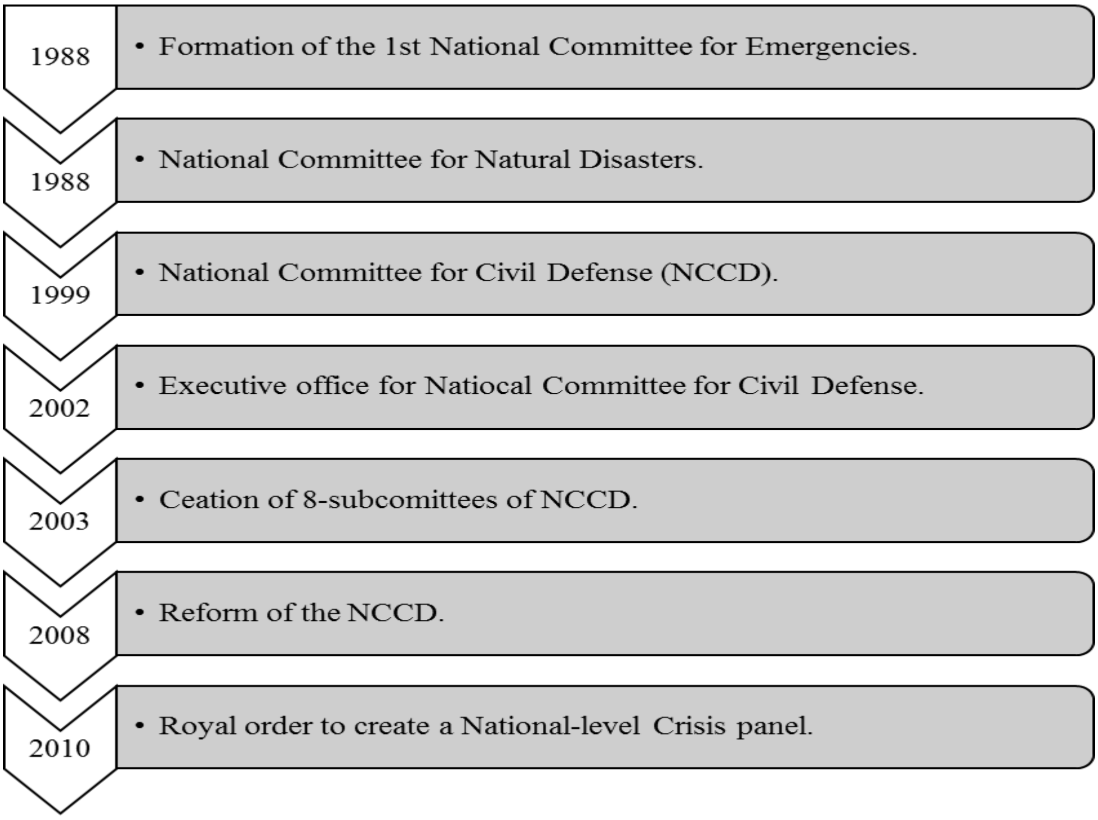
The Head Quarters office, formed of 6 Directorates, provides policies, strategic guidance, finance, and logistical support to the regional operational offices situated in the major towns of each region. Currently there are nine regional organizations: Muscat, Batinah South, Batinah North, Dhakhliyah, Buraimi, Dhahirah, Ash Sharqiyah, Musandam, and Al Wusta as shown in Figure (4.2).

4.2.4.3 National Committee for Civil Defense (NCCD)

The National Committee for Civil Defense (NCCD) is the state organization responsible for planning and coordinating the response to natural or man-made disasters or emergencies that could impact the people, reputation, or environment of Oman. As with all the other essential service providers and agencies in Oman, PAEW falls under the jurisdiction of NCCD.

NCCD's powers involve guiding the planning of PAEW and other Omani providers of essential services and coordinating live national emergencies such as cyclones or oil spills. For this purpose, the NCCD has created the National Emergency Management Plan (NEMP) which consists of a set of operational procedures to be carried out by the respective sectors before, during and after a crisis. As soon as a state of emergency is declared the NCCD takes over and ensures that all government, military, and police sectors discharge their duties as prescribed in the NEMP. The time-line in Figure 4.4 indicates the corner stones of emergency management in the Sultanate of Oman.

Figure 4.4: Timeline of Emergency Management in Oman



(Source: Al-Shaqi, 2011)

4.2.5 The Current PAEW Emergency Response Plan

4.2.5.1 Overview

PAEW routine day-to-day emergencies are managed in coordination with PAEW contractor's representatives and staff, at an engineer's level and would not normally involve PAEW managers unless the event worsens. Non-routine (major) emergencies are managed via an informal grouping of PAEW managers. The importance given to the emergency is based principally on the size or importance of the asset that has failed and the anticipated duration of an event but does not relate to any set service performance targets for service to customers (PAEW, 2011).

The PAEW engineers and managers responsible for managing an emergency do not have access to a common skills, training or equipment database and have not been provided with specialist training in emergency planning, response and management (PAEW, 2011).

4.2.5.2 Crisis Management Facilities and Operational Tools

PAEW currently manages all routine and any non-routine emergencies from operations offices based in the Head Office in Muscat and local regional offices. These offices have only standard office equipment and facilities and have not been adapted for crisis management purposes (PAEW, 2011).

Thus, aside from crisis management facilities, operational tools, mandatory for supporting emergency responses, were to be improved:

- SCADA: integrated SCADA systems instead of uncoordinated and isolated systems in some cases;
- GIS: currently, the only GIS being under development concern the Muscat area only;
- Hydraulic modelling: lack of strategic hydraulic models (under development under the current co-management contract) and modelling capabilities within PAEW (PAEW, 2011).

4.2.5.3 O & M Sub-Contractors Responsibilities

O&M sub-contractors are responsible for carrying out the practical actions to resolve the causes of emergency events. They form an important part of both normal and abnormal responses to emergencies arrangements. For this reason, each PAEW contractor is contractually obliged to have a formal non-normal working hour's standby system with the ability to provide sufficient resources and materials at any time (PAEW, 2011).

4.3 The Challenge of Reducing NRW in Oman

4.3.1 Water Balance Information

The available data indicate that the level of water loss is above 40% (PAEW, 2010). The data in Table (4.3) show that the percentage of losses for most of the regions are most probably due to real losses, which are caused by the physical properties of the components of the system.

Table 4.3: 2010 Water Balance (Mm^3)

Region	Total Production and Supply 1×10^6 (m^3)	Private 1×10^6 (m^3)	Government 1×10^6 (m^3)	Tankers 1×10^6 (m^3)	UFW 1×10^6 (m^3)	UFW (%)
Muscat	106373521	46962849	11060913	4968860	43380899	36-41
Batinah	32670249	6654371	674402	2156022	22726621	70
Dhakhilia	14239099	2993190	983082	3271187	6991640	49
Buraimi	8267152	3640602	505890	1523087	2597572	31
Sharqyah	15952564	4502521	752618	2444588	8252837	52
Dhahira	6229653	2884579	702550	914350	1728174	28
Musandam	4485792	1399391	741658	234850	2109893	47
Total	**189376940**	**69080031**	**15428780**	**16649937**	**87759359**	**44-46**

Source: (PAEW, 2010)

4.3.2 NRW Management within PAEW

Apart from its other responsibilities (water quality, etc.), the Water Operation department is in charge of the various NRW related tasks in the field, such as:

- Monitoring the volume of water produced by the different sources;
- Operating and maintaining the water infrastructures;
- Leak detection and DMA monitoring in Muscat;
- Supervising leak repairs;
- Replacing meters and supporting responding to technical complaints;
- Producing monthly and annual reports.

The primary function of the operations teams is to continuously monitor the network performance through the tasks listed above.

4.3.3 The Al Seeb Wilayat Network – Case Study Location

The values of water losses and NRW in water distribution networks of Oman were estimated and audited taking Al Seeb Wilayat network of Muscat Governorate as a case study. Al Seeb consists of a number of existing older towns primarily located along the coast. The area includes a light industrial estate occupied by small workshops and warehouses. A large percentage of the houses are connected to a fully reticulated water supply network although some houses are still supplied by tankers and also some pockets within the area have development potential.

The water in the area is distributed directly by a network of three types namely, Asbestos Cement (AC), Ductile Iron (DI), and High Density Polyethylene (HDPE) pipes. Some of the pipes are in bad state of maintenance because they are more than 20 years old. The Transmission mains range from 150- 800 mm in diameter and the total length pipe is 29 kilo meters, and the distribution pipelines range from 150- 800 mm in diameter with total length of the network pipe is about 740 kilo meters. Al Seeb transmission and distribution diameters and lengths summary are illustrated in Table (4.4). This information is used in the water audit in Chapter 5.

Table 4.4: Al Seeb Transmission and Distribution Diameters and Lengths Summary

Transmission Mains		Distribution Mains	
Diameter (mm)	**Length (m)**	**Diameter (mm)**	**Length (m)**
150	6,000	80	17,010
		100	183,120
400	15,000	150	262,760
		200	110,096
600	-	250	15,963
		300	45,677
800	8,000	400	41,443
		600	20,300
Total	29,000	800	31,097
		1000	13,533
Material		**Total**	740,999
	100% DI	**Material**	67% HDPE, 33% AC
Reservoirs	Elevated Tank = 1, Service Reservoir = 13, Total = 14		

4.4 The Impact of tropical Cyclone Gonu

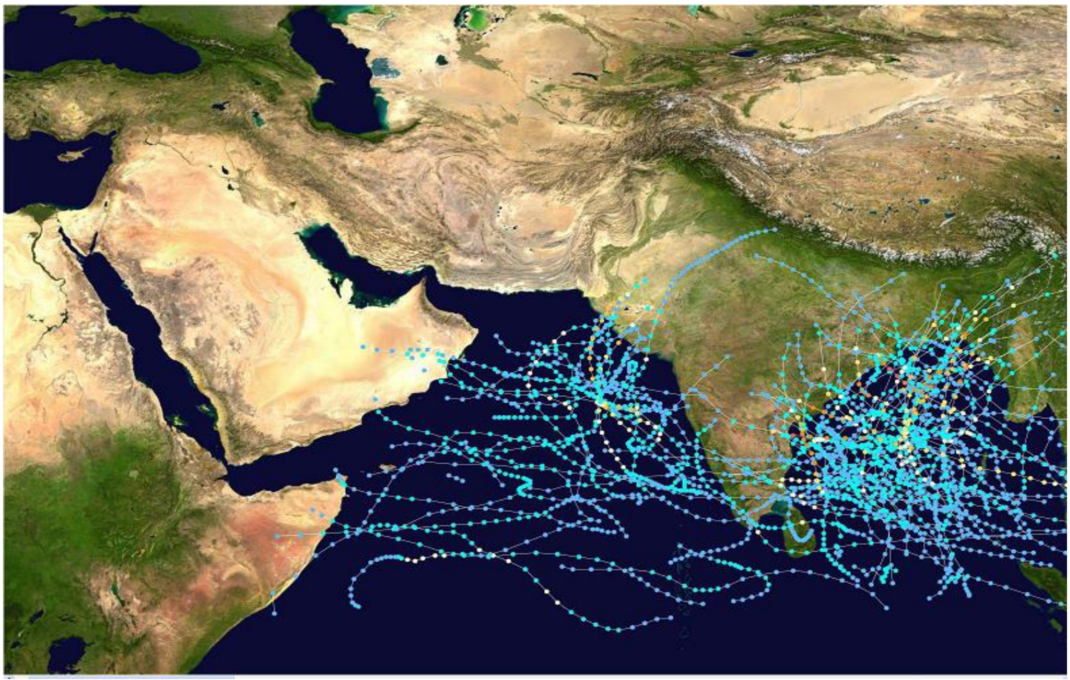
4.4.1 Event Description

Tropical cyclones in Oman are frequent events during the monsoon season from May to August every year and in June 2007 the Sultanate of Oman awoke to one of the worst natural disasters in its recent history. Cyclone Gonu hit the country, causing torrential rains and flash floods. The cyclone claimed the lives of 49 people and left more than 20,000 homeless. The infrastructure services of Oman were under unprecedented stress for days. Like all other services in the country, Gonu severely stretched health care services (Al-Shaqsi, 2010, 2011).

Gonu developed to tropical storm on June 3rd and then to a cyclone in the middle of the Arabian Sea on June 4th with a surface wind speed of (213-232 km/h) (Al Hattaly & Al-Kindy, 2008).

On June 5th it hit the southeast coast of Oman at Ras Al Had and Sur with a wind speed of (213-250 km/h) classifying the storm as the highest severity "Category 4" storm (Table 2.1). Figure (4.5) is a satellite image taken on June 4th. The cyclone then moved toward northeast along the Gulf of Oman coast destroying and flooding the area of Muscat-Quriyat before it started to decrease its storm intensity to become a low pressure/depression and moved towards the northeast to the Coast of Iran June 7th (Al Hattaly & Al-Kindy, 2008).

Figure 4.5: Tracks of Cyclonic Storms in the Northern Indian Ocean (1970 – 2006)



Source: Aljahwari, (2011)

The rainfall associated with cyclone Gonu on June 4th – 5th was the most extreme in the Omani records. The cumulative rainfall in Jabal Asfar- a mountainous station in Quriyat reached 1032 mm within 3 hours, 8 times higher than the annual average and having a return period of 150- 200 years as shown in Table (4.5). Dams were filled to capacity and water spilled over the dam structures. The biggest of Sultanate Oman dams is Al khoud Dam in the Muscat region with a maximum capacity of 12 million cubic meters (mcm), and it was filled overflowing. The total water flood that held by the dams on June 5th to 6th was approximately 71 mcm, in which 41 mcm was in Al khoud Dam (Al Khatry and Helmi, 2011).

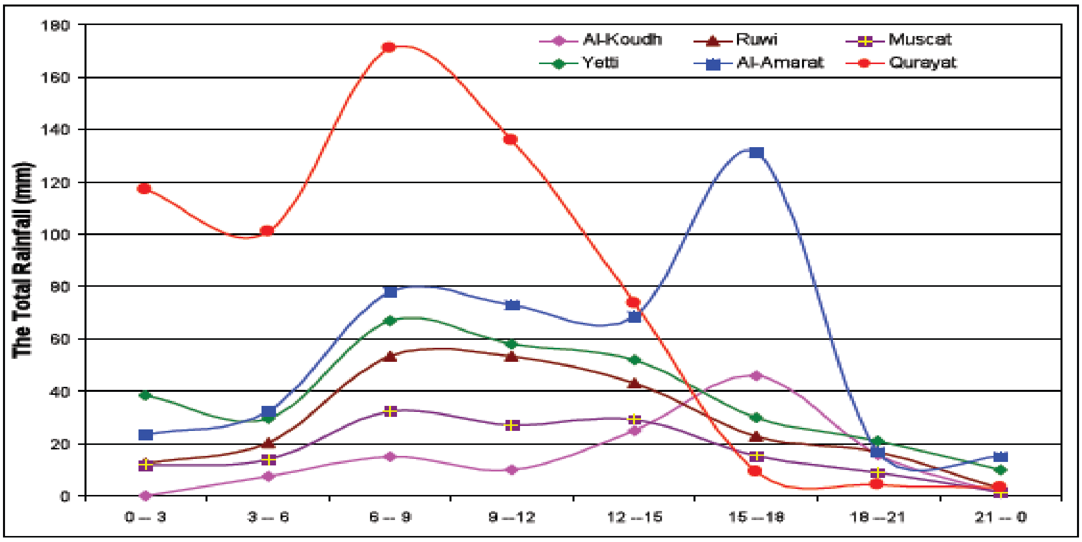
Table 4.5 Cumulative Rainfall in mm Associated with Cyclone Gonu over the Stations of the Affected Areas on the 05th-06th of June, 2007

Station	Location	Rainfall (mm)	Annual Average	Multiple of Annual Average
Jabal Asfar	Sharqiyah	1032	208	8
Jabal Abeyad	Sharqiyah	924	325	6
Hayfaad	Qurayat	626	72	9
Jabal Hilm	Sharqiyah	421	211	2
Ba'ay	Qurayat	378	76	8
Jabal Tayyin	Sharqiyah	348	102	7
Qurayat	Qurayat	322	126	2.5
Al Amarat	Muscat	320	82	7.5
Seeb	Muscat	257	76	7.4

Source: (Al Khatry & Helmi, 2011)

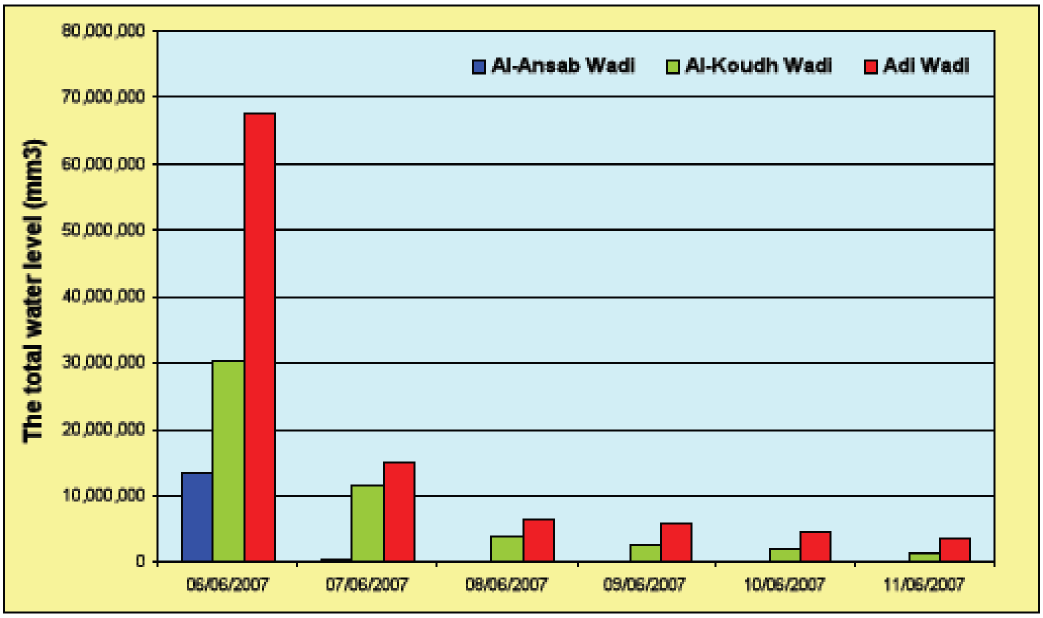
The coast of Oman was exposed to rainfall amounts that had not been witnessed before. For example, the Altaeeyan Dam station recorded more than 900 mm. Figure (4.6) shows the total rainfall in some stations around the Muscat area on 6th June, while Figure (4.7) describes the wadi water level in the same areas from 6th to 11th June 2007 (Al-Awadhi, 2009).

Figure 4.6: The Total Rainfall in Muscat on June 6th, 2007



Source: (Al-Awadhi, 2009).

Figure 4.7: The Total Water Level (mm^3) Muscat Governorate (6th – 11th June, 2007)



Source: (Al-Awadhi, 2009)

4.4.2 The Damage

The Government announced state of alert on June 4th and NCCD implemented several procedures to manage the expected disaster. Cyclone Gonu caused havoc to infrastructure, buildings and properties, and more than 50 lives were lost in the areas of Muscat, Sur and Quriyat. The economic loss was approximately 1.5billion Omani Riyal. The Photos on the sixth of June, 2007 in Figure (4.8) show infrastructure destruction, flooded roads, and human responses on the affected areas.

Figure 4.8: Destruction Caused by Gonu Cyclone

The Height of Water in Al Qurm Area of Muscat

Flooded Roads in Muscat

Road Destruction in Muscat

Human Responses

Source: (Al Hattaly & Al-Kindy, 2008)

Flooding caused by the cyclone left much damage such as: collapsed bridges, the uprooted trees, collapsed houses, broken roads, etc. (See Figures 4.9 and 4.10 for some example of the destruction.) A survey immediately after the cyclone (Table 4.6) showed that of more than 60,000 built units surveyed, 50% were declared damaged (Al-Awadhi, 2009).

Figure 4.9: Heavy Rain Flooded Urban Streets and Buildings in Muscat

Shopping malls at Qurum, Muscat

Residential buildings & streets at Qurum, Muscat

Source: (Inceruh, 2009)

Figure 4.10: Destructive Effects of Storm Floods at Muscat

Source: (Inceruh, 2009)

Table 4.6: The Details of Destruction Survey from Cyclone Gonu

Willayat	House Surveyed	House Accounted	House Damaged	Furniture	House Equipments	Personal Belongs	Transport Vehicles
Mutrah	4273	1135	888	718	730	542	428
Bosher	7179	3894	2776	2680	2721	2310	4065
A'Seeb	30498	12239	9035	7614	7888	6311	5676
Al Amerat	5868	3468	3089	2013	2044	1419	397
Muscat	607	500	470	387	359	369	144
Qurayat	3512	3115	2891	2470	2478	2436	944
Barka	828	20	552	404	414	318	188
Dbai Al-Bayah	68	68	56	54	39	44	3
Bidbid	95	95	86	73	61	73	5
Sur	5984	4825	4294	3458	3132	2764	386
Al-Qabi	7	7	7	0	1	0	0
Dami	160	159	153	76	90	88	10
Al-Kamil	141	134	121	15	29	33	2
Galan Bani Bo Ali	1396	936	759	599	394	511	6
Galan Bani Husain	213	135	117	78	17	56	1
Wadi Bani Khalid	130	129	125	15	21	14	0
Total	61058	31459	25419	20654	20418	17287	12255

Source: (Al-Awadhi, 2009)

4.4.3 Emergency Response to Cyclone Gonu

4.4.3.1 Oman on Alert as Gonu Approaches

On June 5th 2007 Oman's emergency services were placed on full alert as the Sultanate braces for one of the worst cyclonic storms ever to hit the country. The approaching storm is likely to unleash heavy rain, gusting winds and tidal waves. Large coastal swathes stretching from Ras al Hadd to Ras Madrakah will have to bear the brunt of the storm. NCDC urges coastal residents to shift to safer areas Army, Air Force, schools as temporary shelters for people affected (Al-Yahayi, 2009 and Al-Shaqsi, 2010).

The government issued a three-day cyclone alert and announced a full mobilization of the country's Civil Defense apparatus, with the Sultan's Armed Forces, and other security and government agencies also set to play a supportive role. The head of the NCDC convened a special meeting of the committee at the General Headquarters of the Royal Oman Police (ROP) at Qurum. Also in attendance were officials from various ministries represented on the NCDC (Al Jabri, 2012).

4.4.3.2 Actions of PAEW

Once the danger of flood waters were addressed, drinking water restoration became the next priority. PAEW in cooperation with the Ministry of Defense (MOD) and Royal Oman Police (OMP) made their best efforts to restore water supply to the areas, which had been affected by the cyclone. Urgent meetings were conducted with senior directors to discuss the ways to be taken to mitigate the effects of the storm and it convened the Corporate Emergence Control Centre (CECC) at Bousher reservoir. Table (4.7) indicates the sequence of actions during and after the Gonu crisis (Al Jabri, 2012).

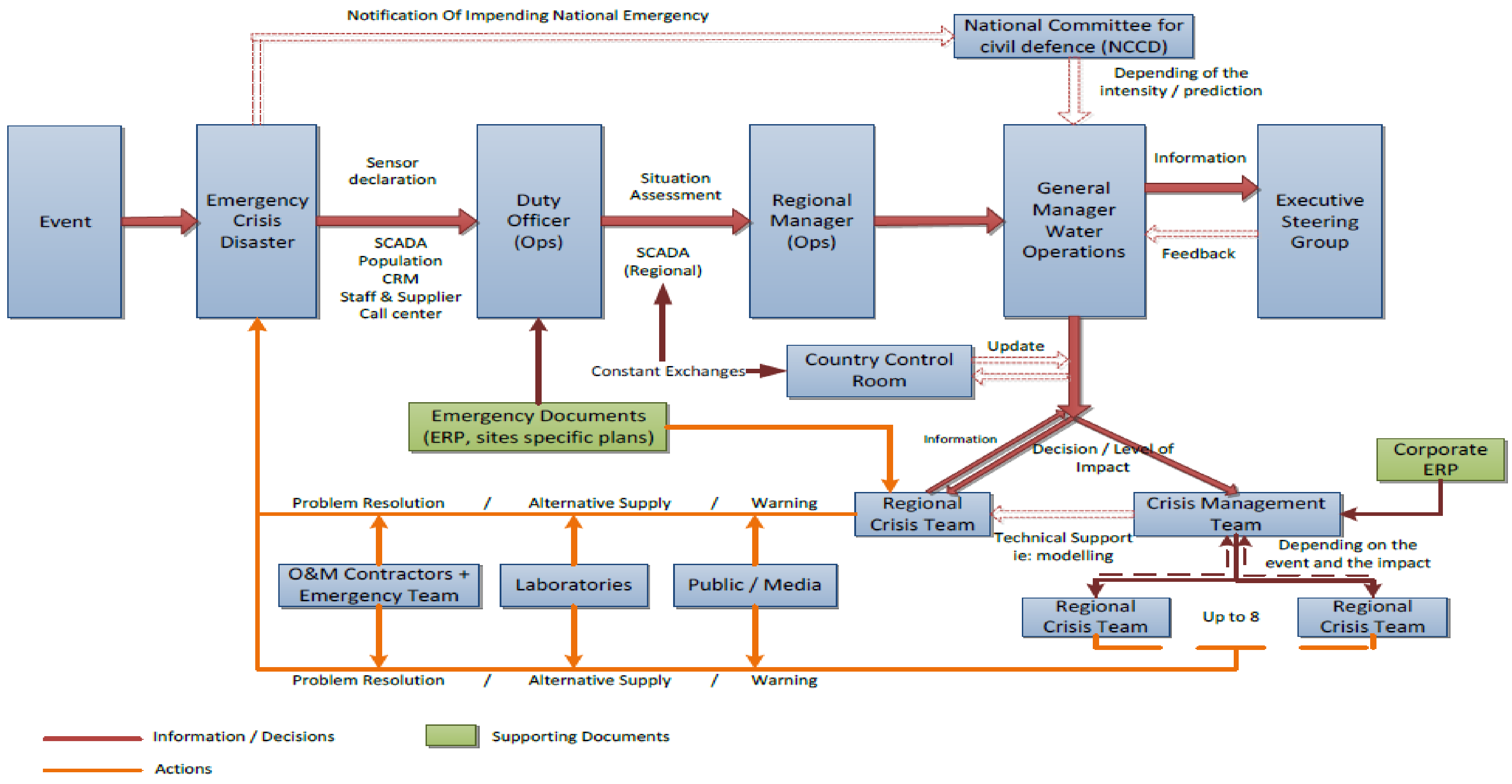
Table 4.7: Sequence of Operation of the CECC during and After Gonu Cyclone

Date	Activities
4/6/2007	Official warnings of approaching storm. Senior management hold emergency meeting.
5/6/2007	PAEW convenes Corporate Emergency Coordination Centre.
6/6/2007	The damage assessment/repair Teams were assembled at CECC.
7/6/2007	CECC starts working on the recovery and restoration of Generator deployed to PAEW water well to power the water. Identifying the effected pipe line to start repair work
8/6/2007	CECC coordinates resumption of water supplies.
9/6/2007	Water delivery by tankers to affected area
10/6/2007	CECC met to evaluate the action which has been taken.
11/6/2007	Gas and electric power was restored, many of the affected systems have been able to restore needed services.
15/6/2007	About 70% of the affected drinking water facilities were again operating.
30/6/2007	100% Restoration of water to Muscat affected areas

4.4.3.3 PAEW Emergency Procedures

Based on the findings presented in the previous sections for the proposed organization and level of emergency, the following diagram (Figure 4.11) shows a summary of the chain of emergency response, from event to problem-solving while implementing mitigation measures and providing alternative supplies.

Figure 4.11: Emergency Procedures



4.4.4 Disturbance to Water Supplies

4.4.4.1 Disturbance to Production

The water supply for Muscat Governorate and the other governorates nearby is totally from the Al Ghubrah and Barka seawater desalination plants. Both stopped operating because of the cyclone. The gas supply was cut to Al Ghubrah desalination (Figure 4.12). On 6th June, as a result of the disruption in the gas supply, Ghubrah Power and Desalination.

Figure 4.12: Al Ghubrah Desalination Plant

Company (GPDC) had to switch to emergency procedures such as running the station on liquid fuel. Within two days the water production from Al Ghubrah reached 25 per cent of plant capacity and this was raised to 80 per cent when the gas supply was restored.

4.4.4.2 Disturbance to Well Fields

Two well fields located in the Wadi Adai and Al Khoudh areas of the Muscat governorate are used as standby reserves. The two well fields can produce about 10 million gallons per day but the Wadi Adai field was totally washed out while the power supply to Al Khoudh field was cut due to the destruction of electricity poles.

4.4.4.3 Disturbance to Distribution System

Most of the transmission pipelines, distribution networks and house connections in the affected areas were disrupted, some of the pipe lines being lifted from their original alignment. As an example, the situation in Al-Amirat Wilayat of Muscat governorate was very severe as the transmission main between the Wadi Adia well field and the Al-Amirat reservoir was totally washed out by the flood in the wadi.

At the same time, many chambers and pipelines appurtenances such as valves, elbows, hydrants, etc. were damaged. Many pumping stations stopped working through high water levels and some pumping equipment and electrical installations was damaged. The storage tanks and reservoirs were also affected in that big cracks appeared in some tanks and reservoirs, and complete or partial failures occurred.

4.5 Risk Analysis Case Study

4.5.1 Introduction

In this research work, risks (due to tropical cyclones, leakage problems, and other human related influences) to the water supply system have been determined as part of a larger study on stress factors in operating water networks and the security of water supply in the Sultanate of Oman. The study was focused on the identification of all hazardous events which may occur to the main desalination plants (source) and within the transmission pipelines which might influence the quality of distributed water either in terms of non-compliance with national drinking water quality standards or the danger of compromising consumer health or confidence.

The risks to water supply system were analyzed using the Coarse Risk Analysis (CRA) method and it covers the major desalination plants and the main water transmission systems with the Al Ghubrah desalination plant and the Greater Muscat and Al Dakhliya Governorates water supply systems as case studies. Brief descriptions are presented below.

4.5.2 Major Desalination Plants

The Sultanate of Oman has been using desalinated water since 1976 when the Al-Ghubrah power and seawater desalination plant was first commissioned. It was installed to meet continuously growing water demand due to population growth and economic development and to reduce reliance on groundwater resources. Desalinated water usage in

Oman is expected to increase further in the future due to new industrial and tourism-related developments.

In Oman, there are six large desalination plants located in Muscat, Al Batina and Ash Sharqiyah Governorates, and one big plant with a capacity of 68000 cubic meters is proposed in Salalah south of Oman. In addition, there are many small scale plants in different locations. Details of the main existing desalination plants are presented in Table (4.8).

Table 4.8: Main Existing Desalination Plants

S.#	Name of Plant	Year of Commissioning		No. of Units	Design Capacity (m^3/day)	Actual capacity (m^3/day)	Type of Desalination
1.	Al Ghubra	Unit 1	1976	7	191000	182000	MSF
		Unit 2	1982				
		Unit 3	1986				
		Unit 4	1986				
		Unit 5	1992				
		Unit 6	1997				
		Unit 7	2002				
2.	Barka I	2003		3	91000	91000	MSF
3.	Barka II	2009		1	120000	120000	RO
4.	Sohar	2007		4	150000	150000	MSF
5.	Sur I	2008		1	12000	12000	RO
6.	Sur II	2009		1	80000	80000	RO
7.	Salalah	Proposed		1	68000	68000	TBC
Total Desalination Capacity (cubic meter per day)						**703000**	

Source: (PAEW Archive)

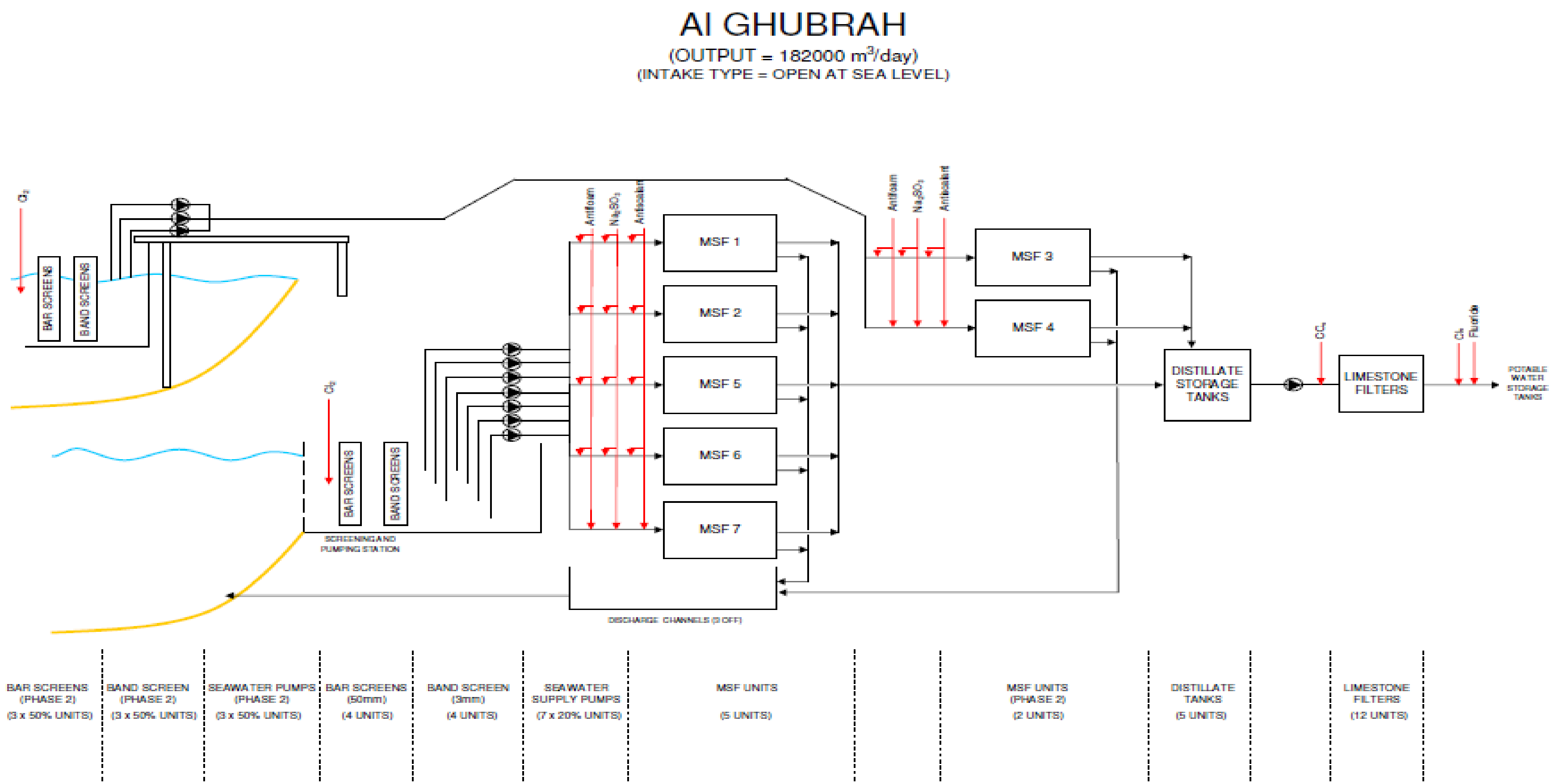
1) Al Ghubra Plant: The first multistage flash (MSF) desalination unit at Al-Ghubrah was constructed in 1976 and had a capacity of 22,750 m^3/day. The other six MSF units each have a capacity of 26,500 m^3/day. PAEW has also proposed a new scheme to upgrade Al-Ghubrah by 2015 to a total capacity of 110,000 m^3/day, built and operated by the private sector. The layout of the plant is presented in Figure (4.13)

2) Barka Plants: The Barka power and seawater desalination plant is located 50 km north-west of Muscat was built in 2003. Barka I has three MSF desalination units each with a capacity of 30,300 m^3/day. The capacity of the reverse osmosis Barka II is 120,000 m^3/day bringing the total desalination capacity for Muscat to 393,000 m^3/day.

3) Sohar Plant: Built in 2007, Sohar Power Company supplies drinking water in the Batinah region and the Sohar industrial port area. It has four MSF desalination units, each with a capacity of 37,500 m^3/day.

4) Sur Plants: The new RO seawater desalination plant at Sur built in 2009 brings an additional desalination capacity of 68,000 m^3/day to satisfy the increasing demand of water in the Sharqiyah Governorate. The new Sur independent water project is located alongside the existing RO plant commissioned in 1993 with a capacity of 12,000 m^3/day.

Figure 4.13: The Layout of Al Ghubrah Power and Desalination Plant



4.5.3 Transmission Mains

1) Greater Muscat: Under normal operation, Ghubrah supplies Quram, Muttrah, Muscat and Al Amerat, whilst Bawsher and Seeb are served from Barka. An outline of the system is presented in Figure (4.14). In an emergency, water may be supplied west from Ghubrah to the Seeb reservoirs or eastward from the Seeb reservoirs to Bawsher.

2) Ad Dakhliyah: is served by the Barka desalination plant. Water is pumped from the Barka transmission main inland to supply several areas. An outline of the system is shown in Figure (4.15).

3) Southern Batinah: is served by the Barka desalination plant. Under normal operation, Barka supplies two coastal and four inland wilayats. An outline of the system is shown in Figure (4.16). In emergencies, water may be pumped south from Sohar desalination plant to Musanaah.

4) North Batinah and Buraymi: The Northern Batinah Region and Buraymi are served from the Sohar desalination plant two coastal wilayats via Buraymi and Sohar service and intermediate reservoirs, from which water flows by gravity to Sohar and three coastal wilayats (Figure 4.17). In an emergency, water may be pumped north from Barka desalination plant.

5) Sharqiyah Regional System: is served by Sur desalination plant. Under normal operation, water from Sur supplies Sur town and its environs and is pumped to Al Kamil from and four wilayats (Figure 4.18).

Figure 4.14: Outline of Greater Muscat Transmission System

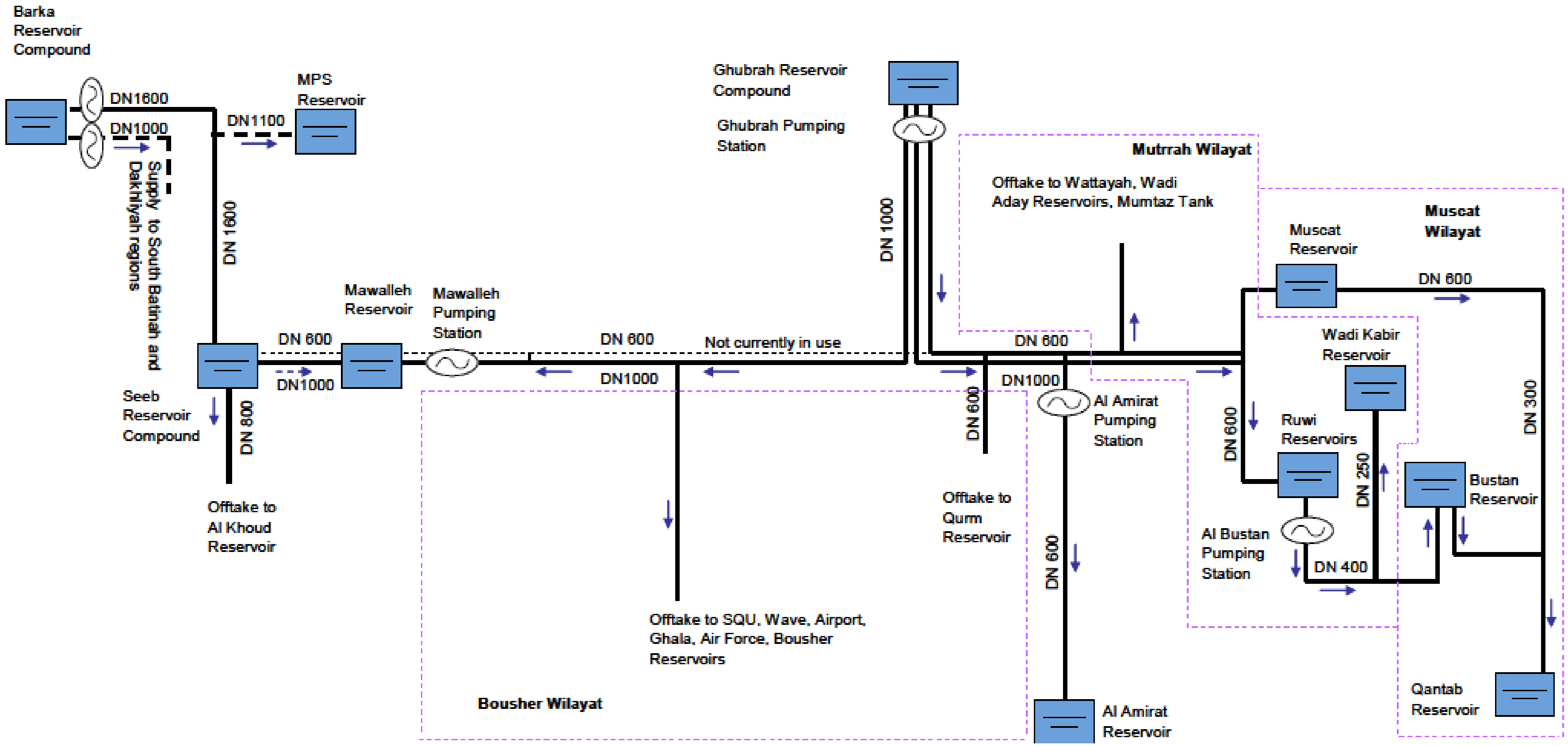


Figure 4.15: Outline of Dakhliyah Transmission System

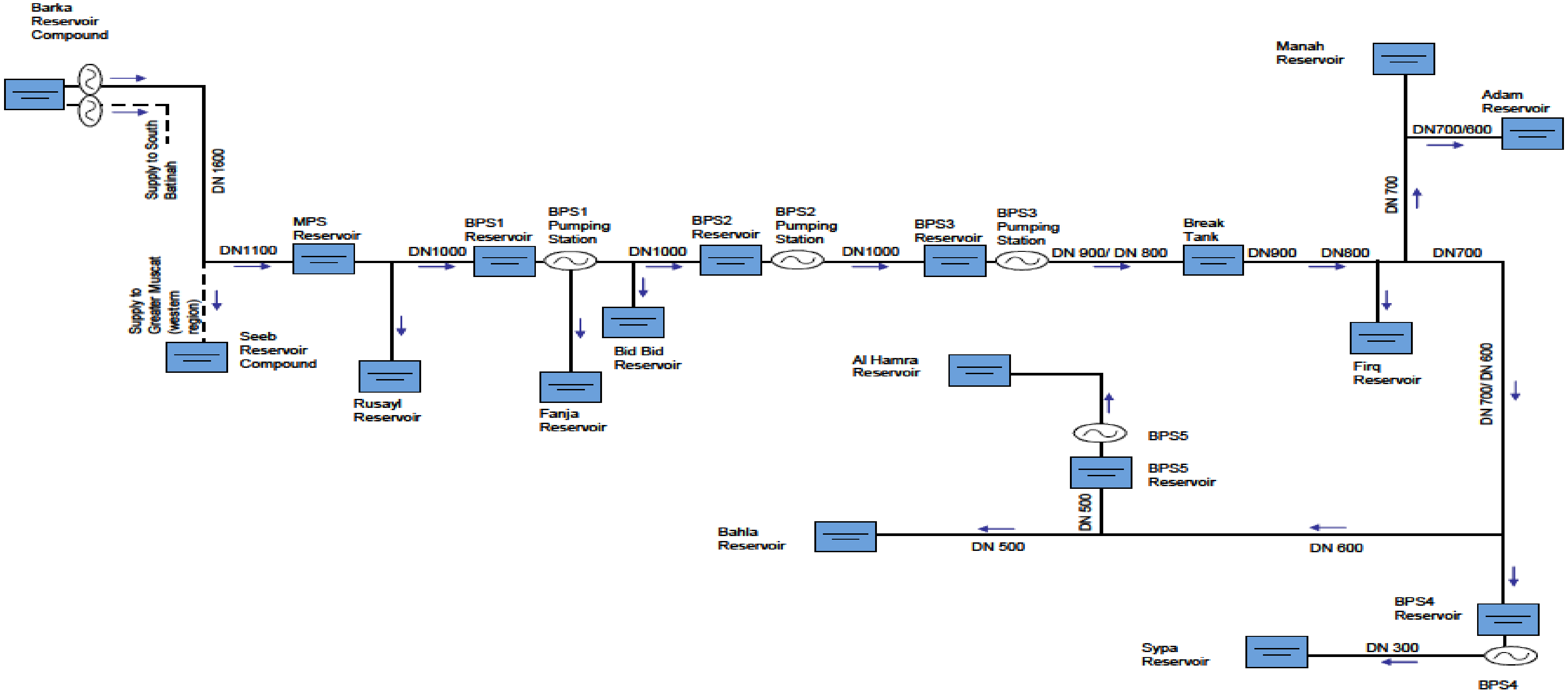


Figure 4.16: Outline of Southern Batinah Transmission System

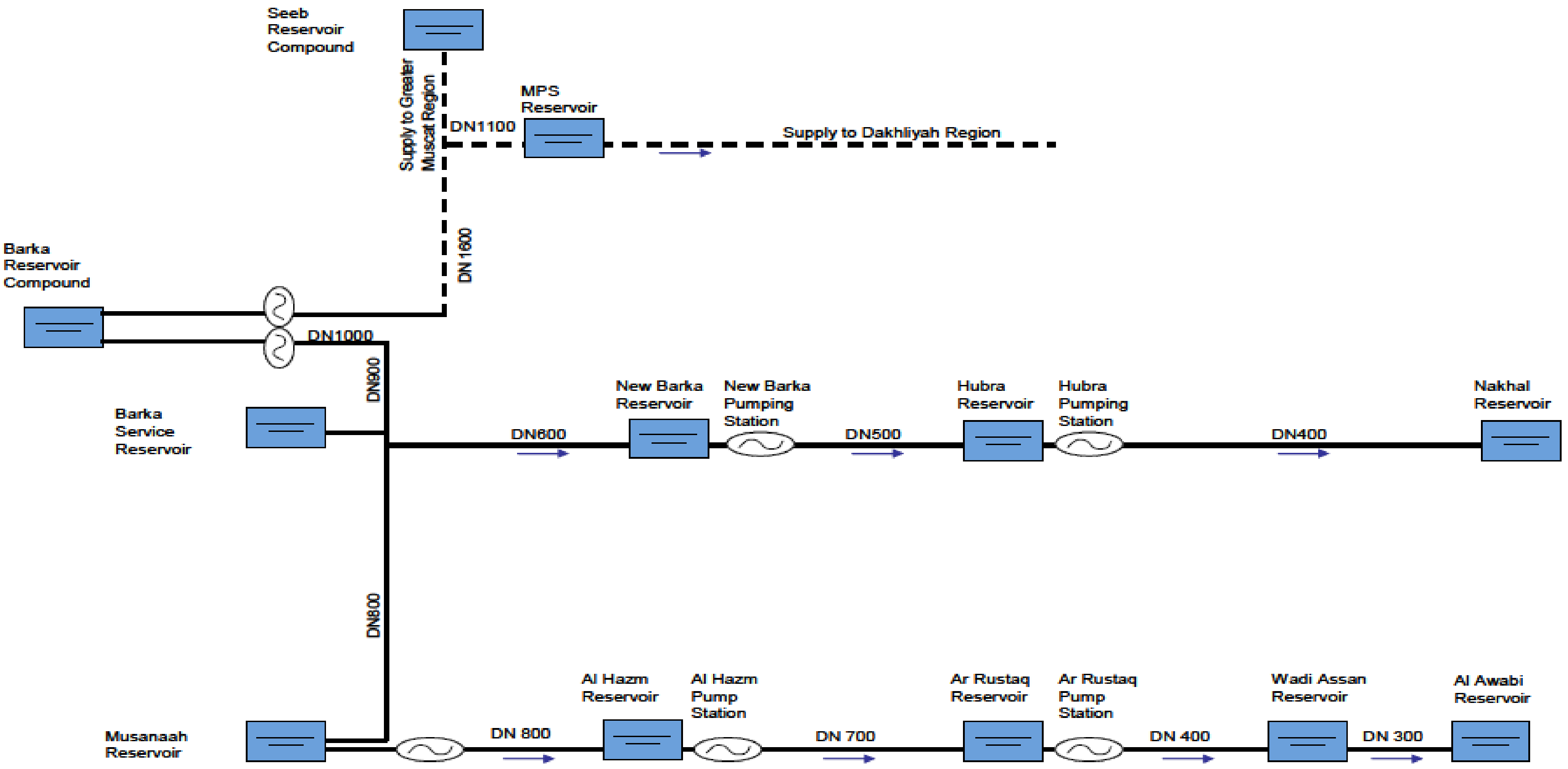


Figure 4.17: Outline of North Batinah Transmission System

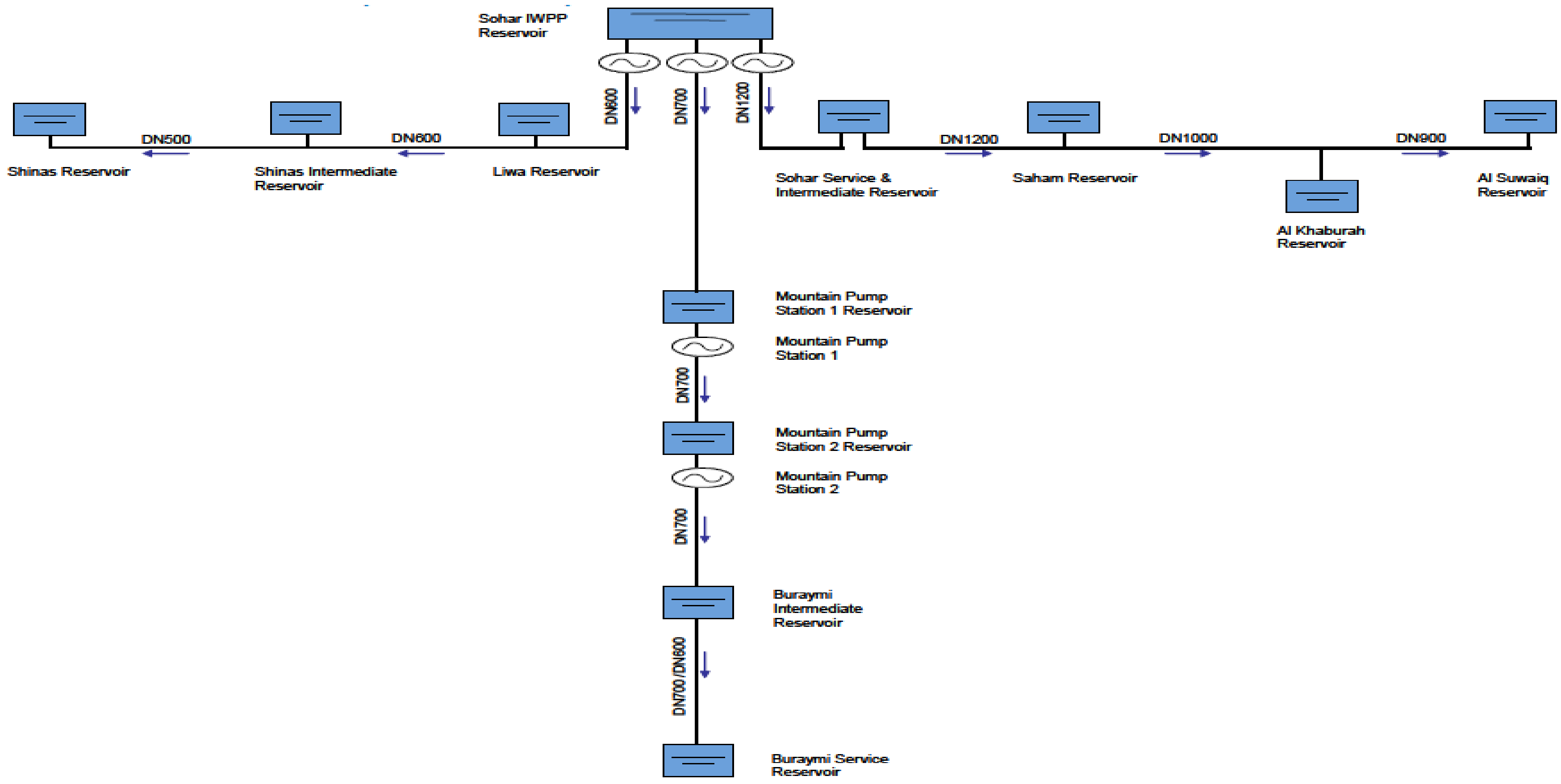
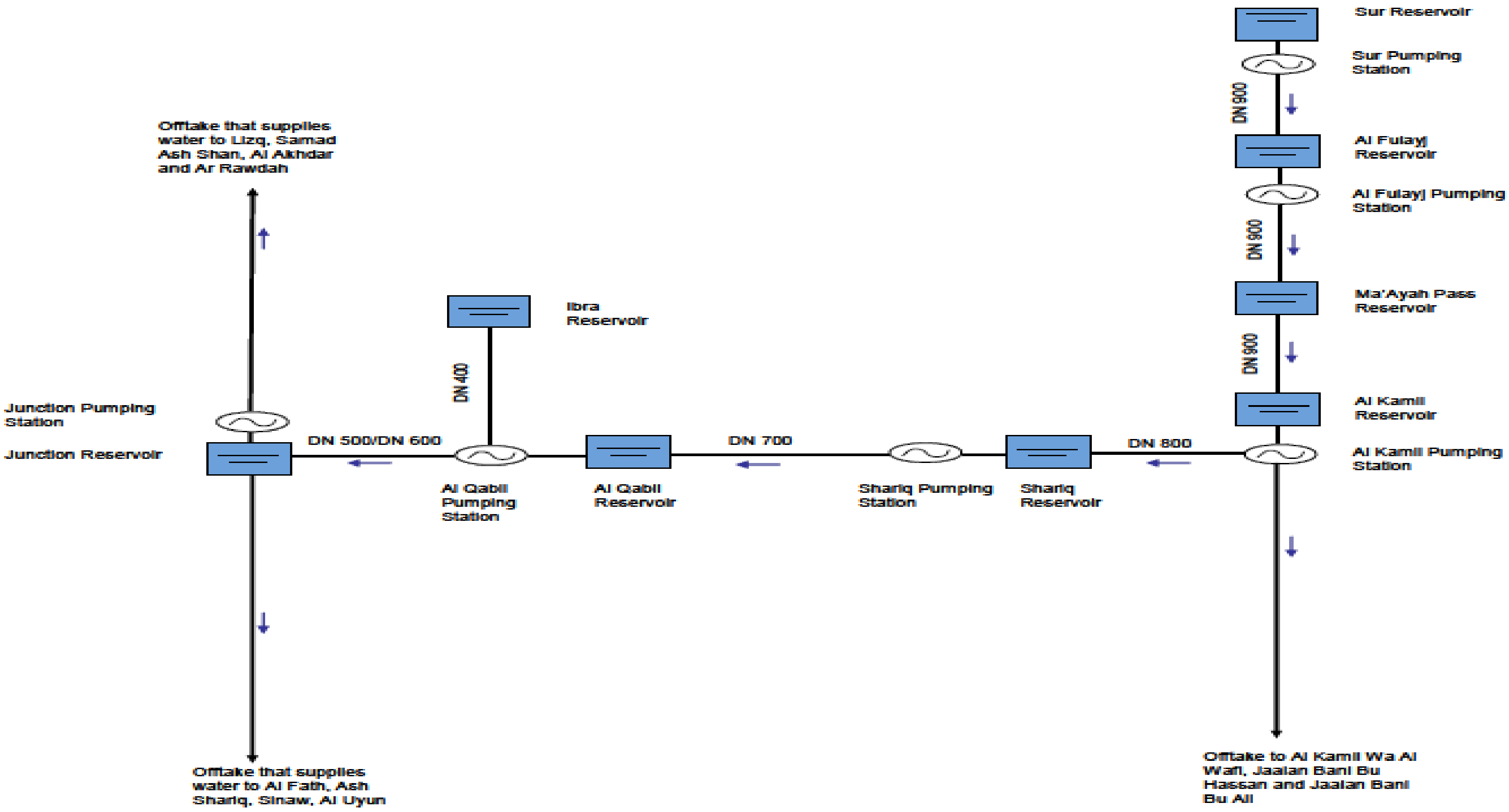


Figure 4.18: Outline of Sharqiyah Transmission System



4.6 Limitations

When dealing with analysis of the stress factors in operating a water network in an arid country taking Oman as case study it is impossible to include all aspects. This thesis is addressed and highlighted the stresses from tropical cyclones and from the problem of water losses and of other manmade hazards. This risk analysis and assessment of water supply systems focused on the major desalination plants and transmission pipelines. The research is based on integrated risk assessments and how the results from risk assessment can be used in decision analysis and in the preparation of a water emergency response plan.

The thesis does not deal with marine hazard or risks of other exceptional events such as earthquakes. Furthermore, the thesis does not focus specifically on crisis management, although risk assessments and decision analyses are important when preparing for a crisis.

The area where the studies are to be conducted was restricted to the Al Seeb Wilayat in Muscat Governorate only.

4.7 Conclusion

This chapter has outlined the case study area used in the present research work and the hazards which exist in the area. Case studies have strength through their ability to deal with a full range of evidence such as documentation, artifacts, interviews, and observations. Limitations of the approach centre on potential issues of validity, researcher bias and the difficulty in generalizing from the case study findings. However, case studies are an important and useful method of data collection, especially in cases of rare phenomena provided the data build on existing knowledge and ensure findings are as applicable to real life as possible.

Tropical storm Gonu was a really exceptional event in which the regions affected in Oman were without water supply for a month. The most valuable lesson learned from Gonu was that all water systems are required to develop emergency response plans based on vulnerability assessments on individual systems.

This experience spotlights the importance of a flood risk management plan which should be prepared and implemented in such cases in order to minimize the impact of such floods resulting from exceptional weather conditions.

Chapter 5 presents the results of the water audit and water losses for the case study using the research methodology described in chapter 3. The analysis of risks for the desalination plants and transmission mains, are presented in chapter 6.

Chapter 5 Water Audit and Water Loss

5.1 General Background

5.1.1 Overview

Water losses in distribution and transmission networks have the major challenge of non-revenue water. This issue represents one of the main stress factors in operating a water network throughout the world including Oman utilities where the production cost of water is high due to the very high operating cost of operating desalination plants. In this part of the research, an attempt is made to identify the level of risks caused by Non Revenue Water (NRW) and how these risks may be reduced. For this purpose, values of water loss and NRW for the Al Seeb Wilayat network of Muscat Governorate were audited, and detailed information was obtained on current water loss prevention and management practices. The results obtained for water losses, NRW, and water balance are presented in this chapter along with the recommended strategy and method for water loss and NRW reduction.

Although it is commonly accepted that any water network cannot be leakage free and water loss cannot be avoided, it is vital to ensure that the level of losses are known, monitored and controlled (IWA, 2003). The problem of water losses in Oman is chronic and its reduction is critical to efficient resource utilization, efficient utility management, enhanced consumer satisfaction, and postponement of capital-intensive additions to capacity. During the period running up to this research, the level of water loss in Oman was shown to be above 40%, which is high by international standards PAEW (2012).

5.1.2 AWWA Water Audit Tool

The components of NRW can be determined by conducting a water balance based on the measurement or estimation of water produced, imported, exported, consumed or lost. The water balance calculation provides a guide to how much is lost as leakage from the network ('real' losses), and how much is due to 'apparent' or non -physical losses (Malcolm, 2010). The first step for any utility aiming to reduce water losses is to prepare a baseline to establish current levels of water losses through a water audit, a critical but often overlooked first step.

In the present study, the AWWA methodology and software were used for water auditing as it is the recognized best practice approach (ref), now being adopted by a number of water agencies and authorities worldwide. AWWA's Free Water Audit Software Package gives the drinking water industry a standardized tool to improve accountability and track water loss standing.

Water Audit as a tool came into the picture in late 1980s to overcome drought related problems, water shortages, leakages and losses (EPA, 2012). The International Water Association (IWA) and the American

Water Work Association (AWWA) initiated a large-scale effort to assess how to reduce the above problems through auditing (Friedman, et al, 2009). With the help of a water audit, operators can identify and quantify what steps can and should be taken to reduce water use and losses. This also saves precious resources and public money (Ganorkar et al, 2013).

The AWWA Water Audit methodology is consistent with that developed and published in 2000 by the International Water Association (IWA) Water Loss Task Force, of which AWWA was a participating member. An important principle of the AWWA method is that all water goes to either consumption or loss and it includes definitions for all uses and water losses. It is designed to function for all units of measure, and it Includes performance indicators for realistic assessments, benchmarking, and target setting (EPA, 2012).

The main advantages of IWA/AWWA Methodology are (EPA, 2012):

- Structured to follow standard international best practice methodology and terminology.
- Accounts for all water uses and calculates non-revenue water (NRW).
- Adopts a specific method for calculating unavoidable annual real losses (UARL).
- Incorporates losses per unit length of main per unit of pressure drop.
- Water utilities worldwide can be compared on the basis of water loss performance indicators.

The software tool is in the form of a Microsoft Excel workbook, and the most current version of the software is Version 5.0, which is available for free download on AWWA's website (WSO, 2014). Upon opening the spreadsheet, the user will find 12 worksheets, three of which require data entry, and two of those three require little information. The other nine sheets serve a variety of functions, including presentation of performance indicators, the automatically populated water balance, and helpful background information and definitions (WSO, 2014).

The software was developed to (Kunkel, 2006):

- Promote the best-practice water audit method developed by the International Water Association and AWWA,
- Assess water supply efficiency in a standard, reliable manner, and
- Give utilities a simple, user-friendly way to compile and compare their water audit data with other utilities.

5.1.3 Assumptions and Limitations of the AWWA tool

There are two principal assumptions behind the AWWA tool. First, standard values are set for flow meter accuracy. The software should enable users to edit the meter accuracy values appropriately, and the software will read what the user has utilized. In other words, before the user starts using the software, it should be set to utility-specific information where available but default values are used where there are no local data.

Secondly, water meters do not stop registering flow rates that do not range within the set AWWA standard accuracy figures. The software assumes that water is flowing within its set range even when that is not true since some meters may either run below or above the set ranges depending on how the specific user is utilizing water. Water utilities differ from one customer to the other.

The AWWA software is the best available solution to water supply and sanitation (Landis, 2015). However, as indicated above, the system has its flaws that should be worked on to improve service delivery. The software is used very widely by water utilities since it helps to reduce cases of water losses and ensures efficiency in the supply. Through use of the software, a best water practice in terms of auditing is achieved and reliability is guaranteed (Landis, 2015).

The major limitation to the AWWA water software is its inability to detect cases of internal corrosion in the system. When internal corrosion of the pipes happens, the water supply is compromised in terms of quality since the water customers will get access to will be contaminated (Landis, 2015). Through this inability to detect cases of internal corrosion within the water supply system, the major goal of supplying quality water at all times may be jeopardized.

5.1.4 Review of NRW Figures and Management

The present PAEW strategy focuses mainly on NRW through improving infrastructure to reduce the amount of water supplied free of charge. Table

(5.1) show that the values of water losses varied between Governorates which gives the percentage of NRW on transmission and distribution networks (PAEW, 2010).

The reasons for high levels of loss are a combination of a number of components: unmetered connections, leakage, operational use, metering errors, and inaccuracies in billing volumes. The split in the volume of water lost is in the ratio of 9% transmission and 91% distribution (both real and apparent) The average loss (both apparent and real losses at that stage) per km of distribution pipe per day is around 40 m^3.

Table 5.1: Regional Network Assessment in Terms of NRW (2010)

Governorate	Total Production (Mm^3)	Total Consumption (Mm^3)	NRW (%)	Trans. Length (km)	Dist. Length (km)	Trans. Loss (%)	Dist. Loss (%)
Muscat	106.373	63.170	40.6	230	2116	2	98
Dhakhliyah	14.24	7.337	48.5	230	378	10	90
Sharqiyah	15.156	7.832	48.3	324	*	14	86
Dhahirah	6.23	4.587	26.4	389	454	74	26
Wusta	1.095	1.189	-8.6	28	11	-	-
Batinah	17.172	1.189	43.6	668	985	28	72
Buraimi	8.267	5.723	30.8	160	270	20	80
Musandam	3.923	2.446	37.7	33	154	7	93
Total	**172.456**	**101.962**	**40.9**	**2062**	**4368**	**9**	**91**

* Full length of distribution mains not known

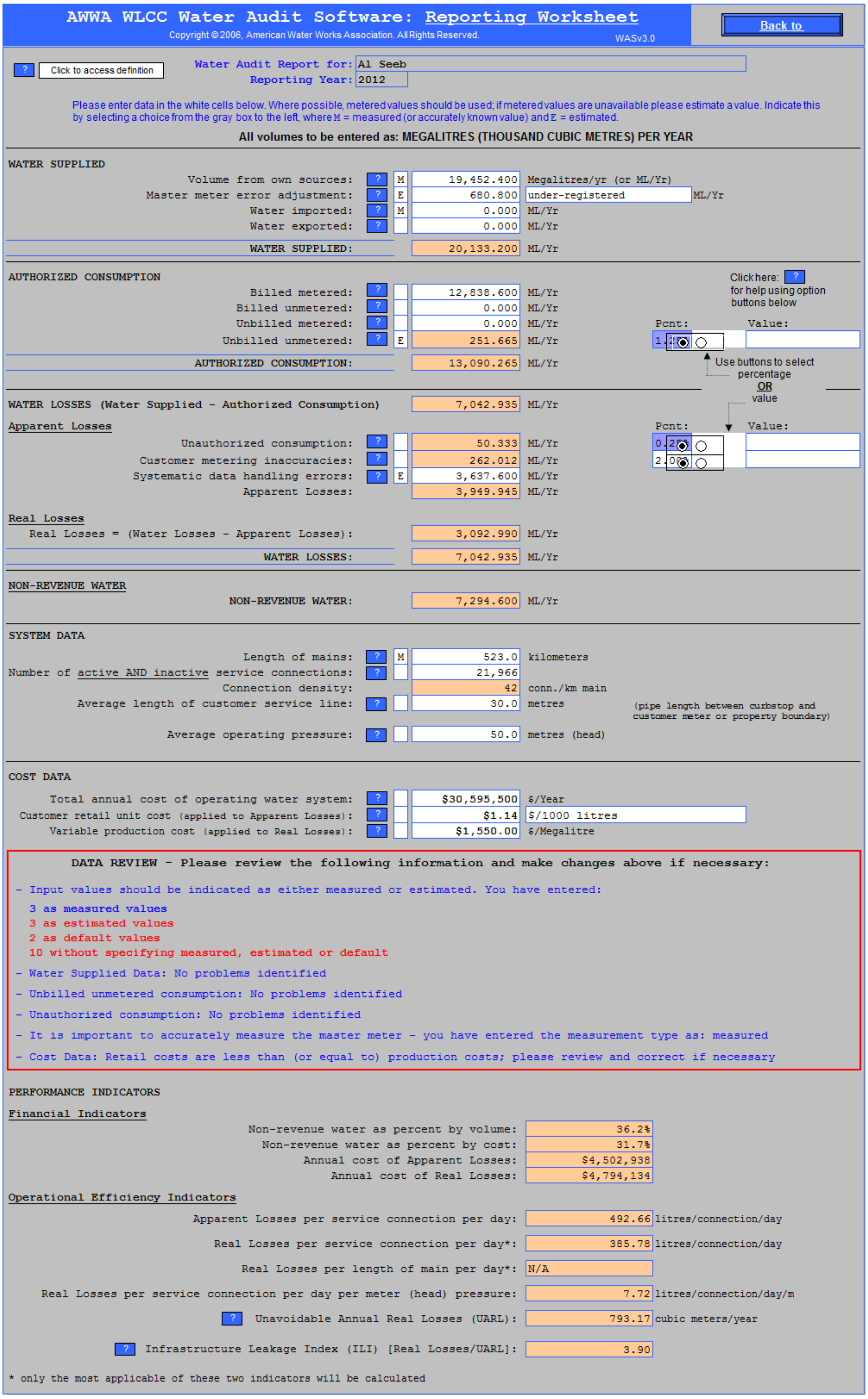
Meter reading, billing and revenue collection is subcontracted to two companies, OIFC (Oman Investment & Finance Company) for the Muscat area, and ONEIC (Oman National Engineer and Investment Company) for the regions. Meters are not read frequently and in time, the more frequent the meters are read the earlier defective meters will be identified and can be replaced. At the same time, few consumer meters are installed in meter boxes exposing them to all weather conditions, especially the sun.

5.2 Losses in Al Seeb Water Supply System

5.2.1 Results of Audit Using AWWA Software

The data for water loss and NRW analysis were collected by the researcher, and data analysis was carried out using the AWWA water auditing software version 3.0. The water supply data, authorized consumption and system data for the last five years (2008-2012) for the Al Seeb water network were collected and entered into the software-reporting sheet and the predicted values of water losses and non-revenue water were obtained.

A sample reporting sheet for 2012 is included as Figure (5.1) and the reporting sheets for years 2008, 20009, 2010 and 2011 are given in Figures (E.1) to (E.4) of Appendix-E. The estimated values of apparent losses, real losses and total water losses, along with non-revenue water for Al Seeb Wilayat are presented in Table (5.2).



AWWA WLCC Water Audit Software: Reporting Worksheet

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Back to

? Click to access definition

Water Audit Report for: Al Seeb
Reporting Year: 2012

Please enter data in the white cells below. Where possible, metered values should be used; if metered values are unavailable please estimate a value. Indicate this by selecting a choice from the gray box to the left, where M = measured (or accurately known value) and E = estimated.

All volumes to be entered as: MEGALITRES (THOUSAND CUBIC METRES) PER YEAR

WATER SUPPLIED

Volume from own sources:	M	19,452.400	Megalitres/yr (or ML/Yr)
Master meter error adjustment:	E	680.800	under-registered ML/Yr
Water imported:	M	0.000	ML/Yr
Water exported:		0.000	ML/Yr
WATER SUPPLIED:		20,133.200	ML/Yr

AUTHORIZED CONSUMPTION

Click here: ? for help using option buttons below

Billed metered:		12,838.600	ML/Yr
Billed unmetered:		0.000	ML/Yr
Unbilled metered:		0.000	ML/Yr
Unbilled unmetered:	E	251.665	ML/Yr
AUTHORIZED CONSUMPTION:		13,090.265	ML/Yr

Pcnt: 1.25% Value:

Use buttons to select percentage OR value

WATER LOSSES (Water Supplied - Authorized Consumption) 7,042.935 ML/Yr

Apparent Losses

Pcnt: 0.25%, 2.00% Value:

Unauthorized consumption:		50.333	ML/Yr
Customer metering inaccuracies:		262.012	ML/Yr
Systematic data handling errors:	E	3,637.600	ML/Yr
Apparent Losses:		3,949.945	ML/Yr

Real Losses

Real Losses = (Water Losses - Apparent Losses):	3,092.990	ML/Yr
WATER LOSSES:	7,042.935	ML/Yr

NON-REVENUE WATER

NON-REVENUE WATER: 7,294.600 ML/Yr

SYSTEM DATA

Length of mains:	M	523.0	kilometers
Number of active AND inactive service connections:		21,966	
Connection density:		42	conn./km main
Average length of customer service line:		30.0	metres (pipe length between curbstop and customer meter or property boundary)
Average operating pressure:		50.0	metres (head)

COST DATA

Total annual cost of operating water system:	$30,595,500	$/Year
Customer retail unit cost (applied to Apparent Losses):	$1.14	$/1000 litres
Variable production cost (applied to Real Losses):	$1,550.00	$/Megalitre

DATA REVIEW - Please review the following information and make changes above if necessary:

- Input values should be indicated as either measured or estimated. You have entered:
  - 3 as measured values
  - 3 as estimated values
  - 2 as default values
  - 10 without specifying measured, estimated or default
- Water Supplied Data: No problems identified
- Unbilled unmetered consumption: No problems identified
- Unauthorized consumption: No problems identified
- It is important to accurately measure the master meter - you have entered the measurement type as: measured
- Cost Data: Retail costs are less than (or equal to) production costs; please review and correct if necessary

PERFORMANCE INDICATORS

Financial Indicators

Non-revenue water as percent by volume:	36.2%
Non-revenue water as percent by cost:	31.7%
Annual cost of Apparent Losses:	$4,502,938
Annual cost of Real Losses:	$4,794,134

Operational Efficiency Indicators

Apparent Losses per service connection per day:	492.66	litres/connection/day
Real Losses per service connection per day*:	385.78	litres/connection/day
Real Losses per length of main per day*:	N/A	
Real Losses per service connection per day per meter (head) pressure:	7.72	litres/connection/day/m
Unavoidable Annual Real Losses (UARL):	793.17	cubic meters/year
Infrastructure Leakage Index (ILI) [Real Losses/UARL]:	3.90	

* only the most applicable of these two indicators will be calculated

Figure 5.1: Water Audit Reporting Worksheet for 2012

Table 5.2: The Values of Water Losses and Non-Revenue Water as Percent by Volume of Water Supplied for Al Seeb Wilayat

Year	Water Losses			Non-Revenue Water (%)
	Apparent (%)	Real (%)	Total (%)	
2008	20.4	25.0	45.4	46.7
2009	19.6	23.4	43.0	44.5
2010	18.3	22.8	41.1	42.3
2011	19.0	17.2	36.2	37.5
2012	19.6	15.4	35.0	36.2

The apparent losses include all types of inaccuracies associated with customer metering as well as data handling errors (meter reading and billing), plus unauthorized consumption, for example, theft or illegal use. At around 19%, the values of apparent losses are very high and this is attributed to the following reasons:

- The performance of the Billing and Collection Company and its delay in issuing water consumption bills.
- Use of estimated meter readings.
- Transcription of the data is inaccurate and disorganized.
- High water pressure in some parts of the network.
- Inaccuracy of the water meters, many of which are 15 years old.
- The lack of an integrated database that enables decision-makers to take the necessary measures to monitor the performance of the Billing and Collection Company.

The values of real losses are comparatively high but the data show that real losses have decreased from approximately 25.0% in 2008 to about 17.2% in 2011 and 15.4% 2014. The most probable reason for the improvement is improved management of the water network and a more intensive maintenance programme.

The values of NRW as a percentage by volume of water supplied (>35%) are very high due to the high apparent losses explained above. Unbilled authorized consumption is low (less than 2%).

5.2.2 Performance Indicators

The performance indicators used in this research were introduced in Section 2.2.4 and this section develops the values gained for specific indicators. The performance indicators in terms of both financial and operational efficiency of the network are calculated in the AWWA software using the methodology outlined in Alegre et. al. (2006).

1) Financial Indicator:

The results for the financial indicators are given in Table (5.3). The total annual cost of operating the Al Seeb water system in 2012 was $30.6 Million. The total annual operating cost in 2008, 2009, 2010, and to 2011 was $16.5, $21.2, $23.5, and $28.3 Million respectively.

Table 5.3: Financial Indicator of Water Losses and NRW for Al Seeb Wilayat

Year	Annual Cost of Water Losses (USD x 10^6)		Non-Revenue Water as Percent of Cost (%)
	Apparent	Real	
2008	3,46	5,77	57.8
2009	3,40	5,60	43.9
2010	3,80	6,45	45.0
2011	4,07	5,02	33.5
2012	4,50	4,79	31.7

The results in Table (5.3) show that the total annual cost of apparent and real losses in the last five years is more that 9.0 Million USD, which is almost equal to one third of total annual operation cost. This value is very high compared to international best practice (Kingdom et al., 2006). The values of NRW as percent of cost are also high and they consensus with the NRW as percent of volume. The non-revenue cost in the year 2012 was 31.7%, which means that one third of water supplied to Al Seeb Wilayat was considered as non-revenue water.

2) Operational Indicators:

The key operational indicators are the losses per service connection per day and the Infrastructure Leakage Index (ILI) as discussed in Section 3.5. The results of apparent and real losses per service connection per day and ILI are given in Table (5.4).

Table 5.4: The Operational Efficiency Indicators for Al Seeb Network

Year	Losses per Service Connection per Day (liter/connection/day)		Infrastructure Leakage Index (ILI) (real losses/ UARL)
	Apparent losses	Real losses	
2008	568.1	697.54	7.0
2009	477.9	578.6	5.8
2010	479.8	599.4	6.0
2011	490.6	444.1	4.5
2012	492.7	385.8	3.9

There is little change in the values of apparent losses per service connection per day (at around 19%) after 2008 whereas the real losses per service connection per day decreased from 697.5 to 385.8 liter/connection/day between 2008 and 2012 due to improvements in the management of the system. The value of ILI also decreased to 3.9 in 2012 for the same reason compared to a target value of 1.0 (Delgado, 2008).

5.2.3 Al Seeb System Water Balance

The water balance for 2012 is presented in Figure (5.2) and the values for 2008 to 2011 are shown in Figures (C.5) to (C.8) of Appendix C.

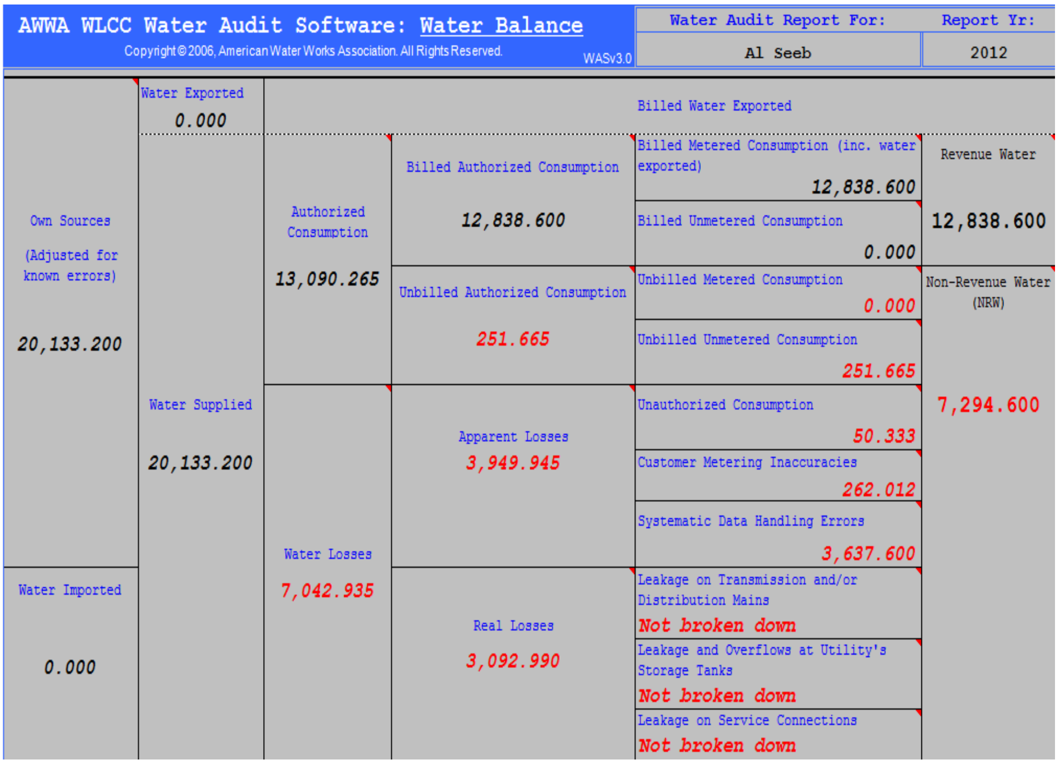

Figure 5.2: Water Balance for Al Seeb Wilayat (Year 2012)

Table (5.5) summarizes the water balance results for 2012. The percentage values are given in the final output which for 2008-2011 are included in Tables (C.1) to (C.4) of Appendix C.

Table 5.5: Al Seeb Water Balance for Year 2012

<table>
<tr><th colspan="3">AWWA Water Audit Software: Water Balance</th><th colspan="2">Report For: Al Seeb Wilayat</th><th>Report Year: 2012</th></tr>
<tr><td rowspan="7">Own Sources (Adjusted for known errors)
(100%)</td><td>Water Exported
(0%)</td><td colspan="4">Billed Water Exported
(0%)</td></tr>
<tr><td rowspan="10">Water Supplied
(100%)</td><td rowspan="4">Authorized Consumption
(65.0%)</td><td rowspan="2">Billed Authorized Consumption
(63.8%)</td><td>Billed Metered Consumption
(63.8%)</td><td rowspan="2">Revenue Water
(63.8%)</td></tr>
<tr><td>Billed Unmetered Consumption
(0%)</td></tr>
<tr><td rowspan="2">Unbilled Authorized Consumption
(1.2%)</td><td>Unbilled Metered Consumption
(0%)</td><td rowspan="8">Non-Revenue Water (NRW)
(36.2%)</td></tr>
<tr><td>Unbilled Unmetered Consumption
(1.2%)</td></tr>
<tr><td rowspan="6">Water Losses
(35.0%)</td><td rowspan="3">Apparent Losses
(19.6%)</td><td>Unauthorized Consumption
(0.3%)</td></tr>
<tr><td>Customer Metering Inaccuracies
(1.3%)</td></tr>
<tr><td rowspan="4">Water Imported
(0%)</td><td>Systematic Data Handling Errors
(18.0%)</td></tr>
<tr><td rowspan="3">Real Losses
(15.4%)</td><td>Leakage on Transmission and/or Distribution mains
Not broken down</td></tr>
<tr><td>Leakage and Overflow at Utility’s Storage Tank
Not broken down</td></tr>
<tr><td>Leakage on Service Connections
Not broken down</td></tr>
</table>

The water balance for Al Seeb Wilayat indicates that around half of the water supplied in 2008 was without revenue and considered as losses, but the condition improved in the subsequent four years due to efficient management of the water network resulting in the value for revenue water now standing at 63.8%. At the same time the water balance data show that the billed unmetered water consumption and unbilled metered water consumption were zero for all the years meaning that these measures are included in the authorized consumption values.

The value of apparent losses was almost constant over the five year period (around 19%) and are mainly attributable to data handling errors (18.0%) related to the performance of the billing and collection company. The customer metering inaccuracies and illegal connections in Al Seeb area were less than 2%. Unbilled authorized consumption is within 2.0%.

5.3 Questionnaire Results

A questionnaire survey was conducted as part of this research (see section 3.3.3). The main objective of the survey was to understand how NRW is perceived by key staff members.

5.3.1 Introduction

As the estimated water losses in Oman are approximately 40 to 50 percent, it was critical to the research that the reasons for such relatively high values should be determined. The purpose of the survey of PAEW staff was first to determine current water loss accounting practices, secondly to gain more information on current water loss prevention and management practices, and finally to make recommendations for more consistent water use accounting and water loss management. For this purpose, the researcher sought to discover from those PAEW staff who are concerned with water losses, what their perceptions were about the published NRW figure, their understanding of the impact and main causes of water loss, and their opinions on PAEW's procedures and policy related to water loss reduction.

This section explains the findings and answers to the questions in the questionnaire regarding water losses reduction management and strategy along with the obstacles for fighting water losses and strategic options. The overall feedbacks on this matter shows that there was uncertainty in stating the exact value of the NRW figure because the relatively junior staff questioned do not know exactly the estimated value. In spite of this, the results in Table 5.6 were consistent with the calculated values as shown in Table (5.2). The answers of the staff to the question:- 'which aspect of PAEW strategy focuses of deriving water loss figure?' as presented in Table (5.7) confirmed that PAEW strategy focuses mainly on NRW.

Table 5.6: The Estimated Percentage of NRW in the Muscat Network

Percentage for the water losses (%)	Percentage (%)
10-20	0
20-30	30
30-40	60
40-50	10
More than 50	3.33
Don’t know	6.67
Total	**100**

Table 5.7: Method of Driving Water Losses Figures in PAEW

Method	Percentage (%)
Leakage Level	10
Leakage level and UFW	50
UFW	30
Non-Revenue Water (NRW)	0
UFW and NRW	10
Don’t know	0
Total	**100**

* UFW (Unaccounted for Water) is a term no longer in wide use

5.3.2 Causes, Impacts and Solutions

The third question was:- ‘What do you think are the main factors that contribute to water losses?’ and the answers are listed in Table (5.8). The data show that staff believe the main factors that contribute to water losses are the inaccuracies in billing volumes and the method of estimating consumption through faulty meters.

Table 5.8: The Main Factors that Contribute to Water Losses

Answers		Prioritize According to Contribution (1 = very high, 6 = very low)					
		1	2	3	4	5	6
Meter Inaccuracies	Percentage of staff (%)	70	20	10	0	0	0
Losses during repair		0	10	10	50	20	10
Age of pipes		10	30	20	30	10	0
Illegal Connection		0	0	0	10	20	70
Service reservoir overflow		0	10	20	0	50	20
Water pressure		20	30	40	10	0	0

The other factors that contribute to water losses are water pressure in the network and to a lesser degree the age of the pipes. The pressure in the network is high in some areas where the pipes are also old causing water leakage problems. It seems that there are relatively few illegal connections in Oman but in spite of this, PAEW periodically runs campaigns to reduce illegal connections and water theft. Some staff mentioned that water from hydrants either authorized or unauthorized is not monitored and accounted properly and also contributes to water losses.

The impact of water losses figures on network operation and cost was also examined. The responses to the question:- ‘What do you think are the possible impacts of the high water loss figures?’ are presented in Table (5.9). The responses emphasize that high water loss figures results in high operation and maintenance (O&M) costs, short lifespan of existing resources and increased expenditure on network development.

Table 5.9: The Possible Impacts to High Water Losses Figures

Answers		Prioritize According to Contribution(1 = very high, 6 = very low)					
		1	2	3	4	5	6
Reduction in pressure	Percentage of staff (%)	10	10	20	50	0	10
Increase expenditure on development		30	20	20	20	10	0
Water contamination		0	10	10	0	30	50
High cost of O&M		50	30	10	0	10	0
Short lifespan of existing resources		30	20	30	10	10	0
Property damage		0	0	0	0	30	70

Table (5.10) summarizes the best solutions that could be utilized to reduce water losses in water systems and is derived from the responses to the question:- ‘What do you consider to be the best solution to the reduce water losses in water systems’?. 60% thought that the first priority was an active leak detection programme and 40% thought that improving metering was highest priority. Other staff thought that improvement of pipe maintenance and replacement of old pipes was important but, there was no perceived need to clamp down on illegal connections. 50% of staff supported increased public awareness not only to encourage the use of water wisely but also to encourage immediate reporting of any incidents such as pipe bursts or leaks in the distribution network.

Table 5.10: The Best Solution to the Reduce Water Losses

Answers		Prioritize According to Contribution(1 = very high, 6 = very low)					
		1	2	3	4	5	6
Improve pipe maintenance	Percentage of staff (%)	0	30	30	20	20	0
Clampdown on illegal connection		0	0	10	0	10	80
Pipe replacement		0	40	10	30	10	10
Active leak detection		60	30	10	0	0	0
Increase public Awareness		0	0	30	10	50	10
Improve metering		40	0	20	40	0	0

5.3.3 Procedures and Policy

The second part of the questionnaire to PAEW staff related to current procedures and policy. Five option were given for each policy (strongly agree, agree, neutral, disagree, and strongly disagree).The responses are summarized in Table (5.11).

Table 5.11: Procedures and Policy for Water Losses

Procedures and Policy	Strongly agree	Agree	Neutral	Disagree	Strongly disagree
	Percentage of staff (%)				
A National Water Policy exists which aims at reducing water losses.	10	70	10	10	0
A Water loss reduction program is implemented.	70	0	20	10	0
Pressure management is used to reduce water losses.	30	50	20	0	0
A Network Maintenance/ Rehabilitation Program is Implemented.	0	80	20	0	0
Measures to fight illegal connections are applied	50	10	10	30	0

Grades: Strongly agree = 5, Agree = 4, Neutral = 3, Disagree = 2, Strongly disagree = 1

Most of the staff agreed that a national water policy exists which aims at reducing water losses and water loss reduction. This means that a policy for water losses reduction is available in Oman and the government is trying to apply this policy for different areas through a water loss reduction program. Pressure management and control is used to reduce water losses and network maintenance, and a rehabilitation program has been implemented.

Table (5.12) gives statistics for the responses. The average values are around 4, which means the staff agree with the available procedures and policy. There is also a consensus in the answers of respondents hence the values of the standard deviation are low.

Table 5.12: Averages and Standard Deviations for Procedures and Policy

Procedures and Policy	Average Value	Standard Deviation
A National Water Policy exists which aims at reducing water losses.	3.8	0.79
A Water loss reduction program is implemented.	3.6	0.70
Pressure management is used to reduce water losses.	4.1	0.74
A Network Maintenance/ Rehabilitation Program is Implemented.	3.8	0.42
Measures to fight illegal connections are applied	3.8	1.4

5.3.4 Obstacles to Fighting Water losses

The last set of questions related to the obstacles to fighting water losses, and in the same way five options were given for each question and the responses are given in Table (5.13) while table (5.14) gives relevant statistics.

Table 5.13: Obstacles to Fighting Water Losses

Obstacles	Strongly agree	Agree	Neutral	Disagree	Strongly disagree
	Percentage Value (%)				
Institutional situation	0	0	20	50	30
Lack of financial means from PAEW	0	10	20	70	0
Lack of appropriate technologies for water loss reduction	30	70	0	0	0
Maintenance system	10	50	0	20	10
Personnel capacities (technicians)	60	40	0	0	0
Personnel awareness	20	30	10	0	40
Public acceptance / awareness	10	30	0	20	40

Grades: Strongly agree = 5, Agree = 4, Neutral = 3, Disagree = 2, Strongly disagree = 1

Table 5.14: Averages and Standard Deviations for Fighting Water Losses

Obstacles	Average Value	Standard Deviation
Institutional situation	1.9	0.74
Lack of financial means from PAEW	2.7	1.06
Lack of appropriate technologies for water loss reduction	3.9	1.1
Maintenance system	3.2	1.3
Personnel capacities(technicians)	4.6	0.51
Personnel awareness	2.9	1.7
Public acceptance / awareness	2.3	1.5

It is clear that the main obstacle is with the leak detection staff (average value = 4.6). It seems there are insufficient qualified staff available to carry out the activities related to leak detection. There are also no formal or refresher training programmes in the use of the leakage equipment and it is clear that training is given a very low priority. The standard deviation for the responses is very small, which means that there is consensus in staff views on the importance of this topic. The other important factor is the lack of appropriate technologies for water loss reduction.

There is no financial justification that prevents PAEW implementing a robust program to fight water losses and 60% of staff agreed that there is problem in system maintenance. The other factors such as personnel awareness and public acceptance/awareness were not seen to be obstacles in fighting water losses.

5.4 Developing a Strategy for Reducing Water Losses

5.4.1 Introduction

To deal effectively with water loss it is important to understand the characteristics and the significance of each of the components of water loss. This is particularly true in countries such as Oman where scarcity of water resources forces the extensive use of desalination to produce potable water. The high costs of producing water in this way are an important element of operational budgets. Energy consumed in the process also results in a high environmental impact, compounded by the need to transport water over long distances, and across mountain ranges, from the coast to the center of Oman (Butler et al, 2006).

5.4.2 Understanding the Starting Point

The best approach to start to draw up a strategy to deal with losses in any water supply system is to understand the sources of leakages in the system. The two most important components of NRW from the Al Seeb Case Study are the real losses and the apparent losses (IWA, 2005) which together need the most resource in terms of logistics, staffing and finance to control water losses. Farley &Trow (2003) suggests that strategies that might enable a better estimate of the actual losses to be made include; distribution input, per capita consumption, non-household water use and operational use. In addition, several factors influence real losses to a lesser or greater extent including; the pressure in the network, (typical flow rate and burst,) awareness time, location time, repair time and the level of background leakage. These factors in turn are also influenced by such factors as; long-term pipe network management, pressure management, speed and quality of repairs and active leakage control measures in place (Farley et al, 2003). Understanding and identification of these factors is a major steps towards dealing effectively with real losses (Butler et al, 2006).

The researcher had a personal interview with Mr. Lambert O. Allan, the first chairman of the IWA Water Loss Task Force at the IWA World water Congress & Exhibition, Montreal, Canada. September 2010. Mr Allan is of the view that, without pressure management nothing else would work so far as leakage control is concerned (Personal Communication, 2010).

PAEW implements an ambitious strategy to monitor and reduce water losses throughout its water networks across the sultanate. The results of the questionnaire survey are interpreted to show that the strategy for reducing water losses should include the following;

1. **Integrated Management:** Reducing NRW is a multi-departmental task that involves front line services such as Water Operations, Customer Services, Asset and Planning and Project Departments with Support Services making a substantial contribution through the recruitment and training of staff and procuring materials and equipment.

2. **Data reporting**: Data reporting should be improved through a three pronged approach:
    - Installing and maintaining a network of devices to measure all inputs to and outputs from all part of the water system.
    - Implementing a fault reporting methodology.
    - Closely monitoring the performance of the Billing and Collection Contractors.

3. **Flow Monitoring:** District Metered Areas should be set up by installing flow meters on system inlets with the outlets either isolated through closing valves or installing flow meters. The net volume of water supplied can then be compared to the volume of water

consumed (either measured or estimated) to assess the level of efficiency losses of the area.

4. **Leak Repair Response:** At the current time all leak repairs are out-sourced in all regions. The recommendation here is to develop limited in-house capability but continue to utilize external companies to provide the most efficient form of leak repair (cost and speed).

5. **Meter accuracy checking and replacement:** It is also important to improve meter reading accuracy and identify meters that require maintenance. The PAEW standards and specifications contain a metering specification designed to improve the accuracy of meters and prolong their working life.

6. **Leakage teams:** It is essential that sufficient leakage teams are to be created and provided with the necessary training and equipment to enable them to carry out their allotted tasks efficiently and to raise leak detection practices in Oman.

5.5 Discussion on Non Revenue Water

5.5.1 The outputs obtained

The need for efficient management of water resources and the accurate metering of water flows are specific issues that require high priority attention in today's international climate of environmental sustainability and conservation of natural resources (Farley & Trow, 2003; WHO, 2001).. There is need for the establishment of strong water systems for distributing potable water to the residents. It is observed that developing countries - like Sultanate of Oman - are facing some deficiencies in water distribution systems that cause high values of NRW and water losses (Lambert, 2003). The values of NRW and water losses in Oman are high reference to the International standards (Ref). For this reason a tool such as the AWWA tool that can monitor the water distribution is necessary for safety, reliability and low cost in the distribution system model.

The first, basic step to developing a strategy for management of NRW was to gain a better understanding of the amount and sources of NRW and the factors that influence its components through calculating the water balance. The AWWA water audit method was used to analyze the factors associated with water losses and the PAEW responses to the problem. The results of the water audit indicate that the percentage of NRW in Oman is more than 35%. The level of NRW in the other Gulf countries has been reported to be as high as 40% for Bahrain, 35% in Saudi Arabia, and 30% in the united Arab Emirate (Zyadin, 2013). Reducing apparent losses goes hand in hand with reducing real losses. Real losses arise from operational costs such as power, maintenance and the treatment costs incurred by the supply agents. Using the AWWA water software ensures early detection of such leakages enabling the supply agents respond immediately thereby reducing the time intervals for maintenance and reconnection to the water supply system.

The study also explored PAEW staff perceptions about the adoption of water-loss management procedures and identified organizational characteristics that may influence management's decisions to adopt such strategies. The inaccuracies in billing volumes and the method of estimating consumptions through faulty meters had the most significant impacts on water losses. Therefore discourages the unscrupulous connecting to water supply (gaps in the billing operations) which may allow some customers to obtain water without payment. The software through improved maintenance reduces the likelihood of damage to property and improves and safeguards the public health. The study found that the number of qualified staff available to carry out the activities related to leak detection was low and appropriate technologies for water loss reduction are lacking. It was also clear that maintenance systems should be improved to achieve better performance of the network by decreasing water losses.

Finally, the software reduces disruption to customers. Repairing leaks proactively before they develop to larger leakages or even breakages that may disrupt water supply services. Moreover, the software allows for accountability for the water utility in the community. Through this, the utility may secure funds aimed at sustaining upkeep of the operations in the future and suggest several policy and strategy implications for reducing water losses.

5.5.2 Limitations of the case study data.

In the determination of the Current Real Loss values, the large meter on the outlet from the main storage reservoir has not been accurately calibrated, giving rise to potentially significant apparent losses. Further, domestic meters are notoriously inaccurate especially when they are not replaced regularly, leading to further apparent losses, although these inaccuracies may cancel each other out. Also excluded from the audit are unregulated or unauthorized use of hydrants and illegal connections.

If those losses were quantified and omitted from the average daily inflow figures from each DMA, a much lower ILI figure might have been attained.

5.6 Conclusion

The study of NRW has determined the components of water loss in the exemplar Al Seeb network. From these water loss indicators, performance indicators were calculated and using with the current internationally accepted method of calculation (the AWWA method). For this purpose, the water system of Al Seeb Wilayat in Muscat was taken as a case study. The implementation of a rigorous Metering and Non Revenue Water Strategy will supply a starting point for PAEW to allow for the proper assessment of losses within the technical and economic limitations.

5.7 Next Step

This chapter has addressed most of the issues, both technical, operational and financial, surrounding water losses from distribution networks in Oman. However, these are the day-to-day issues of operating and managing a water supply and distribution network. The next issue to be addressed in chapter 6 is the likelihood of more extreme yet less frequent system problems. Consequently, the issue of risks to the system follow.

6 Chapter 6 Risk Assessment and Analysis

The risk assessment and resilience approaches that were developed in the literature review in Chapter 2 were applied using the methodology of Chapter 3 to a number of the desalination plants and transmission systems that are described in Chapter 4. Risk assessments and determination of resilience require detailed knowledge of the system under study and this was garnered through the workshop and questionnaire, both detailed in Chapter 3. This chapter concludes with comprehensive evaluations of the risk to and resilience of the water systems under consideration. (David comment here will be considered in chapter 8)

6.1 Approach

Risk analyses and assessments were carried out for the major desalination plants (source) and for the main water transmission systems (transmission). The Al Ghubrah power and desalination plant was taken as a case study for desalination plants, and the Greater Muscat and Al Dakhliya Governorates water supply systems were taken as case studies for transmission systems.

The risks to the desalination plant and to the transmission systems were identified and analyzed initially without any controls and then allowing for mitigating measures. All scores were assigned using the semi quantitative approach of the workshop and interviews, or failing these activities, using the researcher’s comments and observations noted during the field visits.

For each part of the desalination plant and each section of the transmission mains, the risks were assessed and given values for likelihood, and impact (consequence) and consequently risk score in accordance with the likelihood and consequence tables and risk matrix presented in section 3.4.3. Finally, the solutions proposed to mitigate these risks are summarized. In the sections following, the current risk scores were reassessed taking into account the effectiveness of each existing control used to mitigate the risk. Colour coding allows significant hazards to be identified easily in the centre column and the effectiveness of the control is in the right hand column. Inadequately controlled yet significant risks are red in both columns.

6.2 Risks to Al Ghubrah Desalination Plant

The principal risks to the desalination plants were determined during the workshop (see section 3.3.4 and Appendix-A).

- Algal blooms and jellyfish or small fish restricting the capacity of sea intakes.
- Oil spills from accidents at sea and/or from land-based sources.
- Direct ship collisions with sea intake structures.
- Re-circulation of effluents from industry (including desalination plants)
- Excessive suspended solids at the sea intakes from cyclones.
- Mechanical or electrical failure within the treatment process.
- Unavailability of power gas or chemicals.
- Industrial action or unavailability of skilled labor.

The thermal desalination plant at Al Ghubrah is an integrated water and power plant that has been extended several times to increase capacity (see Figure 4.13 for layout). There are a number of surface level intakes but all are located in the same area and reliant on the same pumps and screens. This represents a pinch point where any problems can rapidly result in disruptions to water production.

The plant has extensive maintenance systems in place but, at the time of the visit, the equipment, particularly the screens, were in poor condition and it was evident that ongoing maintenance had considerably reduced the amount of available standby equipment (PAEW Archive).

A particular issue is the 'Red Tide' event which is caused by an accumulation of marine algae. Such events can occur up to four times per year and require intensive maintenance at the intake although, to date, no Red Tide event has closed the plant. Despite maintaining water production during these periods the risk from future algae blooms is significant as the quantity and algae species in any future event may have different impacts on the plant. The site at Al Ghubrah is close to an international oil port and hence is at significant risk from oil contamination. Although oil booms can be deployed and would provide some protection in the event of minor spillages, the surface intakes offer little protection against large spillages.

At the time of the visit, pumps had been removed at both of the pumping stations for maintenance and consequently no standby was available. The poor condition of the pumps and lack of available spares are representative of the generally poor condition of the plant and of the consequent increased risk to supply. There is no evidence of the recirculation of brine causing any disruption to the production of water.

The risks to Al Ghubrah desalination plant are presented in Tables (6.1), (6.2), and (6.3) for Sea Water Quality, Main Treatment Process, and Site Wide Risks respectively. The risk tables present hazardous events, their causes and the likelihood and consequence of their occurrence as a number from the risk matrix.

Table (6.4) summarises the risks to Al Ghubrah desalination plant before and after control measures. The control measures are considered not only for their long term average performance but also for their potential to be ineffective or fail over a short period. For example, jellyfish represent a significant risk to desalination plant intakes but can be controlled by the use of appropriate nets. However, if the net is not regularly inspected and cleaned it will fail and so will not be an effective control when needed.

Table 6.1: Al Ghubrah Treatment Risks-Sea Water Quality

Sea Water Quality																	
Item	**Hazard**	**Hazardous Event**	**Further Details**	**Likelihood**	**Consequence**	**L**	**C**	**Risk**	**Control Measure**	**Monitoring Procedures**	**Corrective Action**	**Likelihood**	**Consequence**	**L**	**C**	**Risk**
Feed Water Quality	Loss of Production	Harmful Algal Blooms	Combinations of particular conditions (i.e. available nutrients, temperature, light), lack of zooplankton grazing, and above threshold seed population density. Excess nutrients are brought into the photo tic zone by i) upwelling (summer monsoon) transported to Gulf of Oman by currents, and ii) deepening of the mixed zone (winter). Historically Sohar plant shut down for five days during red tide.	One in five to twenty years	> 7 days loss of treated water production	3	16	48	Open intake will not reduce the likelihood of issues with surface species. The site was affected by the Red Tide in 2008 Water production was not lost but emergency actions were needed to be taken to deal with the high colour and odour of the seawater being affected with the red tide. Chlorine tables were added to the seawater intake, as hypo chlorination alone was not able to guarantee chlorine residual. Limestone filters backwash frequency was increased to twice a day as filters where overloaded. Fluoride dosing was replaced with hypochlorite dosing to increase the hypochlorite dose to guarantee residual chlorine in the treated water.	N/A	Increase chlorination and in extreme circumstances shut down plant	One in five to twenty years	2 - 7 days loss of treated water production	3	8	24
	Loss of Production	Jellyfish	Combinations of particular conditions (i.e. available food such as bacteria/ micro-zooplankton, temperature, light), lack of predation, and above threshold seed population density. Bacteria and zooplankton density linked to phytoplankton density which in turn is linked to nutrient availability.	One in twenty to fifty years	> 7 days loss of treated water production	2	16	32	In 2003 a heavy ingress of jellyfish into the seawater intake channel was experienced. All the four running rotary bar screens and all the four running travelling bad screens tripped on "MOTOR O/L" protection as they were all jammed with the incoming jellyfish. Water production was lost for two days.	Uncertain	Run screens in Manual and increase cleaning frequency. If not successful initially reduce flow and in extreme circumstances shut down plant (consequence base upon reduced flow).	One in twenty to fifty years	12 - 48 hours loss of treated water production	2	4	8
	Loss of Production	Accidental Oil Spills at Sea	Loading/Discharging	One in five to twenty years	> 7 days loss of treated water production	3	16	48	Implementation of site oil spill emergency procedure, including deployment of booms and avoidance of dispersants. Implementation of cleanup protocols at a National Level	Visual inspection	Shut down plant.	One in five to twenty years	2 - 7 days loss of treated water production	3	8	24
	Loss of Production	Accidental Oil Spills at Sea	Collisions	One in five to twenty years	> 7 days loss of treated water production	3	16	48	Implementation of site oil spill emergency procedure, including deployment of booms and avoidance of dispersants. Implementation of cleanup protocols at a National Level	Visual inspection	Shut down plant.	One in five to twenty years	2 - 7 days loss of treated water production	3	8	24
	Loss of Production	Accidental Oil Spills at Sea	Groundings	One in twenty to fifty years	> 7 days loss of treated water production	3	4	12	Implementation of site oil spill emergency procedure, including deployment of booms and avoidance of dispersants. Implementation of cleanup protocols at a National Level	Visual inspection	Shut down plant.	One in twenty to fifty years	2 - 7 days loss of treated water production	3	4	12
	Loss of Production	Accidental Oil Spills at Sea	Hull Failures	One in twenty to fifty years	> 7 days loss of treated water production	3	4	12	Implementation of site oil spill emergency procedure, including deployment of booms and avoidance of dispersants. Implementation of cleanup protocols at a National Level	Visual inspection	Shut down plant.	One in twenty to fifty years	2 - 7 days loss of treated water production	3	4	12
	Loss of Production	Accidental Oil Spills at Sea	Fires and Explosions	One in five to twenty years	> 7 days loss of treated water production	2	4	8	Implementation of site oil spill emergency procedure, including deployment of booms and avoidance of dispersants. Implementation of cleanup protocols at a National Level	Visual inspection	Shut down plant.	One in five to twenty years	2 - 7 days loss of treated water production	2	4	8

Table 6.1- Cont.: Al Ghubrah Treatment Risks-Sea Water Quality

Item	Hazard	Hazardous Event	Further Details	Likelihood	Consequence	L	C	Risk	Control Measure	Monitoring Procedures	Corrective Action	Likelihood	Consequence	L	C	Risk
Feed Water Quality	Loss of Production	Operational Oil Spills at Sea	Illegal tank washings	One in five to twenty years	12 - 48 hours loss of treated water production	3	4	12	Implementation of site oil spill emergency procedure, including deployment of booms and avoidance of dispersants. surveillance by authorities during daylight hours only	Visual inspection	Shut down plant.	One in five to twenty years	12 - 48 hours loss of treated water production	3	4	12
	Loss of Production	Operational Oil Spills at Sea	Illegal Dumping	One in five to twenty years	12 - 48 hours loss of treated water production	3	4	12	Implementation of site oil spill emergency procedure, including deployment of booms and avoidance of dispersants. surveillance by authorities during daylight hours only	Visual inspection	Shut down plant.	One in five to twenty years	12 - 48 hours loss of treated water production	3	4	12
	Loss of Production	Operational Oil Spills at Sea	Loading Operation Spills	One in five to twenty years	12 - 48 hours loss of treated water production	3	4	12	Implementation of site oil spill emergency procedure, including deployment of booms and avoidance of dispersants. surveillance by authorities during daylight hours only	Visual inspection	Shut down plant.	One in five to twenty years	12 - 48 hours loss of treated water production	3	4	12
	Loss of Production	Re-circulation of facility discharges causing increased salinity	Poorly designed industrial master plan resulting in inefficient flushing of marine discharges in vicinity of desalination plant intake.	One in five to twenty years	> 7 days loss of treated water production	3	16	48	Design of intakes.	Seawater analysis.	None	One in twenty to fifty years	> 7 days loss of treated water production	2	16	32
	Loss of Production	Excessive naturally occurring seawater temperatures (>40oC)	Unseasonal lack of winds in summer in Gulf of Oman, exacerbated by effects of climate change.	One in fifty to one hundred years	2 - 7 days loss of treated water production	1	8	8	None	Seawater analysis.	N/A	One in fifty to one hundred years	> 7 days loss of treated water production	1	8	8

Table 6.2: Al Ghubrah Treatment Risks-Main Treatment Process

Main Treatment Process																
Item	**Hazard**	**Hazardous Event**	**Further Details**	**Likelihood**	**Consequence**	**L**	**C**	**Risk**	**Control Measure**	**Monitoring Procedures**	**Corrective Action**	**Likelihood**	**Consequence**	**L**	**C**	**Risk**
MSF Units	Loss of Production	Structural Failure of Main Process Unit	There are 7 MSF Units. Distillers 1 and 2 were due to be retired in 2009 however the retirement has been postponed due to levels of demand. Both distillers were refurbished in 2008. No specific issues reported with existing units. Assume failure would be for a single unit only	One in fifty to one hundred years	2 - 7 days loss of treated water production	1	8	8	General plant monitoring systems.	Multiple	Removal of Unit from Service.	One in fifty to one hundred years	2 - 7 days loss of treated water production	1	8	8
	Loss of Production	Power Failure Multiple Units (steam/electricity)	History of power failure in 2007 due to the cyclone	One in one to five years	< 12 hours loss of treated water production	4	2	8	General plant monitoring systems.	Multiple	Shutdown of Plant	One in one to five years	< 12 hours loss of treated water production	4	2	8
	Loss of Production	Power Failure Single unit (steam/electricity)	History of power failure in 2007 due to the cyclone	More than one per year	< 12 hours partial reduction in treated water production (>34% of design output)	5	1	5	General plant monitoring systems.	Multiple	Shutdown of Unit	More than one per year	< 12 hours partial reduction in treated water production (>34% of design output)	5	1	5
	Loss of Production	Loss of Process Performance due to Scaling and Fouling	Maintenance schedule system is in place	One in one to five years	12 - 48 hours loss of treated water production	8	4	32	Dosing of anti sealant and cleaning of units.	Multiple	Removal of Unit from Service for cleaning	One in fifty to one hundred years	12 - 48 hours loss of treated water production	1	4	4
CO2 Plant	Loss of Production	Structural Failure	Plant is old and in fair conditions	One in five to twenty years	12 - 48 hours loss of treated water production	4	4	16	None	NA	Shut Down Plant	One in five to twenty years	12 - 48 hours loss of treated water production	4	4	16
	Loss of Production	Mechanical and Electrical Failure	Duty /standby dosing pumps provided	One in one to five years	< 12 hours loss of treated water production	2	8	16	Standby Provided	NA	NA	One in five to twenty years	< 12 hours loss of treated water production	2	4	8
	Loss of Production	Process Performance Failure	Flow and Dose of chemical will largely be constant and is not likely to change in normal operation.	One in one to five years	< 12 hours loss of treated water production	2	8	16	Treated Water monitored	NA	NA	One in twenty to fifty years	< 12 hours loss of treated water production	2	2	4
Chlorine Dosing	Loss of Production	Structural Failure	Chlorine drums are used on site, duty/stanby dosing line	One in five to twenty years	2 - 7 days loss of treated water production	4	8	32	None	Monitors	Alarm generated	One in five to twenty years	2 - 7 days loss of treated water production	4	8	32
	Loss of Production	Mechanical and Electrical Failure	Duty standby injector pumps and ejectors.	One in one to five years	12 - 48 hours loss of treated water production	4	8	32	Standby Equipment provided	NA	Alarm generated	One in five to twenty years	12 - 48 hours loss of treated water production	4	4	16
	Process Performance Failure	Process Performance Failure	Chlorine residual monitored and high and low alarms generated.	More than one per year	12 - 48 hours loss of treated water production	4	16	64	Final Water analyzed for pH	NA	Alarm generated	One in twenty to fifty years	12 - 48 hours loss of treated water production	2	4	8

Table 6.2- Cont.: Al Ghubrah Treatment Risks-Main Treatment Process

Item	Hazard	Hazardous Event	Further Details	Likelihood	Consequence	L	C	Risk	Control Measure	Monitoring Procedures	Corrective Action	Likelihood	Consequence	L	C	Risk
Caustic Soda Dosing	Loss of Production	Structural Failure (leaks) of Tanks or Dosing Pipe work	3 chemical storage tanks provided, 1 duty 2 standby	One in five to twenty years	12 - 48 hours loss of treated water production	4	4	16	Standby unit provided	NA	NA	One in twenty to fifty years	12 - 48 hours loss of treated water production	2	4	8
	Process Performance Failure	Mechanical and Electrical Failure of Make Up Equipment and Dosing Pumps	Duty standby dosing pumps provided.	One in one to five years	12 - 48 hours loss of treated water production	4	8	32	Standby Equipment provided.	NA	NA	One in five to twenty years	12 - 48 hours loss of treated water production	4	4	16
	Loss of Production	Process Performance Failure (Incorrect Quantity Dosed)	Chemical dosing is flow proportional and dosing line is fitted with a flow transmitter with high and low alarms.	One in one to five years	12 - 48 hours loss of treated water production	4	8	32	Treated Water monitored	NA	NA	One in five to twenty years	12 - 48 hours loss of treated water production	4	4	16
Sodium Fluoride Dosing	Loss of Production	Structural Failure (leaks) of Tanks or Dosing Pipe work	3 chemical storage tanks provided, 1 duty 2 standby	One in five to twenty years	12 - 48 hours loss of treated water production	4	4	16	Fluoride Monitor provided on dosed water which generates high and low alarms.	NA	NA	One in twenty to fifty years	12 - 48 hours loss of treated water production	2	4	8
	Loss of Production	Mechanical and Electrical Failure of Make Up Equipment and Dosing Pumps	Duty standby dosing pumps provided.	One in one to five years	12 - 48 hours loss of treated water production	4	8	32	Standby Equipment provided.	NA	NA	One in five to twenty years	12 - 48 hours loss of treated water production	4	4	16
	Process Performance Failure	Process performance Failure (Incorrect Quantity Dosed)	Chemical dosing is flow proportional and dosing line is fitted with a flow transmitter with high and low alarms.	One in one to five years	12 - 48 hours loss of treated water production	4	8	32	Treated Water monitored	NA	NA	One in five to twenty years	12 - 48 hours loss of treated water production	4	4	16
Treated Water Sampling System	Loss of Production	Structural Failure of Sampling Pipe work	NA	One in twenty to fifty years	12 - 48 hours loss of treated water production	2	4	8	None	NA	NA	Regular Spot Checks on treated Water Quality	12 - 48 hours loss of treated water production	2	4	8
	Loss of Production	Mechanical and Electrical Failure	NA	One in five to twenty years	12 - 48 hours loss of treated water production	4	4	16	None	NA	NA	One in five to twenty years	12 - 48 hours loss of treated water production	4	4	16
	Process Performance Failure	Process Performance Failure (Analyzers do not read correctly)	NA	One in one to five years	12 - 48 hours loss of treated water production	4	8	32	Regular Spot Checks on treated Water Quality	NA	NA	One in five to twenty years	12 - 48 hours loss of treated water production	4	4	16

Table 6.3: Al Ghubrah Treatment Risks-Site Wide Risks

Side Wide Risks																
Item	**Hazard**	**Hazardous Event**	**Further Details**	**Likelihood**	**Consequence**	**L**	**C**	**Risk**	**Control Measure**	**Monitoring Procedures**	**Corrective Action**	**Likelihood**	**Consequence**	**L**	**C**	**Risk**
Electrical Power Supply System	Loss of Treated Water Production	Loss of Power Supply (external)	Main supply of power is from onsite generation.	One in one to five years	12 - 48 hours loss of treated water production	5	4	20	Onsite generation of Power.	Multiple	Shut Down Plant	One in one to five years	< 12 hours partial reduction in treated water production (>34% of design output)	4	2	8
Fire	Loss of Treated Water Production	Major Fire on Site	No incidents reported. Emergency Preparedness Procedure Manual in place for site.	One in twenty to fifty years	> 7 days loss of treated water production	2	16	32	Emergency procedure in place.	NA	NA	One in twenty to fifty years	2 - 7 days loss of water production treated	2	8	16
Flooding (origin land side)	Loss of Treated Water Production	Flooding of site and damage to key plant equipment	Historical issues with loss of gas supply through flood damage	One in twenty to fifty years	> 7 days loss of treated water production	2	16	32	Emergency procedure in place.	NA	NA	One in twenty to fifty years	2 - 7 days loss of treated water production	2	8	16
Gas Supply	Loss of Treated Water Production	Disruption of gas supply to IWPP	National reserves depleted; import disrupted (e.g. Dolphin Energy pipeline failure); domestic transmission and distribution network disrupted by extreme event.	One in fifty to one hundred years	> 7 days loss of treated water production	1	16	16	Use of back up fuel l to operate power plant	N/A	Operate on fuel oil and/or diesel	One in fifty to one hundred years	2 - 7 days loss of treated water production	1	8	8
Loss of Labour	Loss of Treated Water Production	Loss of expatriate labour	Poor employment terms and conditions, unsafe working environment, political strike between Oman and country where labour originates	One in fifty to one hundred years	> 7 days loss of treated water production	1	16	16	Ongoing training to maintain labour pool. Omanisation policy.	N/A	N/A	One in fifty to one hundred years	> 7 days loss of treated water production	1	8	8
Nuclear Threat	Loss of Treated Water Production	Nuclear contamination	Military strike or engineering failure of nuclear power plants, facilities or waste transport system in Pakistan, India, Iran, UAE; collision involving nuclear powered vessels or warships carrying nuclear weapons.	One in fifty to one hundred years	> 7 days loss of treated water production	1	16	16	None	N/A	Shut Down Plant	One in fifty to one hundred years	> 7 days loss of treated water production	1	16	16
Cyclones	Loss of Treated Water Production	Cyclone	Cyclonic storm often formed in SE Indian Ocean that tend to develop when surface seawater temperatures are high	One in fifty to one hundred years	2 - 7 days loss of treated water production	1	8	8	Storage of fuel on site; stocks of chemicals on site; use alternative fuel for power plant.	N/A	Shut Down Plant; switch to alternative fuel if required.	One in fifty to one hundred years	2 - 7 days loss of treated water production	1	8	8

Table 6.4: Summary of Risks to Al Ghubrah Desalination Plant

Item	Hazard	Hazardous Event	Before Control			After Control		
			L	C	Risk	L	C	Risk
Sea Water Quality								
Feed Water Quality	Loss of Production	Harmful Algal Blooms	3	16	48	3	8	24
	Loss of Production	Jellyfish	2	16	32	2	4	8
	Loss of Production	Accidental Oil Spills at Sea	3	16	48	3	8	24
	Loss of Production	Accidental Oil Spills at Sea	3	16	48	3	8	24
	Loss of Production	Accidental Oil Spills at Sea	3	4	12	3	4	12
	Loss of Production	Accidental Oil Spills at Sea	3	4	12	3	4	12
	Loss of Production	Accidental Oil Spills at Sea	2	4	8	2	4	8
	Loss of Production	Operational Oil Spills at Sea	3	4	12	3	4	12
	Loss of Production	Operational Oil Spills at Sea	3	4	12	3	4	12
	Loss of Production	Operational Oil Spills at Sea	3	4	12	3	4	12
	Loss of Production	Re-circulation causing increased salinity	3	16	48	2	16	32
	Loss of Production	Excessive seawater temperature	1	8	8	1	8	8
Main Treatment Process								
MSF Units	Loss of Production	Structural Failure of Main Process Unit	1	8	8	1	8	8
	Loss of Production	Power Failure Multiple Units (steam/electricity)	4	2	8	4	2	8
	Loss of Production	Power Failure Single unit (steam/electricity)	5	1	5	5	1	5
	Loss of Production	Loss of Process Performance due to Scaling and Fouling	4	8	32	1	4	4
CO2 Plant	Loss of Production	Structural Failure	4	4	16	4	4	16
	Loss of Production	Mechanical and Electrical Failure	2	8	16	2	4	8
	Loss of Production	Process Performance Failure	2	8	16	2	2	4
Chlorine Dosing	Loss of Production	Structural Failure	4	8	32	4	8	32
	Loss of Production	Mechanical and Electrical Failure	4	8	32	4	4	16
	Process Performance Failure	Process Performance Failure	4	16	64	2	4	8

Table 6.4 - Cont.: Summary of Risks to Al Ghubrah Desalination Plant

Item	Hazard	Hazardous Event	Before Control			After Control		
			L	C	Risk	L	C	Risk
Main Treatment Process								
Caustic Soda Dosing	Loss of Production	Structural Failure (leaks) of Tanks or Dosing Pipe work	4	4	16	2	4	8
	Process Performance Failure	Mechanical and Electrical Failure of Make Up Equipment and Dosing Pumps	4	8	32	4	4	16
	Loss of Production	Process Performance Failure (Incorrect Quantity Dosed)	4	8	32	4	4	16
Sodium Fluoride Dosing	Loss of Production	Structural Failure (leaks) of Tanks or Dosing Pipe work	4	4	16	2	4	8
	Loss of Production	Mechanical and Electrical Failure of Make Up Equipment and Dosing Pumps	4	8	32	4	4	16
	Process Performance Failure	Process Performance Failure (Incorrect Quantity Dosed)	4	8	32	4	4	16
Treated Water Sampling System	Loss of Production	Structural Failure of Sampling Pipe work	2	4	8	2	4	8
	Loss of Production	Mechanical and Electrical Failure	4	4	16	4	4	16
	Process Performance Failure	Process Performance Failure (Analyzers do not read correctly)	4	8	32	4	4	16
Side Wide Risks								
Electrical Power Supply System	Loss of Treated Water Production	Loss of Power Supply (external)	5	4	20	4	2	8
Fire	Loss of Treated Water Production	Major Fire on Site	2	16	32	2	8	16
Flooding (origin land side)	Loss of Treated Water Production	Flooding of site and damage to key plant equipment	2	16	32	2	8	16
Gas Supply	Loss of Treated Water Production	Disruption of gas supply to IWPP	1	16	16	1	8	8
Loss of Labour	Loss of Treated Water Production	Loss of expatriate labour	1	16	16	1	8	8
Nuclear Threat	Loss of Treated Water Production	Nuclear contamination	1	16	16	1	16	16
Cyclones	Loss of Treated Water Production	Cyclone	1	8	8	1	8	8

6.3 Transmission Systems Risks

6.3.1 General

The main risks to the transmission system risks are:

- Loss of supply from the treatment plants.
- Failures in the transmission mains.
- Failures of pumps.
- Loss of power at pumping stations.
- Failure of the Control System.
- Inadequate storage to meet demand.

The risk to main components of water supply system is as follow:

1) Pipelines

There is very little information on the failure rates in large diameter pipelines in Oman, except for those in Muscat. The failures on pipelines in Muscat for 2007 and 2008 are given in Table (6.5) below.

Table 6.5: Pipe Failures in Muscat Water Supply System.

Diameter of Pipe (mm)		100	150-200	250-300	400	600	800+
Length of Pipe (km)		609	1093	384	97	108	114
Year 2007	**Number of Failures**	382	160	63	9	45	2
Year 2008	**Number of Failure**	360	199	49	3	31	1

Source: (PAEW Annual report, 2007 & 2008)

Most failures occur on small diameter pipelines, where service connections are vulnerable and where accidental damage from other works is most likely. There is a high rate of failure on 100 mm diameter pipes in Muscat. We believe that this is due to the poor condition of the 600 mm DI main from Ghubrah to Muscat, which we understand was laid over 30 years ago with only basic external corrosion protection. Looking at the relationship between diameter and numbers of failures in the table above, we would expect a failure rate in 600mm pipes to be around 35 per 1000 km per year, rather than the figure of 351 recorded in Muscat.

The time taken to repair bursts in pipelines, from the time the burst occurs to when the pipeline is operational again, is taken by operation department of the PAEW under normal conditions to be as follows:

- Less than 600 mm diameter 1.5 days
- 600 mm to 1000 mm diameter 2.0 days
- Over 1000 mm diameter 3.0 days

Initially the impact of mains failure assesses the loss of supply. The analysis then considers existing control measures in place, primarily downstream storage in the system. If the volume of emergency storage available exceeds the time to make the repair, there will be no impact on consumers. Where there is still a risk to supply after allowing for downstream storage, the severity of the impact is assessed from the loss of supply to the consumer after storage has been exhausted.

2) Pumping Stations

Pumping stations are at risk from outages due to:

- Failure of individual pump sets.
- Loss of incoming power supply, affecting the whole pump station.
- Failure of the pump control system

All pumping stations include standby pumps which operate when a pump fails, ensuring a continuous supply is maintained. The longer the duration of any outage, the greater risk of simultaneous failures of individual pumps and it is assumed that pumps are repaired in 10 days. Loss of power at pump stations is not uncommon, but electrical outages are usually of short duration. Under normal conditions power is restored to water pumping stations within 24 hours but this may not be possible in extreme weather conditions when there is widespread damage to power lines. This is an example of the need to develop and maintain a reliable emergency plan to deal with the consequences (see Chapter 7). Pumps are controlled automatically by a variety of level states in the reservoirs to which water is delivered. Monitoring of the system ensures that any failure in the control system will be identified within a few hours. Pumps will then be switched to manual operation until the fault can be rectified.

Initially in this research, the consequence of failure is assessed as loss of capacity, ignoring any standby plant and storage in the system downstream. As with bursts in mains, the analysis then considers control measures in place, including standby pumps (assumed to be maintained in good working order) and storage downstream.

3) Reservoirs

There are two main risks for the reservoirs:

- Pollution, either accidental or deliberate.
- Structural failure.

The risk of pollution is minimized by ensuring all reservoirs are fitted with lockable covers, vents are protected with mesh, compounds are securely fenced and the installation is fitted with appropriate alarms and/or video surveillance. Structural failures are very rare.

4) Loss of Supply from the Desalination Plants

The loss of supply from the desalination plant is the largest risk to the security of the supply to consumers. The impact of the various levels of severity of the outage (effectively the duration of the outage) in the risk matrices are considered in this research. Tables (6.6) and (6.7) summarize the forecasted number of hours of storage available at the desalination plants for the 2010 average and peak demands.

Table 6.6: Estimated Number of Days of Storage Available for Average Demands

Desalination Plant	Average Daily Flow (m^3/day)	Storage at Desalination Plant (m^3)	Storage (hours of supply capacity)	Storage (days of supply capacity)
Ghubrah	158,350	163,650	25	1.0
Barka	158,069	182,400	28	1.2
Sohar	102,727	135,000	32	1.3
Sur	32,718	164000	120	5

Source: PAEW (2011)

Table 6.7: Estimated Number of Days of Storage Available for Peak Demands

Desalination Plant	Average Daily Flow (m^3/day)	Storage at Desalination Plant (m^3)	Storage (hours of supply capacity)	Storage (days of supply capacity)
Ghubrah	195,456	163,650	20	0.8
Barka	195,211	182,400	22	0.9
Sohar	126,739	135,000	26	1.1
Sur	40,538	164000	97	4.0

Source: PAEW (2011)

6.3.2 Risk Tables for Transmission Mains

6.3.2.1 Risk Tables for Greater Muscat

The risks to Greater Muscat water supply system including transmission mains, pumping stations, and loss of supply from desalination plant are given in Tables (6.8), (6.9), and (6.10) and are summarized in Table (6.11).

Table 6.8: Risks to Transmission Mains of Great Muscat Water Supply System

Transmission Mains																									
Hazard	Diameter (mm)	Length (km)	Material	Expected nr failures/km/yr	Expected nr 1:x yr failures	Population	Likelihood	Consequence	L	C	Risk	Control Measure	Monitoring Procedures	Corrective Action (days)	Expected repair time (days)	Average daily flow 2010 (m^3)	Downstream storage (m3)	Emergency storage (days supply)	Loss of supply (m3)	Likelihood	Consequence	L	C	Risk
Burst in main from Barka PS to Seeb Res	1600	32.4	Steel	0	2	310874	One in one to five years	Loss of supply to Seeb	4	16	64	Storage downstream. Repairs to be completed to target times	Burst records	Repair main/ replace main	3	123762	166550	1.0	245577	One in one to five years	Loss of supply to Seeb	4	8	32
Burst in main from Al Ghubrah to Qurm, Wattaya, Ruwi, Muscat, Mumtaz Res and Al Amirat PS (1000mm)	1000	27.0	Ductile Iron	0	3	316959	One in one to five years	Loss of supply to much of eastern Greater Muscat	4	16	64	Storage downstream. Repairs to be completed to target times	Burst records	Repair main/ replace main	3	59962	77,790	1.0	121882	One in one to five years	Loss of supply to much of eastern Greater Muscat	4	8	32
Burst in main from Al Ghubrah to Qurm, Wattaya, Ruwi, Muscat, Mumtaz Res and Al Amirat PS (600mm)	600	27.0	Ductile Iron	9	0	316959	More than one per year	Loss of supply to eastern Greater Muscat	5	16	80	Storage downstream. Repairs to be completed to target times	Burst records	Repair main/ replace main	2	21586	77,790	3.3	0	More than one per year	Loss of supply to part of eastern Greater Muscat	5	2	10
Burst in main from Al Ghubrah to Bausher Wilayat (Waver, Airport, Ghala, Bousher Res)	1000	35.0	Ductile Iron	0	2	218740	One in one to five years	Loss of supply to eastern Greater Muscat	4	16	64	Storage downstream. Repairs to be completed to target times	Burst records	Repair main/ replace main	3	76802	132,000	1.4	123752	One in one to five years	Loss of supply to eastern Greater Muscat	4	8	32

Table 6.9: Risks to Pumping Stations of Great Muscat Water Supply System

Pumping Stations																					
Hazard	Standby arrangement	Operational capacity (m3/d)	Likelihood	Consequence	L	C	Risk	Control Measure	Monitoring Procedures	Corrective Action	Records	Average daily flow 2010 (m3)	Downstream storage (m3)	Expected maximum outage time (days)	Emergency storage (days supply)	Loss of supply (m3)	Likelihood	Consequence	L	C	Risk
Pump failure - Barka to Seeb PS	2D + 1S	172800	One in one to five years	loss of supply to Seeb	4	16	64	Maintain standby, through implementation of an appropriate maintenance, repair and replacement policy	Pump fail alarm, condition monitoring	Pump replacement/ repair	Inspection Records	123762	166550	10	1.0	1111910	One in fifty to one hundred years	loss of supply to Seeb	4	4	16
Loss of power - Barka to Seeb PS	-	172800	More than one per year	Loss of supply to Seeb	5	16	80	Downstream storage. Ensure repair of lost supply within 24 hours	Alarm	Repair of supplies to water facilities. These should have a high priority.	-	123762	166550	1	1.0	0	More than one per year	Partial loss of supply to Seeb	5	1	5
Failure of control systems - Barka to Seeb PS	-	172800	One in one to five years	Loss of supply to Seeb	4	16	64	Downstream storage. Alarms and manual override implemented within 12 hours.	Alarm/Manual checking	Repair or replace faulty supplies	-	123762	166550	1	1.0	0	One in one to five years	Partial loss of supply to Seeb	4	2	8
Pump failure - Ghubrah PS	8D + 1S	192000	More than one per year	loss of supply to Eastern Gt. Muscat	5	16	80	Maintain standby, through implementation of an appropriate maintenance, repair and replacement policy	Pump fail alarm	Pump replacement/ repair	Inspection Records	81548	77790	10	0.6	764599	One in one to five years	Partial loss of supply to Eastern Gt. Muscat	4	8	32
Loss of power - Ghubrah PS	-	192000	More than one per year	Loss of supply to Eastern Gt Muscat	5	16	80	Downstream storage. Ensure repair of lost supply within 24 hours	Alarm	Repair of supplies to water facilities. These should have a high priority.	-	81548	77790	1	0.6	30669	More than one per year	Loss of supply to Eastern Gt Muscat	5	8	40
Failure of control systems - Ghubrah PS	-	192000	One in one to five years	Loss of supply to Eastern Gt Muscat	4	16	64	Downstream storage. Alarms and manual override implemented within 12 hours.	Alarm/Manual checking	Repair or replace faulty supplies	-	81548	77790	1	0.6	30669	One in one to five years	Loss of supply to Eastern Gt Muscat	4	8	32

Table 6.10: Risks to Great Muscat Water Supply System Due to Loss of Supply from Desalination Plant

Loss of Supply from Desalination Plant

Hazard	Operational capacity (m^3/d)	Flow to Regional System 2010 (m^3/d)	Storage at desalination plant (m^3)	Storage (hours of supply capacity)	Potential loss of supply (m^3)		Likelihood	Consequence	L	C	Risk	Control Measure	Monitoring Procedures	Corrective Action	Records	Average daily flow 2010 (m^3)	Downstream storage (m^3)	Emergency storage (days' supply)	Loss of supply (m^3)	Likelihood	Consequence	L	C	Risk
					Min	Max																		
Loss of Supply from Ghubrah DP	208644	158350	163650	19	0	0	One in one to five years	< 12 hours partial reduction in treated water production (>34% of design output)	4	2	8	Downstream storage	Inflow from DP	Restore DP output	Inflows from DP	158350	209790	1.0	0	One in one to five years	<12 hours loss of treated water production	4	2	8
Loss of Supply from Ghubrah DP	208644	158350	163650	19	0	0	One in one to five years	<12 hours loss of treated water production	4	2	8	Downstream storage	Inflow from DP	Restore DP output	Inflows from DP	158350	209790	1.0	0	One in one to five years	<12 hours loss of treated water production	4	2	8
Loss of Supply from Ghubrah DP	208644	158350	163650	19	0	153050	One in one to five years	12 – 48 hours loss of treated water production	4	16	64	Downstream storage	Inflow from DP	Restore DP output	Inflows from DP	158350	209790	1.0	0	One in one to five years	<12 hours loss of treated water production	4	2	8
Loss of Supply from Ghubrah DP	208644	158350	163650	19	153050	944801	One in one to five years	2 – 7 days loss of treated water production	4	16	64	Downstream storage	Inflow from DP	Restore DP output	Inflows from DP	158350	209790	1.0	735011	One in one to five years	2 – 7 days loss of treated water production	4	8	32
Loss of Supply from Ghubrah DP	208644	158350	163650	19	944801	>>944801	One in five to twenty years	>7 days loss of treated water production	3	16	48	Downstream storage	Inflow from DP	Restore DP output	Inflows from DP	158350	209790	1.0	>735011	*One in five to twenty years*	>7 days loss of treated water production	3	8	24

Table 6.11: Summary of Risks to Great Muscat Water Supply System

Hazard	Consequence	Before Control			After Control		
		L	C	Risk	L	C	Risk
Transmission Mains							
Burst in main from Barka PS to Seeb Res	Loss of supply to Seeb	4	16	64	4	8	32
Burst in main from Al Ghubrah to Qurm, Wattaya, Ruwi, Muscat, Mumtaz Res and Al Amirat PS (1000mm)	Loss of supply to much of eastern Greater Muscat	4	16	64	4	8	32
Burst in main from Al Ghubrah to Qurm, Wattaya, Ruwi, Muscat, Mumtaz Res and Al Amirat PS (600mm)	Loss of supply to part of eastern Greater Muscat	5	16	80	5	2	10
Burst in main from Al Ghubrah to Bausher Wilayat (Waver, Airport, Ghala, Bousher Res)	Loss of supply to part of eastern Greater Muscat	4	16	64	4	8	32
Pumping stations							
Pump failure - Barka to Seeb PS	Partial loss of supply to Seeb	4	16	64	4	4	16
Loss of power - Barka to Seeb PS	Loss of supply to Seeb	5	16	80	5	1	5
Failure of control systems - Barka to Seeb PS	Loss of supply to Seeb	4	8	32	4	2	8
Pump failure - Ghubrah PS	Partial loss of supply to Eastern Gt. Muscat	5	16	80	4	8	32
Loss of power - Ghubrah PS	Loss of supply to Eastern Gt Muscat	5	16	80	5	8	40
Failure of control systems - Ghubrah PS	Loss of supply to Eastern Gt Muscat	4	16	64	4	8	32
Loss of Supply from Desalination Plant							
Loss of Supply from Ghubrah DP	< 12 hours partial reduction in treated water production (>34% of design output)	4	2	8	4	2	8
Loss of Supply from Ghubrah DP	<12 hours loss of treated water production	4	2	8	4	2	8
Loss of Supply from Ghubrah DP	12 – 48 hours loss of treated water production	4	16	64	4	2	8
Loss of Supply from Ghubrah DP	2 – 7 days loss of treated water production	4	16	64	4	8	32
Loss of Supply from Ghubrah DP	>7 days loss of treated water production	3	16	48	3	8	24

6.3.2.2 Risk Tables for Dakhilya

The risks to Al Dakhilya water supply system are presented in Tables (6.12) - (6.14) and summarized in Table (6.15).

The risks for the other regional water supply systems were just determined without any further controls or suggested solutions and the results are included in Appendix (F).

Table 6.12: Risks to Transmission Mains of Al Dakhilya Water Supply System

Transmission Mains																								
Hazard	Diameter (mm)	Length (km)	Material	Expected nr failures/km/yr	Expected nr 1:x yr failure	Population	Likelihood	Consequence	L	C	Risk	Control Measure	Monitoring Procedures	Corrective Action (days)	Expected repair time (days)	Average daily flow 2010 (m^3)	Downstream storage (m3)	Emergency storage (days supply)	Loss of supply (m3)	Likelihood	Consequence	L	C	Risk
Burst Barka PS to MPS (Dakhliyah	1100	0.4	Mild Steel	0	189	278689	One in fifty to one hundred years	Loss of supply to Dakhliyah	1	16	16	Storage dwnstream. Repairs to be completed to target times	Burst records	Repair main/ replace main	3	21081	63816	2.7	6385	One in fifty to one hundred years	Loss of supply to Dakhliyah	1	8	8
Burst MPS Res to ch 17.8km	1100	17.9	Mild Steel	0	4	278689	One in one to five years	Loss of supply to Dakhliyah	4	16	64	Storage downstream. Repairs to be completed to target times	Burst records	Repair main/ replace main	3	21081	53616	2.2	16585	One in one to five years	Loss of supply to Dakhliyah	4	8	32
Burst ch 17.8km to BPS1 Res	1016	11.7	Mild Steel	0	3	278689	One in one to five years	Loss of supply to Dakhliyah	4	16	64	Storage downstream. Repairs to be completed to target times	Burst records	Repair main/ replace main	3	21081	53616	2.2	16585	One in one to five years	Loss of supply to Dakhliyah	4	8	32
Burst BPS1 Res to BPS2 Res	1016	21.4	Mild Steel	0	1	278689	One in one to five years	Loss of supply to Dakhliyah	4	16	64	Storage downstream. Repairs to be completed to target times	Burst records	Repair main/ replace main	3	21081	50944	2.1	19257	One in one to five years	Partial loss of supply to Dakhliyah	4	2	8
Burst BPS2 Res to Samail Res	1016	3.3	Mild Steel	0	1	254683	One in one to five years	Loss of supply to Samail	4	16	64	Storage downstream. Repairs to be completed to target times	Burst records	Repair main/ replace main	3	9535	50560	5	0	One in one to five years	Partial loss of supply to Samail	4	2	8
Burst BPS3 Res to Break Tank	900	6.9	Mild Steel	0	1	204430	One in one to five years	Loss of supply to Izki, Adam, Manah, Bahla, Al Hamra, Nizwa	4	16	64	Storage downstream. Repairs to be completed to target times	Burst records	Repair main/ replace main	2	5706	40461	6.8	0	One in one to five years	Partial loss of supply to Izki, Adam, Manah, Bahla, Al Hamra, Nizwa	4	2	8
Burst BPS3 Res to Break Tank	800	7	Mild Steel	0	1	204430	One in one to five years	Loss of supply to Izki, Adam, Manah, Bahla, Al Hamra, Nizwa	4	16	64	Storage downstream. Repairs to be completed to target times	Burst records	Repair main/ replace main	2	5706	40461	6.8	0	One in one to five years	Partial loss of supply to Izki, Adam, Manah, Bahla, Al Hamra, Nizwa	4	2	8
Burst Break Tank to ch48.89	900	19.5	Mild Steel	0	1	204430	More than one per year	Loss of supply to Izki, Adam, Manah, Bahla, Al Hamra, Nizwa	5	16	80	Storage downstream. Repairs to be completed to target times	Burst records	Repair main/ replace main	2	5706	40261	6.7	0	More than one per year	Partial loss of supply to Izki, Adam, Manah, Bahla, Al Hamra, Nizwa	5	2	10

Table 6.12 - Cont.: Risks to Transmission Mains of Al Dakhilya Water Supply System

Transmission Mains																								
Hazard	Diameter (mm)	Length (km)	Material	Expected nr failures/km/yr	Expected nr 1:x yr failures	Population	Likelihood	Consequence	L	C	Risk	Control Measure	Monitoring Procedures	Corrective Action (days)	Expected repair time (days)	Average daily flow 2010 (m^3)	Downstream storage (m3)	Emergency storage (days supply)	Loss of supply (m3)	Likelihood	Consequence	L	C	Risk
Burst ch 48.89 to Firq Res take-off	800	27	MILD STEEL	0	1	171133	More than one per year	Loss of supply to Izki, Adam, Manah, Bahla, Al Hamra, Nizwa	5	16	80	Storage downstream. Repairs to be completed to target times	Burst records	Repair main/ replace main	2	4397	40261	8.8	0	More than one per year	Partial loss of supply to Izki, Adam, Manah, Bahla, Al Hamra, Nizwa	5	2	10
Burst Firq Res to take off to Manah Res	700	1.4	MILD STEEL	0	1	171133	More than one per year	Loss of supply to Manah	5	16	80	Storage downstream. Repairs to be completed to target times	Burst records	Repair main/ replace main	2	4397	31461	6.8	0	More than one per year	Partial loss of supply to Manah	5	2	10
Burst Manah take off to Adam Res	600	61	DI	2	0	14419	More than one per year	Loss of supply to Adam	5	8	40	Storage downstream. Repairs to be completed to target times	Burst records	Repair main/ replace main	2	1222	5980	4.6	0	More than one per year	Partial loss of supply to Adam	5	2	10
Burst take-off to Manah Res to BPS4	700	9.7	MILD STEEL	0	1	144703	More than one per year	Loss of supply to Niza, Al Hamra, Bahla	5	16	80	Storage downstream. Repairs to be completed to target times	Burst records	Repair main/ replace main	2	12319	31031	2.2	0	More than one per year	Partial loss of supply to Niza, Al Hamra, and Bahla	5	2	10
Burst take-off to Manah Res to BPS4	600	2.4	DI	0	1	144703	More than one per year	Loss of supply to Niza, Al Hamra, Bahla	5	16	80	Storage downstream. Repairs to be completed to target times	Burst records	Repair main/ replace main	2	12319	31031	2.2	0	More than one per year	Partial loss of supply to Niza, Al Hamra, and Bahla	5	2	10
Burst to take-off to BPS5	600	27	DI	1	0	67416	More than one per year	Loss of supply to Al Hamra, Bahla	5	16	80	Storage downstream. Repairs to be completed to target times	Burst records	Repair main/ replace main	2 d	2637	9749	3.4	0	More than one per year	Partial loss of supply to Al Hamra, and Bahla	5	2	10
Burst from take-off to BPS5 to Bahla	500	10	DI	0	0	51758	More than one per year	Loss of supply to Bahla	5	16	80	Storage downstream. Repairs to be completed to target times	Burst records	Repair main/ replace main	2	2027	3160	1.2	1562	More than one per year	Partial loss of supply to Bahla	5	8	40
Burst BPS4 to Nizwa (Sypa Res)	300	1.9	DI	0	1	77287	More than one per year	Loss of supply to Nizwa	5	16	80	Storage downstream. Repairs to be completed to target times	Burst records	Repair main/ replace main	2	9682	15938	1.3	6620	More than one per year	Partial loss of supply to Nizwa	5	8	40

Table 6.13: Risks to Pumping Stations of Al Dakhilya Water Supply System

Pumping Stations																					
Hazard	Standby arrangement	Operational capacity (m^3/d)	Likelihood	Consequence	L	C	Risk	Control Measure	Monitoring Procedures	Corrective Action	Records	Average daily flow 2010 (m3)	Downstream storage (m3)	Expected maximum outage time (days)	Emergency storage (days supply)	Loss of supply (m3)	Likelihood	Consequence	L	C	Risk
Pump failure - MPS PS	2D+2S	49728	One in one to five years	loss of supply to Dakhliyah	4	16	64	Maintain standby, through implementation of an appropriate maintenance, repair and replacement policy	Pump fail alarm, condition monitoring	Pump replacement/rep air	Inspection Records	21081	63816	10.0	2.7	153954	One in fifty to one hundred years	loss of supply to Dakhliyah	1	16	16
Loss of power - MPS PS	None	-	More than one per year	Loss of supply to Dakhliyah	5	16	80	Downstream storage. Ensure repair of lost supply within 24 hours	Alarm	Repair of supplies to water facilties. These should have a high priority.	-	21081	63816	1.0	2.7	0	More than one per year	Partial loss of supply to Dakhliyah	5	2	10
Failure of control systems to MPS PS	None	-	One in one to five years	Loss of supply to Dakhliyah	4	16	64	Downstream storage. Alarms and manual override implemented within 12 hours.	Alarm/Manual checking	Repair or replace faulty supplies	-	21081	63816	1.0	2.7	0	One in one to five years	Loss of supply to Dakhliyah	4	2	8
Pump failure - BPS1	2D+2S	20160	One in one to five years	loss of supply to Dakhliyah	4	16	64	Maintain standby, through implementation of an appropriate maintenance, repair and replacement policy	Pump fail alarm, condition monitoring	Pump replacement/rep air	Inspection Records	21081	50944	10.0	2.1	166826	One in fifty to one hundred years	Partial loss of supply to Dakhliyah	1	1	1
Loss of power - BPS1	None	-	More than one per year	Loss of supply to Dakhliyah	5	16	80	Downstream storage. Ensure repair of lost supply within 24 hours	Alarm	Repair of supplies to water facilties. These should have a high priority.	-	21081	50944	1.0	2.1	0	One in five to twenty years	Partial loss of supply to Dakhliyah	3	1	3
Failure of control systems to BPS1 PS	None	-	One in one to five years	Loss of supply to Dakhliyah	4	16	64	Downstream storage. Alarms and manual override implemented within 12 hours.	Alarm/Manual checking	Repair or replace faulty supplies	-	21081	50944	1.0	2.1	0	One in five to twenty years	Partial loss of supply to Dakhliyah	3	1	3
Pump failure - BPS2	2D+2S	15792	One in one to five years	loss of supply to Dakhliyah	4	16	64	Maintain standby, through implementation of an appropriate maintenance, repair and replacement policy	Pump fail alarm, condition monitoring	Pump replacement/rep air	Inspection Records	9535	50560	10.0	5.0	47938	One in fifty to one hundred years	loss of supply to Dakhliyah	1	16	16
Loss of power - BPS2	None	-	More than one per year	Loss of supply to Dakhliyah	5	16	80	Downstream storage. Ensure repair of lost supply within 24 hours	Alarm	Repair of supplies to water facilties. These should have a high priority.	-	9535	50560	1.0	5.0	0	More than one per year	Partial loss of supply to Dakhliyah	5	2	10
Failure of control systems to BPS2 PS	None	-	One in one to five years	Loss of supply to Dakhliyah	4	16	64	Downstream storage. Alarms and manual override implemented within 12 hours.	Alarm/Manual checking	Repair or replace faulty supplies	-	9535	50560	1.0	5.0	0	One in one to five years	Partial loss of supply to Dakhliyah	4	2	8

Table 6.13 - Cont.: Risks to Pumping Stations of Al Dakhilya Water Supply System

Pumping Stations																					
Hazard	Standby arrangement	Operational capacity (m3/d)	Likelihood	Consequence	L	C	Risk	Control Measure	Monitoring Procedures	Corrective Action	Records	Average daily flow 2010 (m3)	Downstream storage (m3)	Expected maximum outage time (days)	Emergency storage (days supply)	Loss of supply (m3)	Likelihood	Consequence	L	C	Risk
Pump failure - BPS3	4D+1 S	83290	One in one to five years	Loss of supply to Dakhliyah	4	16	64	Maintain standby, through implementation n of an appropriate maintenance, repair and replacement policy	Pump fail alarm, condition monitoring	Pump replacement/rep air	Inspection Records	5706	40461	10.0	6.8	18480	One in five to twenty years	loss of supply to Dakhliyah	3	8	24
Loss of power - BPS3	None	-	More than one per year	Loss of supply to Dakhliyah	5	16	80	Downstream storage. Ensure repair of lost supply within 24 hours	Alarm	Repair of supplies to water facilties. These should have a high priority.	-	5706	40461	1.0	6.8	0	More than one per year	Partial loss of supply to Dakhliyah	5	2	10
Failure of control systems to BPS3 PS	None	-	One in one to five years	Loss of supply to Dakhliyah	4	16	64	Downstream storage. Alarms and manual override implemented within 12 hours.	Alarm/Manu al checking	Repair or replace faulty supplies	-	5706	40461	1.0	6.8	0	One in one to five years	Partial loss supply to Dakhliyah	4	2	8
Pump failure - BPS4	5D+1 S	43546	More than one per year	Loss of supply to Nizwa	5	16	80	Maintain standby, through implementation of an appropriate maintenance, repair and replacement policy	Pump fail alarm, condition monitoring	Pump replacement/rep air	Inspection Records	9682	15938	10.0	1.3	84074	One in five to twenty years	Loss of supply to Nizwa	3	8	24
Loss of power - BPS4	None	-	More than one per year	Loss of supply to Nizwa	5	16	80	Downstream storage. Ensure repair of lost supply within 24 hours	Alarm	Repair of supplies to water facilties. These should have a high priority.	-	9682	15938	1.0	1.3	0	More than one per year	Partial loss of supply to Nizwa	5	2	10
Failure of control systems to BPS4 PS	None	-	One in one to five years	Loss of supply to Nizwa	4	16	64	Downstream storage. Alarms and manual override implemented within 12 hours.	Alarm/Manu al checking	Repair or replace faulty supplies	-	9682	15938	1.0	1.3	0	One in one to five years	Partial loss of supply to Nizwa	4	2	8
Pump failure - BPS5	3D+1 S	9331	One in one to five years	loss of supply to Al Hamra	4	16	64	Maintain standby, through implementation n of an appropriate maintenance, repair and replacement policy	Pump fail alarm, condition monitoring	Pump replacement/rep air	Inspection Records	2758	1500	10.0	0.2	26994	One in twenty to fifty years	loss of supply to Al Hamra	2	16	32
Loss of power - BPS5	None	-	More than one per year	Loss of supply to Al Hamra	5	8	40	Downstream storage. Ensure repair of lost supply within 24 hours	Alarm	Repair of supplies to water facilties. These should have a high priority.	-	2758	1500	1.0	0.2	2169	More than one per year	Loss of supply to Al Hamra	5	4	20
Failure of control systems to BPS5 PS	None	-	One in one to five years	Loss of supply to Al Hamra	4	8	32	Downstream storage. Alarms and manual override implemented within 12 hours.	Alarm/Manu al checking	Repair or replace faulty supplies	-	2758	1500	1.0	0.2	2169	One in one to five years	Loss of supply to Al Hamra	4	4	16

Table 6.14: Risks to Al Dakhilya Water Supply System Due to Loss of Supply from Desalination Plant

Loss of Supply from Desalination Plant

Hazard	Operational capacity (m^3/d)	Flow to	Storage at desalination plant (m^3)	Storage (hours of supply capacity)	Potential loss of supply (m^3)		Likelihood	Consequence	L	C	Risk	Control Measure	Monitoring Procedures	Corrective Action	Records	Average daily flow 2010 (m^3)	Downstream storage (m^3)	Emergency storage (days' supply)	Loss of supply (m^3)	Likelihood	Consequence	L	C	Risk
		Regional System 2010 (m^3/d)			Min	Max																		
Loss of Supply from Barka DP	210000	21081	182400	21	0	0	One in one to five years	< 12 hours partial reduction in treated water production (>34% of design output)	4	2	8	Downstream storage	Inflow from DP	Restore DP output	Inflows from DP	21081	63816	2.7	0	One in one to five years	<12 hours loss of treated water production	4	2	8
Loss of Supply from Barka DP	210000	21081	182400	21	0	0	One in one to five years	<12 hours loss of treated water production	4	2	8	Downstream storage	Inflow from DP	Restore DP output	Inflows from DP	21081	63816	2.7	0	One in one to five years	<12 hours loss of treated water production	4	2	8
Loss of Supply from Barka DP	210000	21081	182400	21	0	23852	One in one to five years	12 – 48 hours loss of treated water production	4	16	64	Downstream storage	Inflow from DP	Restore DP output	Inflows from DP	21081	63816	2.7	0	One in one to five years	<12 hours loss of treated water production	4	2	8
Loss of Supply from Barka DP	210000	21081	182400	21	23852	129259	One in one to five years	2 – 7 days loss of treated water production	4	16	64	Downstream storage	Inflow from DP	Restore DP output	Inflows from DP	21081	63816	2.7	65443	One in one to five years	2 – 7 days loss of treated water production	4	8	32
Loss of Supply from Barka DP	210000	21081	182400	21	129258.6	>>129259	One in five to twenty years	>7 days loss of treated water production	4	16	64	Downstream storage	Inflow from DP	Restore DP output	Inflows from DP	21081	63816	2.7	>>65443	One in five to twenty years	>7 days loss of treated water production	3	8	24

Table 6.15: Summary of Risks to Al Dakhilya Water Supply System

Hazard	Consequence	Before Control			After Control		
		L	C	Risk	L	C	Risk
Transmission Mains							
Burst Barka PS to MPS (Dakhliyah	Loss of supply to Dakhliyah	1	16	16	1	8	8
Burst MPS Res to ch 17.8km	Loss of supply to Dakhliyah	4	16	64	4	8	32
Burst ch 17.8km to BPS1 Res	Loss of supply to Dakhliyah	4	16	64	4	8	32
Burst BPS1 Res to BPS2 Res	Loss of supply to Dakhliyah	4	16	64	4	2	8
Burst BPS2 Res to Samail Res	Loss of supply to Samail	4	16	64	4	2	8
Burst BPS3 Res to Break Tank	Loss of supply to Izki, Adam, Manah, Bahla, Al Hamra, Nizwa	4	16	64	4	2	8
Burst BPS3 Res to Break Tank	Loss of supply to Izki, Adam, Manah, Bahla, Al Hamra, Nizwa	4	16	64	4	2	8
Burst Break Tank to ch48.89	Loss of supply to Izki, Adam, Manah, Bahla, Al Hamra, Nizwa	5	16	80	5	2	10
Burst ch 48.89 to Firq Res take-off	Loss of supply to Izki, Adam, Manah, Bahla, Al Hamra, Nizwa	5	16	80	5	2	10
Burst Firq Res to take off to Manah Res	Loss of supply to Manah	5	16	80	5	2	10
Burst Manah take off to Adam Res	Loss of supply to Adam	5	8	40	5	2	10
Burst take-off to Manah Res to BPS4	Loss of supply to Niza, Al Hamra, Bahla	5	16	80	5	2	10
Burst take-off to Manah Res to BPS4	Loss of supply to Niza, Al Hamra, Bahla	5	16	80	5	2	10
Burst to take-off to BPS5	Loss of supply to Al Hamra, Bahla	5	16	80	5	2	10
Burst from take-off to BPS5 to Bahla	Loss of supply to Bahla	5	16	80	5	8	40
Burst BPS4 to Nizwa (Sypa Res)	Loss of supply to Nizwa	5	16	80	5	8	40

Table 6.15 - Cont.: Summary of Risks to Al Dakhilya Water Supply System

Hazard	Consequence	Before Control			After Control		
		L	C	Risk	L	C	Risk
Pumping stations							
Pump failure - MPS PS	loss of supply to Dakhliyah	4	16	64	1	16	16
Loss of power - MPS PS	Loss of supply to Dakhliyah	5	16	80	5	2	10
Failure of control systems to MPS PS	Loss of supply to Dakhliyah	4	16	64	4	2	8
Pump failure - BPS1	loss of supply to Dakhliyah	4	16	64	1	1	1
Loss of power - BPS1	Loss of supply to Dakhliyah	5	16	80	3	1	3
Failure of control systems to BPS1 PS	Loss of supply to Dakhliyah	4	16	64	3	1	3
Pump failure - BPS2	loss of supply to Dakhliyah	4	16	64	1	16	16
Loss of power - BPS2	Loss of supply to Dakhliyah	5	16	80	5	2	10
Failure of control systems to BPS2 PS	Loss of supply to Dakhliyah	4	16	64	4	2	8
Pump failure - BPS3	Loss of supply to Dakhliyah	4	16	64	3	8	24
Loss of power - BPS3	Loss of supply to Dakhliyah	5	16	80	5	2	10
Failure of control systems to BPS3 PS	Loss of supply to Dakhliyah	4	16	64	4	2	8
Pump failure - BPS4	Loss of supply to Nizwa	5	16	80	3	8	24
Loss of power - BPS4	Loss of supply to Nizwa	5	16	80	5	2	10
Failure of control systems to BPS4 PS	Loss of supply to Nizwa	4	16	64	4	2	8
Pump failure - BPS5	loss of supply to Al Hamra	4	16	64	2	16	32
Loss of power - BPS5	Loss of supply to Al Hamra	5	8	40	5	4	20
Failure of control systems to BPS5 PS	Loss of supply to Al Hamra	4	8	32	4	4	16
Loss of Supply from Desalination Plant							
Loss of Supply from Barka DP	< 12 hours partial reduction in treated water production (>34% of design output)	4	2	8	4	2	8
Loss of Supply from Barka DP	<12 hours loss of treated water production	4	2	8	4	2	8
Loss of Supply from Barka DP	12 – 48 hours loss of treated water production	4	16	64	4	2	8
Loss of Supply from Barka DP	2 – 7 days loss of treated water production	4	16	64	4	8	32
Loss of Supply from Barka DP	>7 days loss of treated water production	4	16	64	3	8	24

6.4 Interpretation of Risk Analysis Tables

6.4.1 Introduction

The severity of the risks depends first on the likely outcomes, should an event occur but also on the capacity of the mitigation measures to reduce the risks posed. Where the mitigation measures fail to reduce the risk from severe there is a serious residual problem that may require to be addressed using an alternative strategy. In this light, the following discussion interprets the outcomes of the risk tables. A risk score greater than 16 is considered severe and mitigation will required.

6.4.2 Al Ghubrah Desalination Plant and Transmission Mains

The values of risks presented in the tables show that even after control measures the risks values remain the same, which means some potential solution has to be found and adopted to mitigate the effect of specified risks. Table 6.16 shows a summary of significant hazards and the relative risks associated with Al Ghubrah Desalination Plant, and Greater Muscat and Al Dakhilya Water Supply Systems at different stages of the water supply system that makes it easy to identify which stage has the worse risk. The following conclusions can be drawn risk tables and Table 6.16:

Table 6.16: Number of Severe Risks to Water Supply Utilities

Utility	Stage	Number with Severe Risk	
		Before mitigation	After mitigation
Al Gubrah Desalination Plant	Sea Water quality	5	4
	Main Treatment process	9	1
	Side wide risk	3	0
Total		**17**	**5**
Great Muscat Water Supply System	Transmission Main	4	3
	Pumping Stations	6	3
	Loss of supply from Desalination Plant	3	2
Total		**13**	**8**
Al Dakhilya Water Supply System	Transmission Main	15	4
	Pumping Stations	18	5
	Loss of supply from Desalination Plant	3	2
Total		**36**	**11**

- The risk to the main treatment processes and side wide works of the Al Ghubrah plant can be controlled, but the risk due to feed water quality could remain high even after applying the mitigation measures, because Al Ghubrah is close to an international oil port and hence it is at significant risk from oil contamination. At the same time it is always exposed to harmful Algal Blooms.
- In total Al Ghubrah Desalination Plant is faced with 17 severe risks, however most are reduced after mitigation. The remaining 5 hazardous ratings are less serious indicating that even after the mitigation measures put in place they are still at high risk.
- As evident from table (6.16), risks associated with transmission mains and pumping stations are worse compared to those associated with the loss of supply from the desalination plant. The most severe risks are

those associated with pipe rather than with the pump failure since when pump failure is caused by lack of power supply, there can be another source of supply. However, where a single pipe fails it must either be repaired or replaced.

- At Muscat Water supply's transmission main there are 4 high hazard situations, the highest having a risk score of 80 and the remaining 3 having risk scores of 64. After mitigation measures the 3 remain with high risk although the score decreases to 32 and remain severe risks.
- The equivalent high risks associated with the Al Dakhilya Water Supply System are transmission main (15), pump failure (18) and loss of supply from the desalination plant (3). Some of these risks can be mitigated significantly such that they are no longer a threat to the water supply. However, after mitigation 4 high risk events at the transmission main, 5 resulting from pump failure, and 2 resulting from loss of supply from desalination plant remain resistant to the mitigation measures thus still posing high risk to the system.
- Irrespective of the corrective measures put in place, pump failure, loss of power, and failure of control systems at Ghubrah PS will still pose extreme risks that will almost certainly need urgent action.
- Lastly, there are low risks associated with loss of power at Barka to Seeb PS after corrective measure have been implemented.

6.5 System Resilience

6.5.1 Evaluation of Resilience

Based on the results of a risk assessment, the resilience of a system can be evaluated and the resultant risk score is translated to a level of resilience. A simple scoring method developed by Hughes and Healy (2014) outlined in section 2.3.6 was adapted for use in this study by replacing the risk descriptors by risk scores from the above analysis. The resulting translation procedure is given in Table (6.17), and generates a resilience score ranging from 4 (very high resilience) to 1 (low resilience).

Table 6.17: Translation of Risk Score to level of resilience

Risk Score	Level of Resilience (score)	Resilience Ranking
1-5	4	very high
6-15	3	High
16 -32	2	Moderate
> 32	1	Low

Adapted from Hughes and Healy (2014)

The resilience scores have been assigned as follow:

4 Very high resilience: The risks to the system are very low.

3 High resilience: The risks to the system are acceptable.

2 Moderate resilience: The risks to the system are major.

1 Low resilience: The risks to the system are significant or extreme.

The risks to each parts of the water supply systems were identified and the impact of each risk is assessed and assigned score from 1 to 80 depending on the level of risk as described in Table 3.5. For each risk the desalination plant and the transmission system were given a score based upon its level of resilience using figures given in Table (6.17), and as mentioned earlier, high score represents good resilience while low scores represent poor resilience. The total or overall resilience score for each part was produced by weighting these scores for the differing risks. The overall resilience scores were estimated before and after control (mitigation) measures. The levels of resilience for Al Ghubrah desalination plant are presented in Table (6.18). The Level of Resilience for Great Muscat and Al Dakhilya Water Supply Systems are illustrated in Table (6.19) and (6.20).

Table 6.18: The Level of Resilience for Al Ghubrah Desalination Plant

Item	Hazard	Hazardous Event	Before Control		After Control	
			Risk	Resilience Score	Risk	Resilience Score
Sea Water Quality						
Feed Water Quality	Loss of Production	Harmful Algal Blooms	48	1	24	2
	Loss of Production	Jellyfish	32	2	8	3
	Loss of Production	Accidental Oil Spills at Sea	48	1	24	2
	Loss of Production	Accidental Oil Spills at Sea	48	1	24	2
	Loss of Production	Accidental Oil Spills at Sea	12	3	12	3
	Loss of Production	Accidental Oil Spills at Sea	12	3	12	3
	Loss of Production	Accidental Oil Spills at Sea	8	3	8	3
	Loss of Production	Operational Oil Spills at Sea	12	3	12	3
	Loss of Production	Operational Oil Spills at Sea	12	3	12	3
	Loss of Production	Operational Oil Spills at Sea	12	3	12	3
	Loss of Production	Re-circulation causing increased salinity	48	1	32	2
	Loss of Production	Excessive seawater temperature	8	3	8	3
Overall Sea Water Quality Resilience Score			**2.3 (moderate)**		**2.7 (high)**	
Main Treatment Process						
MSF Units	Loss of Production	Structural Failure of Main Process Unit	8	3	8	3
	Loss of Production	Power Failure Multiple Units (steam/electricity)	8	3	8	3
	Loss of Production	Power Failure Single unit (steam/electricity)	5	4	5	4
	Loss of Production	Loss of Process Performance due to Scaling and Fouling	32	2	4	4
CO2 Plant	Loss of Production	Structural Failure	16	2	16	2
	Loss of Production	Mechanical and Electrical Failure	16	2	8	3
	Loss of Production	Process Performance Failure	16	2	4	4
Chlorine Dosing	Loss of Production	Structural Failure	32	2	32	2
	Loss of Production	Mechanical and Electrical Failure	32	2	16	3
	Process Performance Failure	Process Performance Failure	64	1	8	3

Table 6.18 - Cont.: The Level of Resilience for Al Ghubrah Desalination Plant

Item	Hazard	Hazardous Event	Before Control		After Control	
			Risk	Resilience Score	Risk	Resilience Score
Main Treatment Process						
Caustic Soda Dosing	Loss of Production	Structural Failure (leaks) of Tanks or Dosing Pipe work	16	2	8	3
	Process Performance Failure	Mechanical and Electrical Failure of Make Up Equipment and Dosing Pumps	32	2	16	2
	Loss of Production	Process Performance Failure (Incorrect Quantity Dosed)	32	2	16	2
Sodium Fluoride Dosing	Loss of Production	Structural Failure (leaks) of Tanks or Dosing Pipe work	16	2	8	3
	Loss of Production	Mechanical and Electrical Failure of Make Up Equipment and Dosing Pumps	32	2	16	3
	Process Performance Failure	Process Performance Failure (Incorrect Quantity Dosed)	32	2	16	2
Treated Water Sampling System	Loss of Production	Structural Failure of Sampling Pipe work	8	3	8	3
	Loss of Production	Mechanical and Electrical Failure	16	2	16	2
	Process Performance Failure	Process Performance Failure (Analyzers do not read correctly)	32	2	16	2
Overall main Treatment Process Resilience Score				**2.2 (moderate)**		**2.8 (high)**
Side Wide Risks						
Electrical Power Supply System	Loss of Treated Water Production	Loss of Power Supply (external)	20	2	8	3
Fire	Loss of Treated Water Production	Major Fire on Site	32	2	16	2
Flooding (origin land side)	Loss of Treated Water Production	Flooding of site and damage to key plant equipment	32	2	16	2
Gas Supply	Loss of Treated Water Production	Disruption of gas supply to IWPP	16	2	8	3
Loss of Labour	Loss of Treated Water Production	Loss of expatriate labour	16	2	8	3
Nuclear Threat	Loss of Treated Water Production	Nuclear contamination	16	2	16	2
Cyclones	Loss of Treated Water Production	Cyclone	8	3	8	3
Overall Side Wide Risks Resilience Score				**2.1 (moderate)**		**2.6 (high)**

Table 6.19: The Level of Resilience for Great Muscat Water Supply System

Hazard	Consequence	Before Control		After Control	
		Risk	Resilience Score	Risk	Resilience Score
Transmission Mains					
Burst in main from Barka PS to Seeb Res	Loss of supply to Seeb	64	1	32	2
Burst in main from Al Ghubrah to Qurm, Wattaya,	Loss of supply to much of eastern Greater Muscat	64	1	32	2
Ruwi, Muscat, Mumtaz Res and Al Amirat PS (1000mm)			1		2
Burst in main from Al Ghubrah to Qurm, Wattaya,	Loss of supply to part of eastern Greater Muscat	80	1	10	3
Ruwi, Muscat, Mumtaz Res and Al Amirat PS (600mm)			1		3
Burst in main from Al Ghubrah to Bausher Wilayat (Waver, Airport, Ghala, Bousher Res)	Loss of supply to part of eastern Greater Muscat	64	1	32	2
Overall Transmission Mains Resilience Score		**1.0 (low)**		**2.3 (moderate)**	
Pumping Stations					
Pump failure - Barka to Seeb PS	Partial loss of supply to Seeb	64	1	16	2
Loss of power - Barka to Seeb PS	Loss of supply to Seeb	80	1	5	4
Failure of control systems - Barka to Seeb PS	Loss of supply to Seeb	64	1	8	3
Pump failure - Ghubrah PS	Partial loss of supply to Eastern Gt. Muscat	80	1	32	2
Loss of power - Ghubrah PS	Loss of supply to Eastern Gt Muscat	80	1	40	1
Failure of control systems - Ghubrah PS	Loss of supply to Eastern Gt Muscat	64	1	32	2
Overall Pumping Stations Resilience Score		**1.0 (low)**		**2.3 (moderate)**	
Loss of Supply from Desalination Plant					
Loss of Supply from Ghubrah DP	< 12 hours partial reduction in treated water production (>34% of design output)	8	3	8	3
Loss of Supply from Ghubrah DP	<12 hours loss of treated water production	8	3	8	3
Loss of Supply from Ghubrah DP	12 – 48 hours loss of treated water production	64	1	8	3
Loss of Supply from Ghubrah DP	2 – 7 days loss of treated water production	64	1	32	2
Loss of Supply from Ghubrah DP	>7 days loss of treated water production	48	1	24	2
Overall Loss of Supply from Desalination Plant Resilience Score		**1.8 (moderate)**		**2.6 (high)**	

Table 6.20: The Level of Resilience for Al Dakhilya Water Supply System

Hazard	Consequence	Before Control		After Control	
		Risk	Resilience Score	Risk	Resilience Score
Transmission Mains					
Burst Barka PS to MPS (Dakhliyah	Loss of supply to Dakhliyah	16	2	8	3
Burst MPS Res to ch 17.8km	Loss of supply to Dakhliyah	64	1	32	2
Burst ch 17.8km to BPS1 Res	Loss of supply to Dakhliyah	64	1	32	2
Burst BPS1 Res to BPS2 Res	Loss of supply to Dakhliyah	64	1	8	3
Burst BPS2 Res to Samail Res	Loss of supply to Samail	64	1	8	3
Burst BPS3 Res to Break Tank	Loss of supply to Izki, Adam, Manah, Bahla, Al Hamra, Nizwa	64	1	8	3
Burst BPS3 Res to Break Tank	Loss of supply to Izki, Adam, Manah, Bahla, Al Hamra, Nizwa	64	1	8	3
Burst Break Tank to ch48.89	Loss of supply to Izki, Adam, Manah, Bahla, Al Hamra, Nizwa	80	1	10	3
Burst ch 48.89 to Firq Res take-off	Loss of supply to Izki, Adam, Manah, Bahla, Al Hamra, Nizwa	80	1	10	3
Burst Firq Res to take off to Manah Res	Loss of supply to Manah	80	1	10	3
Burst Manah take off to Adam Res	Loss of supply to Adam	80	1	10	3
Burst take-off to Manah Res to BPS4	Loss of supply to Niza, Al Hamra, Bahla	80	1	10	3
Burst take-off to Manah Res to BPS4	Loss of supply to Niza, Al Hamra, Bahla	80	1	10	3
Burst to take-off to BPS5	Loss of supply to Al Hamra, Bahla	80	1	10	3
Burst from take-off to BPS5 to Bahla	Loss of supply to Bahla	80	1	40	1
Burst BPS4 to Nizwa (Sypa Res)	Loss of supply to Nizwa	80	1	40	1
Overall Transmission Mains Resilience Score			**1.1 (low)**		**2.6 (high)**

Table 6.20 – Cont: The Level of Resilience for Al Dakhilya Water Supply System

Hazard	Consequence	Before Control		After Control	
		Risk	Resilience Score	Risk	Resilience Score
Pumping Stations					
Pump failure - MPS PS	loss of supply to Dakhliyah	64	1	16	2
Loss of power - MPS PS	Loss of supply to Dakhliyah	80	1	10	3
Failure of control systems to MPS PS	Loss of supply to Dakhliyah	64	1	8	3
Pump failure - BPS1	loss of supply to Dakhliyah	64	1	1	4
Loss of power - BPS1	Loss of supply to Dakhliyah	80	1	3	4
Failure of control systems to BPS1 PS	Loss of supply to Dakhliyah	64	1	3	4
Pump failure - BPS2	loss of supply to Dakhliyah	64	1	16	2
Loss of power - BPS2	Loss of supply to Dakhliyah	80	1	10	3
Failure of control systems to BPS2 PS	Loss of supply to Dakhliyah	64	1	8	3
Pump failure - BPS3	Loss of supply to Dakhliyah	64	1	24	2
Loss of power - BPS3	Loss of supply to Dakhliyah	80	1	10	3
Failure of control systems to BPS3 PS	Loss of supply to Dakhliyah	64	1	8	3
Pump failure - BPS4	Loss of supply to Nizwa	80	1	24	2
Loss of power - BPS4	Loss of supply to Nizwa	80	1	10	3
Failure of control systems to BPS4 PS	Loss of supply to Nizwa	64	1	8	3
Pump failure - BPS5	loss of supply to Al Hamra	64	1	32	2
Loss of power - BPS5	Loss of supply to Al Hamra	40	1	20	2
Failure of control systems to BPS5 PS	Loss of supply to Al Hamra	32	2	32	2
Overall Pumping Stations Resilience Score			**1.1 (low)**		**2.8 (high)**
Loss of Supply from Desalination Plant					
Loss of Supply from Barka DP	< 12 hours partial reduction in treated water production (>34% of design output)	8	3	8	3
Loss of Supply from Barka DP	<12 hours loss of treated water production	8	3	8	3
Loss of Supply from Barka DP	12 – 48 hours loss of treated water production	64	1	8	3
Loss of Supply from Barka DP	2 – 7 days loss of treated water production	64	1	32	2
Loss of Supply from Barka DP	>7 days loss of treated water production	64	1	24	2
Overall Loss of Supply from Desalination Plant Resilience Score			**1.8 (moderate)**		**2.6 (high)**

6.5.2 Interpretation of System Resilience

The average values of resilience scores for the main components of Al Gubrah desalinization plant, and Great Muscat and Al Dakhiliya water supply systems are presented in table 6.21.

Table 6.21: The Average Resilience Scores to Water Supply Utilities

Utility	Stage	The Average Resilience Score	
		Before Control	After Control
Al Gubrah Desalination Plant	Sea Water quality	2.3	2.7
	Main Treatment process	2.2	2.8
	Side wide risk	2.1	2.6
Great Muscat Water Supply System	Transmission Main	1.0	2.3
	Pumping Stations	1.0	2.3
	Loss of supply from Desalination Plant	1.8	2.6
Al Dakhilya Water Supply System	Transmission Main	1.1	2.6
	Pumping Stations	1.1	2.8
	Loss of supply from Desalination Plant	1.8	2.6

It seems that the existing resilience of desalination plants is higher than the water supply systems, and the resilience of the transmission mains and pumping station is very low. However, by associated mitigation measures the resilience of the water utilities could be reach to more than 70%.

The results of this analysis demonstrates that the overall resilience scores for Al Ghubrah desalination plant before mitigation measures is moderate (average = 2.2), and by applying mitigation measures the level of resilience is high (resilience score = 2.7). The current resilience of Great

Muscat and Al Dakhilya Water Supply Systems is low, but could be increased by adopting different control measures.

6.6 Limitations of the Risk and Resilience Assessments

The complexity of water supply systems mainly arises from the fact that the water supply system has a large number of components or subsystems (including sources, treatment, distribution, etc.). The water supply system has uncertain operation and environmental conditions. This complexity introduces uncertainties in any risk assessment. When dealing with risk assessment methods for drinking water systems it is difficult to include all aspects. This thesis has focused on risk assessments of the major parts of the water supply system – treatment and transmission mains and how the results from the risk assessment can be used in decision (Mays, 2004).

Uncertainty is a further important factor in complex risk assessments. In this research, difficulties were found (Ang and Tang, 1984) both in representing risk information accurately and describing the risk mechanisms. Risk ranking (e.g. Burgman, 2005; Cox, 2008) was particularly useful when comparing risks to pipelines and pumping stations but it has several limitations since, for example, uncertainties are typically not included and chains of events and interactions between events are not easily considered.

The work suffered from the two main uncertainties which are frequently mentioned by analysts (El-Baroudy and Simonovic, 2004); insufficient data for statistic inferences and vagueness and variations of risk information. However, the detail of the risk analyses carried out in the tables above and the inclusion in the analysis of two pipeline networks is considered to compensate for any lack of statistical evaluation. Natural hazards usually belong to the former, while human-caused failures are in the latter category.

Determination of resilience used an approach from the transportation sector (Hughes and Healy, 2014). These authors took a relatively simplistic approach which may limit its validity. Further, due to the time constraints in this research, further approaches to resilience determination, for example from other sectors, could not be considered. Additional work is desirable to consolidate the resilience scores found.

6.7 Summary

The anticipation and management of risk is one step towards increasing resilience of water supply systems subject to different hazards. The results of this research show that the water utilities in Oman are exposed to significant risks that will certainly need mitigation measures to improve system resilience ahead of any future event such a tropical storm. The output of the risk assessment has been used to link to the resilience assessment and translate to a level of resilience. The results reveal that the level of resilience is moderate and it could reach a high level by applying the solutions and mitigation measures suggested in this study.

Increasing the resilience of the system requires effective, flexible, agile and rapid implementation of response and recovery actions. The final element of this thesis in Chapter 7 is to develop the emergency response plan using the outcomes of the risk and resilience analysis.

Chapter 7 Emergency Response Plan

7.1 Introduction

This chapter explains the proposed strategy for the response to routine and non-routine water related emergencies in Oman. The results of the water audit and the risk assessments show that the water losses and risks to the water supply systems are high and the resilience, particularly of parts of the system is low. The research has shown that additional mitigation measures are urgently required as is an emergency response plan. The actions and strategies noted in the literature in order to enhance the resilience for water systems have been considered in this study to mitigate consequence of risks and enhance resilience of water systems in Oman (section 2.3). The additional mitigation and the emergency response plan outlined in this chapter have been developed by combining the research outputs of chapters 5 and 6 of this thesis with PAEW's existing plan in an effort to better meet PAEW's vision, mission and objectives.

Current emergency response practice in Oman is focused principally on resolving the cause of the problem as quickly as possible. No detailed risk analysis had been carried out to prioritize mitigation works, develop specific response protocols or protect vulnerable customers. This chapter addresses the proposed strategy for the response to routine emergencies such as leakage causing damage and non-routine emergencies such as tropical cyclones.

7.2 Events that Cause Emergency

7.2.1 Types of emergency

Various types of events may cause a state of emergency to arise in any given area. Whybark (2015) argues that they can be grouped as follows:

- Credible Threats - The major credible threats expected are acts of terrorism. As an example, bomb explosions can disrupt water systems hindering the supply and circulation of water.
- Major disasters - include destructive events such as hurricanes and tornadoes, storms and earthquakes which are beyond human understanding and can cause considerable damage to the water system.
- Catastrophic events - incidences that leave behind a considerable number of casualties. The damage and disruption may affect the population, infrastructure and even government functions and, in particular may cause considerable damage to the water system.

7.2.2 Level of emergency

All emergencies require some form of response. However, the major determinant which could trigger an emergency response is gauged against the potential damage that it may cause and loss of life (Manuel, 2014). Also of importance is the extent of area affected in relation to the population of that area. The level of emergency in response to water supply depends on the threat posed. Some problems such as blockages are not a major threat and not need a rapid response compared to threats from terrorists. Manuel (2014) considers a response is necessary in both cases but prompt and fast actions are required for major emergencies while a more planned set of actions are appropriate in others.

7.2.3 Response actions for specific events

In an emergency response plan, a category of response must be defined for each specific type of event. For example, in the outbreak of cholera in the Philippines discussed in Chapter 2 (Brower, Magno & Diling, 2014), the cause of the outbreak was initially wrongly attributed resulting in an inappropriate initial response. The response required was institutional where several agencies both private and governmental were tasked with formulating an institutionalizing the water supply and sanitation in the area resulting in a decrease and later disappearance of the disease.

7.2.4 Alternative water supplies

During emergencies, alternative measures must be put in place to ensure that customers still get access to water until the time when the system is restored. Most countries depend on the water supply system put in place by the government and rarely have alternative to water supply but many developing countries such as (Kihila, 2014) depend only on harvested rain water as an alternative to their supply. America and The Philippines have alternative water supply measures in place, which play a greater role in cases of emergencies.

In Oman, the emergency committee at the Public Authority of Electricity and Water (PAEW) has identified the most important mechanism to prepare for any threat that may occur. The committee is always briefed on the status of each district and the mechanisms in place in the event of a disaster affecting the Sultanate (Almarez, Peòaroya & Rubio, 2015). The alternative water sources include surface water reservoirs and well fields which are capable of supplying water during the period of the disaster.

7.2.5 Outage Scenarios

At times, there are cases when the water supply is cut either due to maintenance practices or emergencies causing an outage in that particular area. In this case the emergency response should be to ensure that the supply is back to normal as quickly as possible through an outage back up plan (Manuel, 2014).

7.2.6 Mitigation Measures

The analysis leading to the Emergency Response Plan (ERP) has clearly defined mitigation measures; first, an improved response to a crisis which ensures early restoration of service and a good relation with the customers, and secondly, the assessment helps avert harmful acts by the citizens to the existing water systems (Lum & Margesson, 2014). Thirdly, there should be proper site review to reduce the effect of the natural disaster. Finally, the response and recovery methods should be well defined such that restoration of services becomes the top most priority in cases of crisis.

7.3 Proposed Emergency Response Strategy

7.3.1 Introduction

Risk analysis and mitigation is always the first line of defense for a water utility as it is better to avoid an emergency than to deal with all its impacts, however, non-routine emergencies will always occur. The analysis of data and the results of risk assessments and water auditing show the need to develop an emergency response plan to rapidly resolve any possible water emergency event and ensure that customers affected by any emergency are kept informed and directed to alternative sources of potable water when required.

In this section of the study the researcher proposed a set of actions and procedures that PAEW are recommended to take into account when developing the detailed emergency response plan based on data obtained from the risk analysis process and from the water audit. The proposed actions comprehensively address the needs of PAEW at this stage of its development and are designed to support the business. Thus, the aims of the emergency response plan are to:

- Improve efficiency and standards of service
- Provide high quality water services throughout Oman
- Increase staff knowledge and skills
- Achieve international recognition as a high quality supplier of utility services.

PAEW shall continue to manage day to day operations but in other more serious non-routine situations or any other natural hazards as in the case of tropical cyclone (Ex. Gonu), PAEW should adopt an integrated approach to emergency management and:

- Support the NCCD of Oman in live emergencies and exercises and comply with its requirements;
- Train and equip regional PAEW staff to be as self-sufficient as possible in an emergency;
- Have national and regional Crisis Management Teams trained to deal instinctively with any type of emergency;
- Target the regional deployment of emergency response equipment and resources based on a robust risk assessment of common events in each region.

7.3.2 Key Change Components in the Proposed Strategy

The analyses in Chapters 6 and 7 show that a significant overhaul of parts of the PAEW supply system are required to produce a satisfactory level of resilience while others require minor improvement. The parts requiring overhaul are; Manuals, Plans and Procedures; Emergency Alternative Water Supplies, and; Planning and Preparedness. Some improvement is also desirable on the Emergency Response Organizational Structure. Consequently, the strategy requires that the response management should address the following issues:

1) **Manuals, Plans and Procedures:** New PAEW Emergency Response Manuals with the following contents should developed

- Management: This section shall contain emergency definition codes, and the structure, responsibilities and roles of the Crisis Management Team;
- Contact Information: for all staff, sites, suppliers and service providers, external agencies and priority customers;
- Regional Information: specific to the local region and shall contain a description and schematic plan of the region's operating regime;
- Regional Event Response Plans: specific to the local region containing plans for responding to known events that occur in the region;
- PAEW Emergency Procedures: the PAEW generic procedures for managing the overall system.

2) **Emergency Alternative Water Supplies:** This strategy presents the methods that form part of the Alternative Water Supplies Procedures and include, in addition to the delivery of water by tankers, making water available for Public Collection at selected Schools (NCCD Designated Refuges), Mosques and other locations using static water tanks and bottled water provided via prior agreement with a consortium of Omani bottled water producers.

3) **Planning and Preparedness:** PAEW shall formally organize and manage its interactions with government and non-government agencies, business and customers via memorandums of understanding and in the cases of essential suppliers and service provider's contracts which include rigid sections regarding emergency response times. In support of this a PAEW advisory service shall be offered to priority establishment to enable them to improve their resilience to water related emergencies.

4) **Emergency response organizational structure:**

- Create a PAEW emergency response working group: that agree common emergency terms and definitions, emergency level coding, minimum quantities emergency drinking water, emergency management document structure and hierarchy, crisis management structure for all levels, and set service performance targets.
- Create an executive steering group: A PAEW Executive Steering Group under the chairmanship of His Excellency the Chairman with the support of the three permanent general managers. The Executive Steering Group will consider the strategic, legal, financial and reputational impacts to PAEW of major emergencies.
- Create national and regional management teams: Crisis Management Teams shall have the responsibility for managing all the practical and tactical elements of non-routine emergencies.

7.4 Recommended Further Mitigation Measures

7.4.1 Urgent and Desirable Mitigation measures

The resilience analysis in Chapter 6 shows that average scores for many components within the water supply system are in the range 2.2 to 2.8 indicating that the system is only moderately resilient (Hughes and Healy, 2014) even after control measures have been implemented. Furthermore, some risk elements have scores less that 2 (low resilience) indicating that urgent mitigation measures are desirable. Tables 6.18 to 6.20 summarize the resilience scores and all scores of 2 or less are considered to require further mitigation measures in addition to the control measures identified in Chapter 6. The principles of these mitigation measures were discussed in workshop and this research has detailed (in Table 7.1) the reductions of risk by the mitigation measures.

From the research it was clear that significant risks might still be present and a further set of future enhancements would be desirable, these being listed in the right column of Table (7.1). Five different options of outages of the two desalination plants have been considered, to show the effectiveness of the mitigation measures for supplying parts of those areas which are normally supplied from the Al Ghubra and/or Barka desalination plants. The work undertaken in this research has highlighted the mitigation measures desirable but there is a clear case for further resilience evaluation and consideration in the future of alternative mitigation measures.

7.4.2 Outage Responses

The outage responses for different scenarios are presented in Table (7.1) and the alternative sources of water in case of emergency are based on the analysis of risk and resilience discussed in detail in Chapter 6. The risk data show that the loss of water supply from desalination plants (main sources) due to complete or partial disruption of the plants is one of the major problems that could occur as explained in the risk and resilience tables in chapter 6. The researcher proposed different mitigation measures in order to reduce risks and enhance resilience. Further advanced mitigation measures and emergency actions are also proposed in this chapter along with alternative sources of water as illustrated in Tables (7.1) and (7.2)

7.4.3 Additional Water Sources

Table (7.2) evaluates a range of further system enhancements in the form of procurement of additional water sources. Normally new sources are implemented because demand predictions show that existing supplies will be insufficient at some time horizon. However, in this case, where the system has low resilience, the author has concluded that additional sources are highly desirable to meet demands in emergencies improve resilience.

Table 7.1: Mitigation Measures to Address Outages of Al Ghubra and Barka Desalination Plants

Sr.	Scenario	Deficit (%)	Action /Response	Urgent Mitigation Measure	Advance Mitigation measure.
1	Complete disruption of Al Ghubra desalination plant	60	Full reliance on produced water from Barka desalination plant and from Wadi Aday and Al Khoud well fields.	• Monitoring and control of the marine environment to prevent potential threats leading to loss of production at the coastal desalination plants. • Online monitors for algae and hydrocarbons to ensure that seawater quality is continuously assessed. Procedures should be prepared for action when seawater quality changes. • Increase the storage capacity in distribution reservoir and within transmission system to cover the shortage during the interruption. • Speed up the repair time as quick as possible and insure an adequate spares are available on site. • Additional supply can be secured by the interconnection between Sohar and Barka. • Ensure the Wadi Adai and Al Khoud wellfield are well maintained and ready to put on line at any time. • Providing customers with is clear information with what is happening. Requesting to save water during the outage. • The resilience of the desalination plants can be improved, lowering the risk of long term loss of production, but not eliminated it.	• Measures to reduce the impact of marine environmental threats on the coastal desalination plants and/or the land based transmission systems. • Improvements to the existing desalination plants to increase reliability, this could include the provision of two intakes, additional screens, duplicate electrical power lines, additional chemical and gas storage etc. • Provide additional desalination plant capacity elsewhere along the coast, and enhance security of supply by increasing redundancy. • The potential for increasing the capacity of the existing wellfield. In addition develop inland wellfield in brackish groundwater area with desalination facility as emergency source • **Strategic grid,** A strategic grid linking all the water production (desalination) plants would provide flexibility and give resilience in the event of any failure at the desalination plants. This allows treated water to be moved easily around the transmission system allowing the majority of the population to be served from at least two desalination plants. Combined with sufficient local storage it provides the level of security essential to counter risks to the desalination plant production from the marine environment or catastrophic plant failure.
2	Partial disruption of Al Ghubra desalination plant	30-50	Full reliance on produced water from Al Ghubra and Barka desalination plants, and from Wadi Aday and Al Khoud well fields.		
3	Complete Disruption of Barka desalination Plant	25	Full reliance on produced water from Al Ghubra desalination plant and Wadi Aday and Al Khoud well fields.		
4	Partial Disruption of Barka desalination Plant	10-20	Full reliance on produced water from Al Ghubra and Barka desalination plants, and from Wadi Aday and Al Khoud well fields.		
5	Full uspension of Al Ghubra and Barka desalination plants	80-85	Full reliance on produced water from Al Khoudh and Wadi Aday well fields .		

Table 7.2 Recommendations for Providing Alternative Sources of Water to Improve System Resilience

Sr.	Alternative Source of water	Objective	Explanations
1.	**Wadi Dayqah Project** Construction of a new purification works, transmission mains and booster station to utilize water from the Wadi Dayqah.	• Provide additional water to meet the increasing demand in Muscat, • Provide an alternative source other than desalinated water for security of supply • Provide a cheaper and more sustainable alternative to desalinated water.	• This strategic project will be able to provide Muscat with sufficient quantity of water in case of outage of Al Ghubrah desalination plant.
2.	**Interconnections** Reinforcement the connection of the transmission Systems between Ghubrah to Barka Bark to Sohar.	Security of water supply by additional interconnections between transmission systems and reinforcement of existing connections.	• To transfer water to the area affected by water scarcity in exceptional events by securing water supply to different areas.
3.	**Construct Emergency Reservoirs** Water storage in different parts of the Governorate of Muscat. This will increase service reservoir capacity downstream.	This is probably the optimum solution for interruptions in the supply due to the outage of Al Ghubrah desalination plant or failure in the pumps station or transmission maim between Al Ghubrah and distribution reservoir.	• To secure water storage with sufficient capacity for 7 days of supply till year 2025, and for the predicted future water demand for 2 days until year 2035.
4.	**Wellfield** • Develop inland wellfield in brackish groundwater area with desalination. facility as emergency source. • Develop inland brackish groundwater area together with desalination plant facilities as emergency sources.	This will provide water for emergency source.	• The well fields are an important source of water supply, but as desalination capacity is extended the well fields will be retained as emergency backup during serious disruptions to the local water supply. • It may also be feasible to use the well fields as storage for desalinated water to provide extended supplies over a longer period. This would be a useful addition to the security of supply strategy.
5.	**Portable Water Treatment Plants** To take non-potable water from streams, gullies, and wells etc. and make it suitable for human consumption.	For alternative water supply during an emergency.	• The well fields will be retained as an emergency backup in the event of serious disruptions to the local water supply.

7.5 Emergency Response Plan to Address Outages

The findings of the water audit in chapter 5 and the risk analyses in chapter 6 have been used to develop an Emergency Response Plan (ERP) and the actions that should be taken in case of emergency outages of the Al Ghubra and Barka desalination plants. A range of failure modes of these plants would result in a range of deficits of supply, based on the output capacity of the plants. These deficits are factored into the analysis, as are the continued operation (or not) of the two wellfields. The outcomes of the analysis are presented in Tables (7.3) to (7.5).

The ERP sits alongside the mitigation measures since, should an emergency occur, such as the loss of a source, an immediate rearrangement of the water supplies to meet consumers' demand is required. Consequently, the ERP is not shown directly by the risk tables but, since risks are high, then the only response possible is to make the best use of the water available by alternative arrangements.

Table (7.3) evaluates the case where one or more prime source of water has suffered from an outage and emergency pumping responses are necessary. In each case water would be pumped in an emergency from parts of the system and/or from the two wellfields which will still have sufficient water, to those areas which are normally supplied from the Al Ghubra and/or Barka desalination plants.

Table 7.3: Pumping Response Strategies to Address Outages of Al Ghubra and Barka Desalination Plants

Sr.	Scenario	Deficit (%)	Available Resource	Pumping method
1	Complete disruption of Al Ghubra desalination plant	60	Full reliance on produced water from Barka desalination plant and well fields.	• Pumping the water from Barka Desalination plant and Al Khoudh well field to western side through Al Seeb, Rusail and Al Khoudh reservoirs. • Pumping the water to the eastern side from Wadi Aday well field to through Al Ghubra reservoirs • Supplying airport and Bousher reservoirs in the eastern side with water from Al Mawaleh pumping station.
2	Partial disruption of Al Ghubra desalination plant	30-50	Full reliance on limited produced water from Al Ghubra and Barka desalination plants, and from Wadi Aday and Al Khoud well fields.	• Pumping the water from Wadi Aday well field to Al Ghubra reservoirs to cover the deficit in water supply to the eastern side. • Cover the water supply to western side through Barka desalination plant.
3	Complete Disruption of Barka desalination Plant	25	Full reliance on produced water from Al Ghubra desalination plant and Wadi Aday and Al Khoud well fields.	• The water will pumped to the western side from Al Ghubra desalination plant and Al Khoudh well field. • The eastern side will be supplied with water from Al Ghubra desalination plant and Wadi Aday well field.
4	Partial Disruption of Barka desalination Plant	10-20	Full reliance on produced water from Al Ghubra and Barka desalination plants, and from Wadi Aday and Al Khoud well fields.	• The water will be pumped from Al Khoud well field and partially from Al Ghubra desalination plant to western side. • The water supply to eastern side will be covered by Al Ghubra desalination plant and Wadi Aday well field.
5	Full suspension of Al Ghubra and Barka desalination plants	80-85	Full reliance on produced water from well fields in Wadi Aday and Al Khoudh	• The water will be pumped to the western side from Al Khoudh well field. • The water will be pumped to the eastern side from Wadi Aday well field.

Table 7.4: Responses to Failures within the Transmission Systems

Sr.	Hazard	Corrective measure	Mitigation Measures
1	Burst of mains.	Increase the volume of downstream storage. Repairs to be completed to the target times.	• Interlink system, this will be appropriate where systems are close together. • Increase the downstream storage, In most systems there is already a significant volume of storage and in many cases only a small additional volume may be required. • Local storage within the transmission system, Treated water storage within the transmission system allows customers to receive a guaranteed water supply independent of any interruptions at the desalination plants. It therefore provides a resilient solution for short term interruptions. • Provide alternative source of supply, This is more likely to be economic if prolonged outages are foreseen. It should be possible to keep existing wellfields on standby at low cost. In addition to that tinkering should developed. • Reliance on storage in the system, an appropriate measure in conjunction with keeping spare pumps and motors in store as replacement. One more spare units is recommended where an existing pump station has no space for additional pumps. • Minimize times to identify and rectify failures: As with pipeline failures, it is necessary to be realistic about achievable repair time, to ensure that action can be taken as quickly as possible to repair faults and restore supplies. • Standby generators, at the present time most pumping stations do not have standby generators. This should be considered if the power outages may be expected to exceed the length of time covered by downstream storage in the system.
2	Pumps failure; • Breakdowns of pump and motor. • loss of incoming supply. • failure of control system.	Maintain standby, through implementation of an appropriate maintenance, repair and replacement policy.	
3	Loss of power.	Downstream storage. Ensure repair of lost supply within 24 hours.	
4	Service reservoirs.	Downstream storage. Alarms and manual override implemented within 12 hours.	

Table 7.5: Intermittent Supply Strategies in Response to three Emergency Outage Scenarios.

Sr.	Scenario	Water availability	Periods	Remarks
1	Full or partial suspension of the Ghubra purification station.	20 million gallons/day from Barka DP, 10 million gallons/day from AL Khoudh and Wadi Adai wells field and 12 million gallon/day from Sohar DP.	**Al Seeb.** FS-2, FS-4 and FQ15 Continues supply. FS-1, from day 1 to day 2 (7am-7aam). FS-3, from day 4 to day 5 (7am – 7am). FS-16, from day 2 to day 3 (7am-7am). FS11, from day 6 to day 8 (7am-7am). 4 TFS are available to server others by tankers. **Bausher.** FQ-1, FQ-5 and FQ-6 continue supply. FQ-2, from day 1 to day 2 (7am-7am) FQ-4, from day 5 to day 6 (7am-7am). FQ-7 and FQ-11 Continues supply. FQ-8 from day 2 to day 3 (7am-7am). FQ-9 from day 6 to day 7 (7am-7am). FQ-13, FW-1 and FW-4 Continues supply. FQ-1, from day 7 to day 5 (7am-7am). FQ-19 from day 7 to day 8 (7am-7am). FQ-10, FQ-13,FQ16FQ-17 and FW-3 Continues supply. FQ-14, from day 3 to day 4 (7am-7am). FQ-15, from day 7 to day 8 (7am to 7am). 1 TFS is available to server others by tankers. **Muttrah** FR-8, FR-9, FM-1 and FM-4 Continues supply. FR-10 from day 2 to day 4 (7am-7am). FR-12, FR-11 from day 4 to day 5 (7am-7am). FR-1, FR-2, FR-5, FR-6, CBD and FM-3 Continues supply. FR-3, from day 2 to day 4 (7am to 7am). FR-4, from day 5 to day 7 (7am-7am). FR-13, FR-14, FM-7, FW-2 and FW-5 Continues supply. FM-5 from day 3 to day 4 (7am-7am). FM-6 from day 7 to day 7 (7am-7am). 1 TFS is available to server others by tankers.	All hospitals, police station and school well getting continues supply.
2	Full or partial suspension of Barka purification station.	42 million gallons /day from Ghubra DP, 10 million gallons /day from Al Khoudh and Wadi Adai well field and 12 million gallon/day from Sohar DP		
3	Full suspension of the Ghubra and Barka purification stations.	12 million gallons/day from sohar DP and 10 million gallons/day from AL Khoudh and Wadi Adai wells field.		

It will be noted that the system has particularly low resilience to bursts (see for example Table (6.20)). Table (7.4) considers further scenarios where components of the transmission system have failed but the sources are still operational. Thus, a range of emergency responses to transmission system failures within Muscat and Al Dakhliya are presented in this table.

A further category of response to an emergency outage, when one or more of the sources fail to deliver the quantity of water required, is to supply consumers intermittently on a rota basis and this category of response is outlined in Table (7.5). It will be noted that the same failure modes are considered in all of the analyses.

7.6 Conclusion

This chapter has discussed the proposed Emergency Response Plan (ERP) to both routine and non-routine water related emergencies. In addition to the ERP a number of additional mitigation measures were evaluated. These have the effect of improving resilience and are recommended to be implemented before the ERP is finalized. The responses have been developed directly from the data and results of the water audit and risk analyses of the water supply systems in Oman. The chapter has also outlined the strategically important emergency scenarios which cause outages of available water sources and transmission systems, and the emergency response actions that have to be undertaken. The main conclusions drawn from this work and from chapters 5 and 6 are discussed in chapter 8.

Chapter 8 Discussion and Conclusions

8.1 Introduction

This research analyzed the stress factors encountered when operating a water network in an arid country with Oman taken as a case study. Two particular stress factors were investigated, namely non-revenue water, and as an example of an extreme natural event, a tropical cyclone, the analysis being focused on the improvement of the resilience of water systems to manmade and natural hazards. The impact of tropical cyclone Gonu was highlighted in chapter four and the problem of non-revenue water in chapter five. In chapter six, the author analyzed risks on water desalination plants and supply systems to improve the resilience of the water systems and in chapter seven, a strategy for the response to routine and non-routine water-related emergencies is presented.

8.2 Non Revenue Water

The principal strategy for management of NRW was to use the AWWA water audit method. The AWWA software is the best available solution to water supply and sanitation (Landis, 2015), was found to be easy to apply in Oman and is widely used, particularly in the United States (Alliance for Water Efficiency, 2016). However, the main benefit of using the software was that the researcher was forced to look for data that would not otherwise be held or readily available by PAEW. The software also allowed a critical evaluation to be made of operational practices. For example, understanding how to improve repair response time, investigate meter accuracy and increase management awareness were all improved through the use of the software.

The AWWA Water Audit Method features rational terms and definitions and several strong performance indicators (Kunkel, G. 2006) which were valuable to the research. These indicators are more consistent and reliable than the traditional unaccounted-for water percentage. Since all water supplied to a distribution system should be consumed by valid users or wasted through loss, the software further enabled the identification of apparent losses which in practice in Oman arise mainly from commercial bad practice.

The audit results indicate that the percentage of NRW in Oman is more than 35% but this compares favorably with other Gulf countries where the values are as high as 40% for Bahrain, 35% in Saudi Arabia, and 30% in the United Arab Emirates (Zyadin, 2013).

The study explored the perceptions of PAEW staff about the adoption of water-loss management procedures and identified organizational characteristics that influence management's decisions. The study also revealed that the inaccuracies in billing volumes and the method of estimating consumption through faulty meters had the most significant impacts on water losses. The study found that there were insufficient qualified staff available to carry out leak detection activities and they lack appropriate technologies. It was also clear that improved maintenance regimes would achieve better network performance by decreasing water losses.

8.3 Water System Risks

This study developed a comprehensive risk assessment and analysis for water utilities applicable in arid countries that identifies the various risks posed by both natural and manmade disasters and puts forward practical risk management strategies to mitigate these risks.

The research has contributed to understanding the risks to desalination plants and this is particularly relevant and transferrable since all gulf countries rely on desalting seawater. It was found that the risks to the main treatment processes (Table 6.4) can be controlled but the risk due to feed water quality might remain high even after implementing mitigation measures because (in the case of Muscat) the intake is close to an international oil port with a significant risk of oil contamination. It is also always exposed to harmful algal blooms. In total the Al Ghubrah Desalination Plant is faced with 17 severe risks but most are reduced after control measures are implemented. The remaining 5 hazardous ratings pose risks indicating that even after the mitigation measures are put in place they are still at high risk. This compares well with data from the United Arab Emirates (Walid Elshorbagy, Abu-Bakr Elhakeem (2007).

The risks associated with the transmission mains and pumping stations (Tables 6.11 and 6.15) are worse compared to those associated with the loss of supply from the desalination plant. The analysis showed that the most severe risks are those associated with pipe rather than pump failure since when pump failure is caused by lack of power supply, there can be another source of supply. However, where a single pipe fails it must either be repaired or replaced. This is in line with international experience (Alliance for Water Efficiency, 2016).

8.4 Resilience of the water systems

Chapter 6 of this thesis presents nine tables of detailed determination of risks to the water systems in Oman, work which is new to Arab countries. These tables, together with three summary tables are in themselves an advancement of knowledge since no other such detailed evaluations are available. Furthermore, the thesis proposes a method of translating the detailed risk evaluations into resilience scores using a methodology used in transportation networks. The average resilience scores are given in table 8.1 (replicated from Table 6.2.1).

The research has shown that the resilience of the desalination plants is currently higher than the water supply systems, and the resilience of the transmission mains and pumping station is very low. By implementing mitigation measures the resilience of the water utilities could reach 70%

compared to theoretical approaches to evaluating water network resilience which produce scores of greater than 60% (Dziedzic and Karney, 2014).

Table 8.1: The Average Resilience Scores to Water Supply Utilities

Utility	Stage	The Average Resilience Score	
		Before Control	After Control
Al Gubrah Desalination Plant	Sea Water quality	2.3	2.7
	Main Treatment process	2.2	2.8
	Side wide risk	2.1	2.6
Great Muscat Water Supply System	Transmission Main	1.0	2.3
	Pumping Stations	1.0	2.3
	Loss of supply from Desalination Plant	1.8	2.6
Al Dakhilya Water Supply System	Transmission Main	1.1	2.6
	Pumping Stations	1.1	2.8
	Loss of supply from Desalination Plant	1.8	2.6

8.5 Emergency Response Plan

The proposed Emergency Response Plan (ERP) to both routine and non-routine water related emergencies has been disused. In addition to the ERP a number of additional mitigation measures were evaluated. It was found that these have the effect of improving resilience and are recommended to be implemented at a national level (by NCCD) before the ERP is finalized. The responses were developed directly from the data and results of the water audit and risk analyses of the water supply systems. Furthermore, the emergency response actions that have to be undertaken were developed from the outline of the strategically important emergency scenarios which cause outages of available water sources. The proposed ERP has been built on the experiences of other countries and is considered to be well ahead of international practice (Whybark, 2015, Lum and Margesson 2014, McEntire, 2014).

The research has shown that the system is only moderately resilient (Hughes and Healy, 2014) even after control measures have been evaluated and implemented. Furthermore, some risk elements (with all scores of 2 or less) have very low resilience indicating that urgent mitigation measures are desirable in addition to the control measures identified. The workshop was found to be a particularly valuable tool for identifying risks and mitigation approaches and this research has detailed (in Table 7.1) the reductions of risk by the mitigation measures. The techniques of the workshop are considered to be most appropriate for use in other Gulf countries.

Five different options of outages of the two desalination plants were considered but the research shows that there is a clear case for further resilience evaluation and consideration in future, of alternative mitigation measures, a message which could also be usefully learned in other arid countries. Normally new sources are implemented because demand predictions show that existing supplies will be insufficient at some time horizon. However, in this case, where the system has low resilience, the author has concluded that additional sources are highly desirable to meet demands in emergencies and improve resilience. It should be noted that implementation of this conclusion will take time because of the investment required.

8.6 Conclusions

The conclusions have been drawn to address how this study addressed and covered the five research objectives. The main conclusions drawn from the present study are:

1) The financial impact posed by Non-Revenue Water (NRW) was found to be 32% of the total revenue budget. This is high in comparison with international norms (WHO, 2011). Six potential methods of improvement were identified which should be capable of reducing the impact by 90%.

2) The risks to the Omani water network associated with natural and manmade hazards were identified through a workshop. The detailed risk scoring and ranking together with the identification of the security of supplies and communication of the risk assessment process has contributed to an advancement of knowledge which can be applied to water networks in the Middle East and other arid countries.

3) The results emphasize that exceptional events can have a severe impact on water system management. This type of risk is difficult to recognize in advance and, if predicted, the actual risk associated with every exceptional event is very difficult to assess.

4) The study concluded that resilience of parts of the water system in Oman is low and mitigation measures are certainly needed. The suggested solutions will help in anticipating and managing risk and improving the resilience of the water supply systems in the face of different hazards.

5) The study developed an emergency response strategy suitable for available resources and the water systems in place. This strategy enhances the existing approach used by the water undertaker (PAEW) and describes the actions to be undertaken in emergencies. The study concluded that the proposed outage scenarios will certainly help in reducing risk and enhance the resilience of water systems in Oman.

8.7 Prospective Research

In this research, difficulties were found (Ang and Tang, 1984) both in representing risk information accurately and describing the risk mechanisms. Risk ranking (e.g. Burgman, 2005; Cox, 2008) was particularly useful when comparing risks to pipelines and pumping stations. The work suffered from the two main uncertainties which are frequently mentioned by analysts (El-Baroudy and Simonovic, 2004); insufficient data for statistic inferences and vagueness and variations of risk information. However, the detail of the risk analyses carried out in the tables above and the inclusion in the analysis of two pipeline networks is considered to compensate for any lack of statistical evaluation.

The approach used to determine resilience (Hughes and Healy, 2014) is relatively simplistic which may limit its validity and additional research is recommended to consolidate the resilience approach. This might be undertaken in collaboration with water utilities in other Gulf countries.

A formal process for risk management should be established to enable continuing on-going risk assessments to add detail to the present study, respond to unforeseen risks and hazards that arise, and develop capacity within PAEW for risk management and planning.

The strategy developed in this study can be implemented in a country similar to Oman that may have risks from exceptional events and experiencing NRW. Other developing and arid countries may also experience such risks but with different magnitude and the risk evaluation tables could provide a useful format for this further work.

Since all Gulf countries depend entirely on desalinated sea water for potable supplies, and since well fields should only be used during emergencies and considered as strategic reserves, further marine studies to identify and evaluate risks of sea water contamination are highly desirable. Of particular value would be marine water quality models.

Finally, this research was prompted by the near catastrophe caused by the tropical cyclone Gonu. It is self-evident that an increased understanding of the origin and tracks of future cyclones would be highly desirable, particularly in the face of climate change. This would must be conducted at a regional scale.

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Appendix- A

Security of Supply Risk Workshop

A -1 Programme and attendee list

Title: Security of Supply Risk Workshop	
Follow-up on: workshop conducted by Mott MacDonald on 8 Sep. 2009	
Location and Date: PAEW Main Office, Muscat, 17 June 2013	
Scope of the Workshop: - *Identify security of supply risk.* - *Communicate the risk assessment process.* - *Share information on risks.*	
Sponsor and Organizer: Public Authority for Electricity and Water (PAEW)	
Organizing Committee Members: - *Kassim Al Jabri, Senior Manager for Project Design - Chairperson* - *Majed Abusharkh, Water Network Design Expert* - *Ibrahem Osman, Senior Desalination Plant engineer* - *Ziad Al ASwad, Senior Design Engineer*	
Workshop Agenda:	
09:00 - 09:30	Opening of the workshop.
09:30 - 10:00	Introduction and purpose of the workshop.
10:00 - 11:00	Main outcome of the previous workshop.
11:00 - 11:30	Coffee break.
11:30 - 01:00	Treatment (desalination) & land based transmission risks.
01:00 - 02:00	Lunch.
02:00 - 02:30	Risk matrix review and discussion on likelihood and consequence tables.
02:30 - 03:00	Risk table review and comments on potential mitigation measures to reduce the risk.
03:00 - 03:30	Summary of the workshop.
03:30 - 04:00	Closing session

Attendees:

Name	Position	Organization
Ahmed Al Abri	Project Manager	PAEW
Ahmed Taleb	Control Engineer	PAEW
Ali Al Bulashey	Operation manager.	Al Gubrah desalination plant.
Humaid Al-Khusaibi	Head of Microbiology	PAEW
Ibrahem Osman	Senior Desalination Plant Eng.	PAEW
Kassim Al Jabri	Senior Manager for Project Design	PAEW
Majed Abusharkh	Water Network Design Expert	PAEW
Mohed AlKalbani	Project Manager	PAEW
Padmasiri Dissanayake	Senior Water specialist	PAEW
Sulaiman Al-Safy	Head of section	Previously with Al Guhbaria desalination plantae, now with PAEW.
Sharifa Al-Mazroui	Head of Chemistry	PAEW
Ziad Al Aswad	Senior Design Engineer	PAEW

A - 2 Methodology – work groups

The attendees were divided into two working group based on their specialty and experience, see table (A1.&A2.). The first group was assigned to the desalination plant, while the second one was assigned to the transmission pipe lines. For further details about the methodology used in the workshop refer to chapter 3section 3.3.4.

Table A1. Group one for land based transmission risks.

Name	***Position***	***Organization***
Ahmed Al Abri	Project Manager	PAEW
Ziad Al Aswad	Senior Design Engineer	PAEW
Padmasiri Dissanayake	Senior Water specialist	PAEW
Sharifa Al-Mazroui	Head of section	PAEW
Kassim Al Jabri	Senior Manager for Project Design	PAEW
Majed Abusharkh	Water Network Design Expert	PAEW

Table A2. Group two for Treatment (desalination).

Name	***Position***	***Organization***
Mohed AlKalbani	Project Manager	PAEW
Ahmed Taleb	Control Engineer	PAEW
Ali Al Bulashey	Operation manager.	Al Ghprah
Humaid Al-Khusaibi	Head of Microbiology	PAEW
Ibrahem Osman	Senior Desalination Plant Eng.	PAEW
Sulaiman Al-Safy	Head of section	PAEW

A - 3 Output from workshop

The risks identified by the two working group are given in tables A3, A4, A5 and A6.

Table A3. Desalination plant – key risk identified in the workshop.

Hazard	Cause
Harmful algae blooms.	• Produce toxins which considered risk to human health. • Increase suspended organic matters and blocks intake membranes and filters. • Unpleasant odor
Jellyfish blooms.	• Clog and damage intake screen and restrict intake. • Block seawater cooling intakes.
Accidental oil spills at sea.	• Contamination of the intake. • Making the product water non potable. • Unpleasant odor.
Failure of the intake system.	• Total shutdown of the plant
Mechanical or electrical failure.	• Failure of both duty and standby units • Failure of Membranes • Failure of Control System. • Structural failure of MSF units. • Chemical mixing and dosing equipment. Chemical Spills

Table A4. Transmission pipelines (mains) – key risks identified in the workshop.

Hazard	Cause
Burst in mains	- Ageing/deterioration of pipes. - Corrosion. - Lack of proper maintenance. - Deterioration due to temperature change. - Poor quality/material of pipeline. - External sabotage/vandalism of pipelines. - Operational issues – valve closures leading to surge. - Growth of iron in mains resulting in internal pitting. - Failure to ensure maintenance of air valves, failure in joints and fittings. - Natural disasters; e.g. flooding. - General losses and leakage in mains leading to bursts.
Contamination of mains	- Inadequate chlorination of mains. - Contamination from sewage. - Bacterial growth in mains.

Table A5. Pumping stations – key risks identified in the workshop.

Hazard	Cause
Pump failure	- Interlock failure as a result of over running of pumps. - Mechanical failure; e.g. damage to impellor (split casing pumps). - Cavitation. - Flooding of pump stations. - Non availability of vendors and hence long response times to fix pumps. - Non availability of spares. - Pumps over run when used daily.
Loss of power	- Power failure. - Low voltage problems.
Failure of control system	- Failure of starters, motors. - Operational errors. - Remote monitoring failure

Table A6. Reservoirs – key risks identified in the workshop.

Hazard	Cause
Pollution	- External pollution as a result of open covers/cracked vents due to birds/ reptiles falling in. - Algal growth leading to stagnant water. - Failure of online chemical dosing. - Lack of proper monitoring leading to bacterial growth. - Fouling due to sedimentation. - External threats – deliberate polluting. - Dead pockets in reservoirs that change its course over time.
Structural	- Improper waterproofing. - Failure due to incorrect location of reservoirs resulting from wadi flows that change its course time.
Operational	- Incorrect adherence to operational management of reservoir storage resulting in lack of storage available in reservoirs. - Over reliance on well water that when outages occur in the well fields there is an increase in demand on reservoirs that result in its drawdown.

A - 4 General comments of the workshop.

Following identification of key risk by the two groups in Table A1- A4, a discussion of the general comments that were made during the workshop is given in Table A5. Those comments were further validated by reviewing the daily and monthly reports of the desalination plant.

Table A7. General comments raised during the workshop discussion.

#	Comment
1	Difficulty in obtaining reliable data to make informed decisions.
2	Due to the delay in commissioning of projects and lack of co-ordination between production and supply; there is a delay water delivery to costomers.
3	Lack of operation and maintenance contractual requirements.
4	Lack of proper maintenance of assets.
5	There is a risk of over reliability on control systems that may yield incorrect results leading to failure of control systems.
6	Well-fields only to be used in the event of an emergency and not under normal operating conditions.
7	The participants strongly agree on the need for risk matrix to evaluate the risk potential.
8	High risk levels should have minimum mitigation measures that have to be undertaken to minimize the effect and consequences of risks.

A – 5 Risk matrices

A risk guidance has been developed following consultation with risk experts from different sections. It is supported by background guidance along with the findings from workshop and previous consultations for PAEW. Consequence and Likelihood Categories to Generate Risk Scores are given Table A8.

Table A8. Consequence and likelihood categories and risk scores generated during the Security of Supply Risk Workshop.

Likelihood	Consequences					
	Severity	A	B	C	D	E
Level	Score	(1)	(2)	(4)	(8)	(16)
1	(1)	1	2	4	8	16
2	(2)	2	4	8	16	32
3	(3)	3	6	12	24	48
4	(4)	4	8	16	32	64
5	(5)	5	10	20	40	80
Risk Score		< 6		6-16		> 16
Colour		Green		Amber		Red
Risk Rating		Minor		Major		Significant

Green scores: < 6 represent minor risks that may not need any mitigation measures.
Amber scores: 6 to 16 represent major risks that may need mitigation measures.
Red scores: > 16 represent significant risks that certainly need mitigation measures.

The workshop also addressed the frequency of risks using a scale of 1–5 and the result is given in Table A9.

Table A9. Periods and the scores of likelihood.

Level	Description	Score
1	One in 50 to 100 years.	1
2	One in 20 to 50 years.	2
3	One in 5 to 20 years.	3
4	One in 1 to 5 years.	4
5	More than one per year.	5

The identified hazards is assessed and agreed on during the workshop in order to determine the consequence score.

The consequence of the severity of hazards of different durations is made available from the following sources:

- Annual reports,
- Action Plan for Sudden Ingress of Jellyfish.
- Emergency Plan 2 - Black Out.
- Emergency Plan 3 - Oil Contamination.
- Operation Incident Report.
- Process Description.
- Intake Documentation.
- Technical Data Sheet - Trichlorisocyanuric Acid
- Operation & Maintenance Report.

The score of the consequences for desalination plant and transmission main are illustrated in Table A10 and A11

Table A10. Severity level and consequences of durations of outages of the desalination plants.

Severity level	Consequence	Score
A	< 12 hours partial reduction in treated water production (>34% of design output).	1
B	<12 hours loss of treated water production.	2
C	12 – 48 hours loss of treated water Production.	4
D	One sites affected for > 4 days. 2 – 7 days loss of treated water production.	8
E	>7 days loss of treated water production.	16

Table A11. Severity level and consequences of transmission main outages.

Severity level	Consequence	Score
A	<500 properties without water for 12 hours.	1
B	<1,000 properties without water for 12 hours or one industrial customer. <500 properties without water for 24 hours.	2
C	<10,000 properties without water for 12 hours or two to ten industrial customers. <1,000 properties without water for 24 hours or one industrial customer. <500 properties without water for 48 hours.	4
D	<50,000 properties without water for 12 hours or more than ten industrial customers. <10,000 properties without water for 24 hours or two to ten industrial customers. <1000 properties without water for 48 hours or one industrial customer. <500 properties without water for 2-5 days.	8
E	100,000 properties without water for 12 hours or more than one hundred industrial customers. <50,000 properties without water for 24 hours or more than ten industrial customers. <10,000 properties without water for 48 hours or 2 to 10 industrial customers. <1000 properties without water for 2-5 days or one industrial customer. <500 properties without water for >5 days	16

As an outcome of the workshop comments and discussion, the risk assessment table (Form), Table (A12) was developed. This table was used by the management of both the desalination plants and PAEW and the output forms the basis of the risk tables (Tables 8.1)

Table A10. Risk Assessment Table (Form) – PAEW.

No	Hazard	Hazardous Event	Likelihood (L)	Consequence (C)	Likelihood Score	Consequence Score	Risk (Pre-Rating)	Control Measure	Likelihood (L)	Consequence (C)	Likelihood Score	Consequence Score	Risk (Post-Rating)

Source :Adopted from AWWA.

Appendix- B
Questionnaire for PAEW Staff

This questionnaire has been prepared within the framework of the research project entitled "Analysis of the Stress Factors in Operating a Water Network in an Arid Country" that carried out by Eng. Kassim Mana Abdulla Al Jabri for partial fulfillment of the requirements for the award of the degree of Doctor of Philosophy from University of Abertay Dundee.

As the levels of water losses in Oman are estimated at approximately 40 to 50 percent, one of the **main purpose** of this research works is to survey a cross section of the public water system in Muscat Governorate, to first determine current water loss accounting practices and resulting loss estimates, gain more information on current water loss prevention and management practices, and then to make recommendations for more consistent water use accounting and water loss management.

The aim of this questionnaire is to assess the views of stakeholder in PAEW (staff) on the current status of water losses in of Oman from technical and strategic aspects. It seeks to discover from PAEW staff who are concerned with water losses, what their perceptions are about the stated NRW figure, their understanding of the impact and main causes of water loss, and their opinions on PAEW's procedures and policy related to water loss reduction.
The questionnaire consists of primary and secondary questions and sub-divided into two main sections. The first section addresses the basic information, and the second one deals with water losses water networks.

The researcher is highly appreciative of your cooperation in completing this questionnaire. Your contribution of great importance in providing the researcher with correct and accurate data that reflect the current reality of the various water losses and the level of NRW in Oman.

Note that all data contained in this questionnaire is for the purpose of scientific research, and the researcher took the permission of His Excellency the president of PAEW for the collection of this information. Information provided will remain anonymous – the researcher has asked for your name and contact details only so he can contact you if further clarification should be required.

Eng. Kassim Mana Al Jabri

Definition of Terms:

Unaccounted for Water (UFW) or Water Losses	The difference between the volumes of water delivered into a network and the volume of water that can be accounted for by legitimate consumption (the difference between system input and authorized consumption). **Water Losses or UFW = Apparent Losses + Real Losses**
Apparent Losses	Includes all type of inaccuracies associated with customer metering as well as data handling errors (meter reading and billing), plus unauthorized consumption (theft or illegal use). **Apparent Losses = Unauthorized consumption + Meter Under Registration + Data Handling Errors**
Real Losses	The annual volume lost through all types of leaks, breaks and overflow depends on frequencies, flow rates, and average duration. **Real Losses = Leakage on Mains + Overflow of Tanks + Leakage on Service Connections**
Revenue Water (RW)	Water which is charged to customer to provide revenue to the utility.
Non-Revenue Water (NRW)	The difference between the volumes of water delivered into a network and billed consumption (water which does not provide any revenue to the utility). **NRW = Water Losses (UFW) + Unbilled Authorized Consumption**

Water Balance and Terminology

<table>
<tr><td rowspan="9">System input volume

(corrected for known errors)</td><td rowspan="4">Authorised consumption</td><td rowspan="2">Billed Authorised Consumption</td><td>Billed Metered Consumption</td><td rowspan="2">Revenue water</td></tr>
<tr><td>Billed Unmetered Consumption</td></tr>
<tr><td rowspan="2">Unbilled Authorised Consumption</td><td>Unbilled Metered Consumption</td><td rowspan="7">Non-Revenue Water (NRW)</td></tr>
<tr><td>Unbilled Unmetered Consumption</td></tr>
<tr><td rowspan="5">Water losses</td><td rowspan="2">Apparent losses</td><td>Unauthorized Consumption</td></tr>
<tr><td>Customer Metering Inaccuracies</td></tr>
<tr><td rowspan="3">Real losses</td><td>Leakage on Transmission and Distribution Mains</td></tr>
<tr><td>Leakage and Overflow at Utility’s Storage Tanks</td></tr>
<tr><td>Leakage on Service Connections up to Point of Customer Metering</td></tr>
</table>

Basic Information

Name of Contact Person:					
Position:			**Department:**		
Job Related to Water Loss					
Telephone:		**Fax:**		**Mobile:**	
E-mail:					

A- Water Loss in Muscat Networks

1.	**General Information**		
1.1	What is your estimated percentage for the water losses (UFW) in Muscat Networks?		
	o 10-20%	o 20-30%	o 30-40%
	o 40-50%	o More than 50%	o Don't know
1.2	What do you think the main factors that contribute to water losses? Please prioritize the factors according to their contribution (1 = very high, 6 = very low)		
	o Meter Inaccuracies	o Losses during repair	o Age of pipes
	o Illegal Connection	o Service reservoir overflow	o Water pressure
	Your opinion based on your experience:		
1.3	What do you consider to be the best solution to the reduce water losses in water systems? Please prioritize the measures according to their efficiency(1 = very high, 6 = very low)		
	o Improve pipe maintenance	o Clampdown on illegal connection	o Pipe replacement
	o Active leak detection	o Increase public Awareness	o Improve metering
	Your opinion based on your experience:		
1.4	In which method of PAEW strategy focuses of deriving water loss figure:		

	o Leakage Level (%)	o Leakage level (%) and UFW	o UFW
	o Non-Revenue Water	o UFW and NRW	o Don't know
1.5	What do you think the possible impacts to high water losses figures? Please prioritize the impacts according to their effect (1 = very high, 6 = very low)		
	o Reduction in pressure	o Increase expenditure on development	o Water contamination
	o High cost of O&M	o Short lifespan of existing resources	o Property damage

2.	**Procedures and Policy**	**Strongly agree**	**Agree**	**Neutral**	**Disagree**	**Strongly disagree**
2.1	A National Water Policy exists which aims at reducing water losses.					
2.2	A Water loss reduction program is implemented.					
2.3	Pressure management is used to reduce water losses.					
2.6	A Network Maintenance/ Rehabilitation Program is Implemented.					
2.7	Measures to fight illegal connections are applied					
3.	**Obstacles for Fighting Water Losses**	**Strongly agree**	**Agree**	**Neutral**	**Disagree**	**Strongly disagree**
3.1	Institutional situation					
3.2	Lack of financial means from PAEW					
3.3	Lack of appropriate technologies for water loss reduction.					
3.4	Maintenance system					
3.5	Personnel capacities(technicians)					
3.6	Personnel awareness					
3.7	Public acceptance / awareness					

B- Staff Opinion

Please state your opinion on the issue of water losses in Oman:

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Appendix- C

Water Audit reporting Worksheets and Water Balances

AWWA WLCC Water Audit Software: Reporting Worksheet

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Water Audit Report for: Al Seeb
Reporting Year: 2008

Please enter data in the white cells below. Where possible, metered values should be used; if metered values are unavailable please estimate a value. Indicate this by selecting a choice from the gray box to the left, where M = measured (or accurately known value) and E = estimated.

All volumes to be entered as: MEGALITRES (THOUSAND CUBIC METRES) PER YEAR

WATER SUPPLIED

Volume from own sources:	M	14,182.000	Megalitres/yr (or ML/Yr)
Master meter error adjustment:	E	709.100	under-registered ML/Yr
Water imported:	M	0.000	ML/Yr
Water exported:		0.000	ML/Yr
WATER SUPPLIED:		14,891.100	ML/Yr

AUTHORIZED CONSUMPTION

Click here: ? for help using option buttons below

				Pcnt:	Value:
Billed metered:		7,941.900	ML/Yr		
Billed unmetered:		0.000	ML/Yr		
Unbilled metered:		0.000	ML/Yr		
Unbilled unmetered:		186.139	ML/Yr	1.25%	
AUTHORIZED CONSUMPTION:		8,128.039	ML/Yr		

Use buttons to select percentage OR value

WATER LOSSES (Water Supplied - Authorized Consumption) 6,763.061 ML/Yr

Apparent Losses

				Pcnt:	Value:
Unauthorized consumption:		37.228	ML/Yr	0.25%	
Customer metering inaccuracies:		162.080	ML/Yr	2.00%	
Systematic data handling errors:	E	2,836.400	ML/Yr		
Apparent Losses:		3,035.707	ML/Yr		

Real Losses

Real Losses = (Water Losses - Apparent Losses):	3,727.354	ML/Yr
WATER LOSSES:	6,763.061	ML/Yr

NON-REVENUE WATER

NON-REVENUE WATER: 6,949.200 ML/Yr

SYSTEM DATA

Length of mains:	M	366.0	kilometers
Number of active AND inactive service connections:		14,640	
Connection density:		40	conn./km main
Average length of customer service line:		30.0	metres (pipe length between curbstop and customer meter or property boundary)
Average operating pressure:		50.0	metres (head)

COST DATA

Total annual cost of operating water system:	$16,470,000	$/Year
Customer retail unit cost (applied to Apparent Losses):	$1.14	$/1000 litres
Variable production cost (applied to Real Losses):	$1,550.00	$/Megalitre

DATA REVIEW - Please review the following information and make changes above if necessary:

- Input values should be indicated as either measured or estimated. You have entered:
  - 3 as measured values
  - 2 as estimated values
  - 2 as default values
  - 11 without specifying measured, estimated or default
- Water Supplied Data: No problems identified
- Unbilled unmetered consumption: No problems identified
- Unauthorized consumption: No problems identified
- It is important to accurately measure the master meter - you have entered the measurement type as: measured
- Cost Data: Retail costs are less than (or equal to) production costs; please review and correct if necessary

PERFORMANCE INDICATORS

Financial Indicators

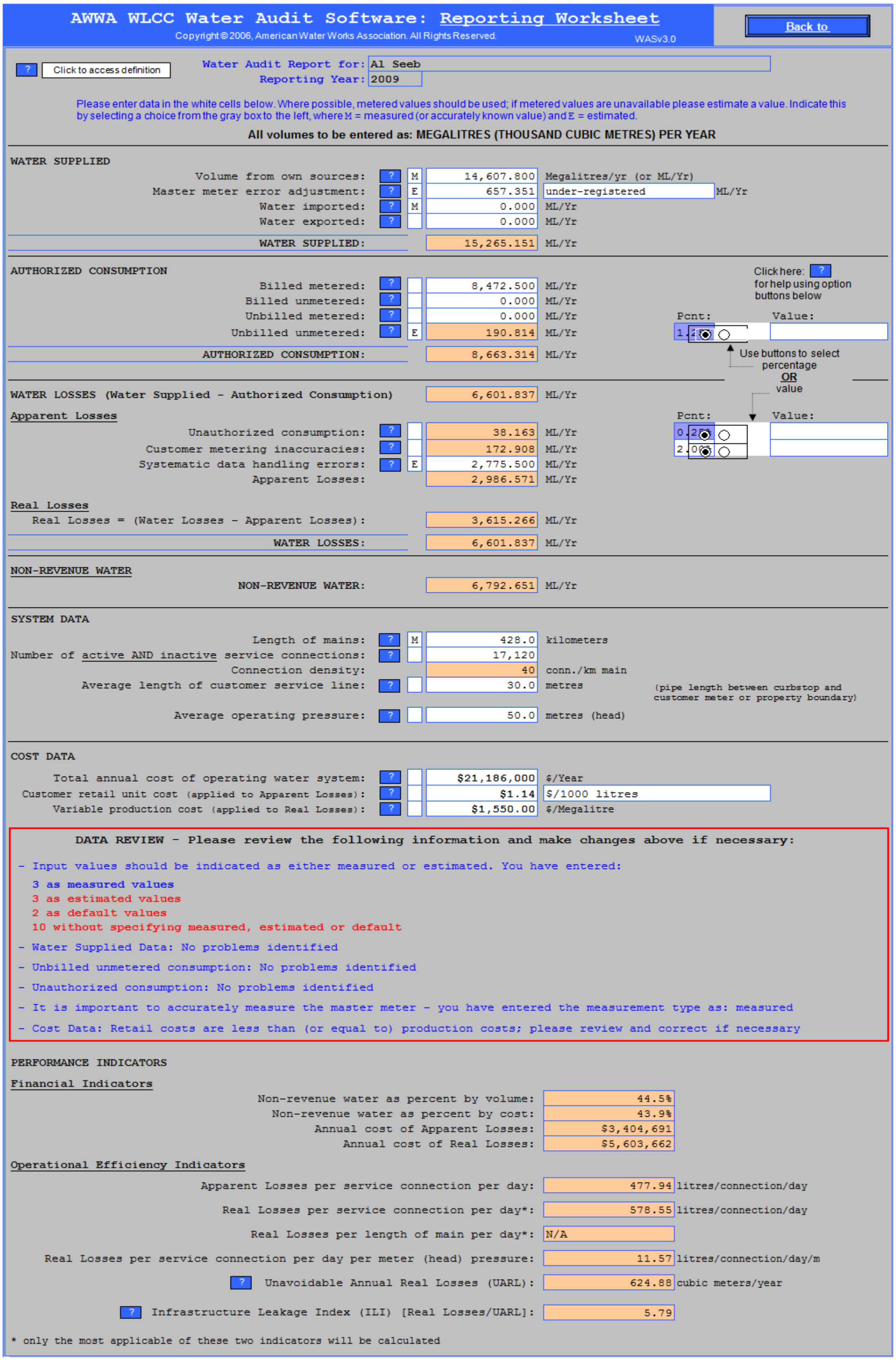
Non-revenue water as percent by volume:	46.7%
Non-revenue water as percent by cost:	57.8%
Annual cost of Apparent Losses:	$3,460,706
Annual cost of Real Losses:	$5,777,399

Operational Efficiency Indicators

Apparent Losses per service connection per day:	568.10	litres/connection/day
Real Losses per service connection per day*:	697.54	litres/connection/day
Real Losses per length of main per day*:	N/A	
Real Losses per service connection per day per meter (head) pressure:	13.95	litres/connection/day/m
Unavoidable Annual Real Losses (UARL):	534.36	cubic meters/year
Infrastructure Leakage Index (ILI) [Real Losses/UARL]:	6.98	

* only the most applicable of these two indicators will be calculated

Figure C.1: Water Audit Reporting Worksheet for Year 2008



AWWA WLCC Water Audit Software: Reporting Worksheet

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Water Audit Report for: Al Seeb

Reporting Year: 2009

Please enter data in the white cells below. Where possible, metered values should be used; if metered values are unavailable please estimate a value. Indicate this by selecting a choice from the gray box to the left, where M = measured (or accurately known value) and E = estimated.

All volumes to be entered as: MEGALITRES (THOUSAND CUBIC METRES) PER YEAR

WATER SUPPLIED

Volume from own sources:	M	14,607.800	Megalitres/yr (or ML/Yr)
Master meter error adjustment:	E	657.351	under-registered ML/Yr
Water imported:	M	0.000	ML/Yr
Water exported:		0.000	ML/Yr
WATER SUPPLIED:		15,265.151	ML/Yr

AUTHORIZED CONSUMPTION

Click here: ? for help using option buttons below

				Pcnt:	Value:
Billed metered:		8,472.500	ML/Yr		
Billed unmetered:		0.000	ML/Yr		
Unbilled metered:		0.000	ML/Yr		
Unbilled unmetered:	E	190.814	ML/Yr	1.25%	
AUTHORIZED CONSUMPTION:		8,663.314	ML/Yr		

Use buttons to select percentage OR value

WATER LOSSES (Water Supplied - Authorized Consumption) 6,601.837 ML/Yr

Apparent Losses

				Pcnt:	Value:
Unauthorized consumption:		38.163	ML/Yr	0.25%	
Customer metering inaccuracies:		172.908	ML/Yr	2.00%	
Systematic data handling errors:	E	2,775.500	ML/Yr		
Apparent Losses:		2,986.571	ML/Yr		

Real Losses

Real Losses = (Water Losses - Apparent Losses):	3,615.266	ML/Yr
WATER LOSSES:	6,601.837	ML/Yr

NON-REVENUE WATER

NON-REVENUE WATER: 6,792.651 ML/Yr

SYSTEM DATA

Length of mains:	M	428.0	kilometers
Number of active AND inactive service connections:		17,120	
Connection density:		40	conn./km main
Average length of customer service line:		30.0	metres (pipe length between curbstop and customer meter or property boundary)
Average operating pressure:		50.0	metres (head)

COST DATA

Total annual cost of operating water system:	$21,186,000	$/Year
Customer retail unit cost (applied to Apparent Losses):	$1.14	$/1000 litres
Variable production cost (applied to Real Losses):	$1,550.00	$/Megalitre

DATA REVIEW - Please review the following information and make changes above if necessary:

- Input values should be indicated as either measured or estimated. You have entered:
  - 3 as measured values
  - 3 as estimated values
  - 2 as default values
  - 10 without specifying measured, estimated or default
- Water Supplied Data: No problems identified
- Unbilled unmetered consumption: No problems identified
- Unauthorized consumption: No problems identified
- It is important to accurately measure the master meter - you have entered the measurement type as: measured
- Cost Data: Retail costs are less than (or equal to) production costs; please review and correct if necessary

PERFORMANCE INDICATORS

Financial Indicators

Non-revenue water as percent by volume:	44.5%
Non-revenue water as percent by cost:	43.9%
Annual cost of Apparent Losses:	$3,404,691
Annual cost of Real Losses:	$5,603,662

Operational Efficiency Indicators

Apparent Losses per service connection per day:	477.94	litres/connection/day
Real Losses per service connection per day*:	578.55	litres/connection/day
Real Losses per length of main per day*:	N/A	
Real Losses per service connection per day per meter (head) pressure:	11.57	litres/connection/day/m
Unavoidable Annual Real Losses (UARL):	624.88	cubic meters/year
Infrastructure Leakage Index (ILI) [Real Losses/UARL]:	5.79	

* only the most applicable of these two indicators will be calculated

Figure C.2: Water Audit Reporting Worksheet for Year 2009

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Water Audit Report for: Al Seeb
Reporting Year: 2010

Please enter data in the white cells below. Where possible, metered values should be used; if metered values are unavailable please estimate a value. Indicate this by selecting a choice from the gray box to the left, where M = measured (or accurately known value) and E = estimated.

All volumes to be entered as: MEGALITRES (THOUSAND CUBIC METRES) PER YEAR

WATER SUPPLIED

Volume from own sources:	M	17,554.000	Megalitres/yr (or ML/Yr)
Master meter error adjustment:	E	702.160	under-registered ML/Yr
Water imported:	M	0.000	ML/Yr
Water exported:		0.000	ML/Yr
WATER SUPPLIED:		18,256.160	ML/Yr

AUTHORIZED CONSUMPTION

Click here: ? for help using option buttons below

Billed metered:		10,532.400	ML/Yr
Billed unmetered:		0.000	ML/Yr
Unbilled metered:		0.000	ML/Yr
Unbilled unmetered:	E	228.202	ML/Yr
AUTHORIZED CONSUMPTION:		10,760.602	ML/Yr

Pcnt: 1.2 Value:

Use buttons to select percentage OR value

WATER LOSSES (Water Supplied - Authorized Consumption) 7,495.558 ML/Yr

Apparent Losses

Pcnt: 0.2, 2.0 Value:

Unauthorized consumption:		45.640	ML/Yr
Customer metering inaccuracies:		214.947	ML/Yr
Systematic data handling errors:	E	3,072.000	ML/Yr
Apparent Losses:		3,332.587	ML/Yr

Real Losses

Real Losses = (Water Losses - Apparent Losses):	4,162.971	ML/Yr
WATER LOSSES:	7,495.558	ML/Yr

NON-REVENUE WATER

NON-REVENUE WATER: 7,723.760 ML/Yr

SYSTEM DATA

Length of mains:	M	475.7	kilometers
Number of active AND inactive service connections:		19,028	
Connection density:		40	conn./km main
Average length of customer service line:		30.0	metres (pipe length between curbstop and customer meter or property boundary)
Average operating pressure:		50.0	metres (head)

COST DATA

Total annual cost of operating water system:	$23,547,150	$/Year
Customer retail unit cost (applied to Apparent Losses):	$1.14	$/1000 litres
Variable production cost (applied to Real Losses):	$1,550.00	$/Megalitre

DATA REVIEW - Please review the following information and make changes above if necessary:

- Input values should be indicated as either measured or estimated. You have entered:
  - 3 as measured values
  - 3 as estimated values
  - 2 as default values
  - 10 without specifying measured, estimated or default
- Water Supplied Data: No problems identified
- Unbilled unmetered consumption: No problems identified
- Unauthorized consumption: No problems identified
- It is important to accurately measure the master meter - you have entered the measurement type as: measured
- Cost Data: Retail costs are less than (or equal to) production costs; please review and correct if necessary

PERFORMANCE INDICATORS

Financial Indicators

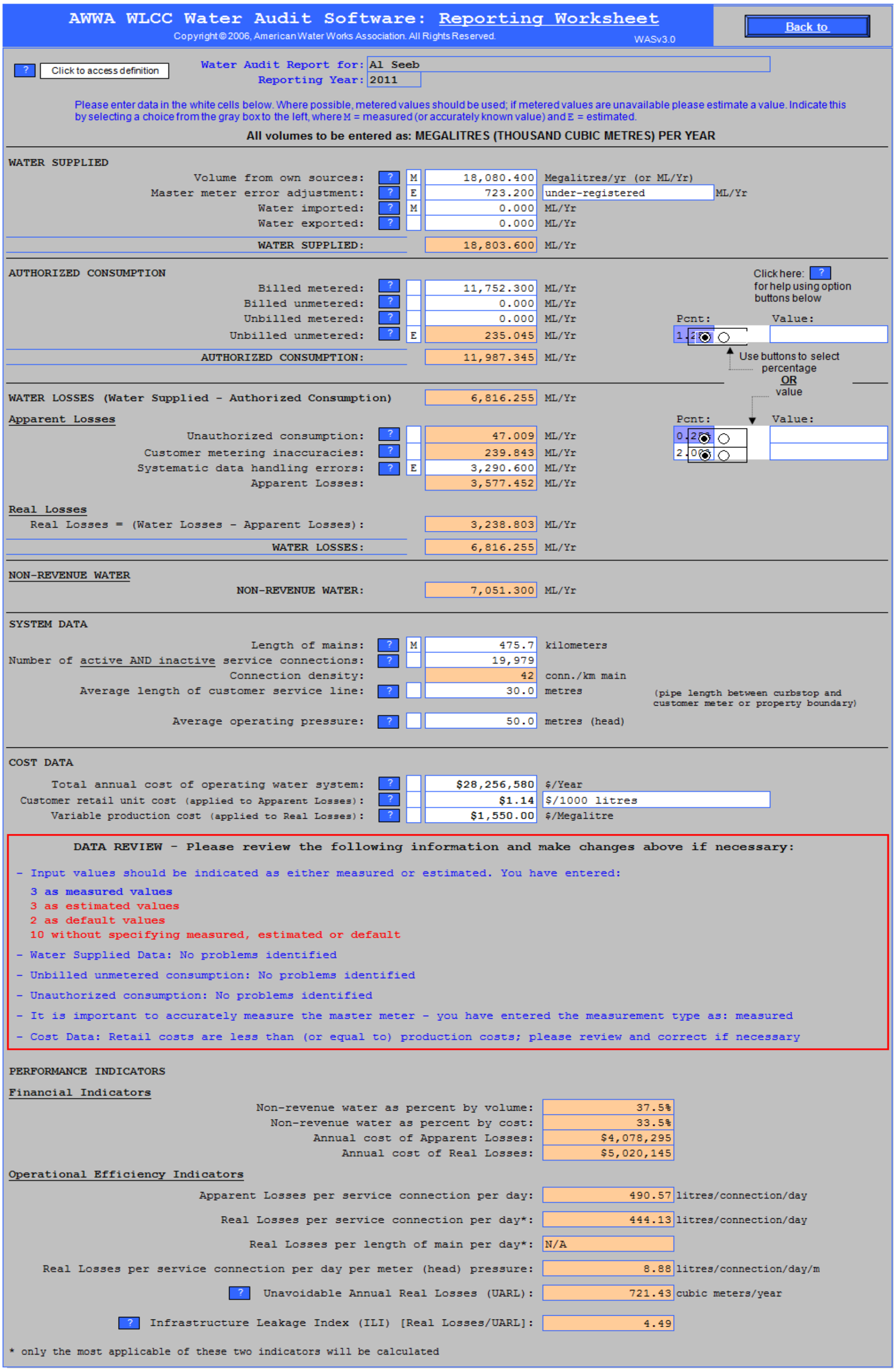
Non-revenue water as percent by volume:	42.3%	
Non-revenue water as percent by cost:	45.0%	
Annual cost of Apparent Losses:	$3,799,150	
Annual cost of Real Losses:	$6,452,605	

Operational Efficiency Indicators

Apparent Losses per service connection per day:	479.84	litres/connection/day
Real Losses per service connection per day*:	599.40	litres/connection/day
Real Losses per length of main per day*:	N/A	
Real Losses per service connection per day per meter (head) pressure:	11.99	litres/connection/day/m
Unavoidable Annual Real Losses (UARL):	694.52	cubic meters/year
Infrastructure Leakage Index (ILI) [Real Losses/UARL]:	5.99	

* only the most applicable of these two indicators will be calculated

Figure C.3: Water Audit Reporting Worksheet for Year 2010



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Water Audit Report for: Al Seeb

Reporting Year: 2011

Please enter data in the white cells below. Where possible, metered values should be used; if metered values are unavailable please estimate a value. Indicate this by selecting a choice from the gray box to the left, where M = measured (or accurately known value) and E = estimated.

All volumes to be entered as: MEGALITRES (THOUSAND CUBIC METRES) PER YEAR

WATER SUPPLIED

Volume from own sources:	M	18,080.400	Megalitres/yr (or ML/Yr)	
Master meter error adjustment:	E	723.200	under-registered	ML/Yr
Water imported:	M	0.000	ML/Yr	
Water exported:		0.000	ML/Yr	
WATER SUPPLIED:		18,803.600	ML/Yr	

AUTHORIZED CONSUMPTION

Click here: ? for help using option buttons below

				Pcnt:	Value:
Billed metered:		11,752.300	ML/Yr		
Billed unmetered:		0.000	ML/Yr		
Unbilled metered:		0.000	ML/Yr		
Unbilled unmetered:	E	235.045	ML/Yr	1.25%	
AUTHORIZED CONSUMPTION:		11,987.345	ML/Yr		

Use buttons to select percentage OR value

WATER LOSSES (Water Supplied - Authorized Consumption) 6,816.255 ML/Yr

Apparent Losses

				Pcnt:	Value:
Unauthorized consumption:		47.009	ML/Yr	0.25%	
Customer metering inaccuracies:		239.843	ML/Yr	2.00%	
Systematic data handling errors:	E	3,290.600	ML/Yr		
Apparent Losses:		3,577.452	ML/Yr		

Real Losses

Real Losses = (Water Losses - Apparent Losses):	3,238.803	ML/Yr
WATER LOSSES:	6,816.255	ML/Yr

NON-REVENUE WATER

NON-REVENUE WATER: 7,051.300 ML/Yr

SYSTEM DATA

Length of mains:	M	475.7	kilometers
Number of active AND inactive service connections:		19,979	
Connection density:		42	conn./km main
Average length of customer service line:		30.0	metres (pipe length between curbstop and customer meter or property boundary)
Average operating pressure:		50.0	metres (head)

COST DATA

Total annual cost of operating water system:	$28,256,580	$/Year
Customer retail unit cost (applied to Apparent Losses):	$1.14	$/1000 litres
Variable production cost (applied to Real Losses):	$1,550.00	$/Megalitre

DATA REVIEW - Please review the following information and make changes above if necessary:

- Input values should be indicated as either measured or estimated. You have entered:
  - 3 as measured values
  - 3 as estimated values
  - 2 as default values
  - 10 without specifying measured, estimated or default
- Water Supplied Data: No problems identified
- Unbilled unmetered consumption: No problems identified
- Unauthorized consumption: No problems identified
- It is important to accurately measure the master meter - you have entered the measurement type as: measured
- Cost Data: Retail costs are less than (or equal to) production costs; please review and correct if necessary

PERFORMANCE INDICATORS

Financial Indicators

Non-revenue water as percent by volume:	37.5%
Non-revenue water as percent by cost:	33.5%
Annual cost of Apparent Losses:	$4,078,295
Annual cost of Real Losses:	$5,020,145

Operational Efficiency Indicators

Apparent Losses per service connection per day:	490.57	litres/connection/day
Real Losses per service connection per day*:	444.13	litres/connection/day
Real Losses per length of main per day*:	N/A	
Real Losses per service connection per day per meter (head) pressure:	8.88	litres/connection/day/m
Unavoidable Annual Real Losses (UARL):	721.43	cubic meters/year
Infrastructure Leakage Index (ILI) [Real Losses/UARL]:	4.49	

* only the most applicable of these two indicators will be calculated

Figure C.4: Water Audit Reporting Worksheet for Year 2011

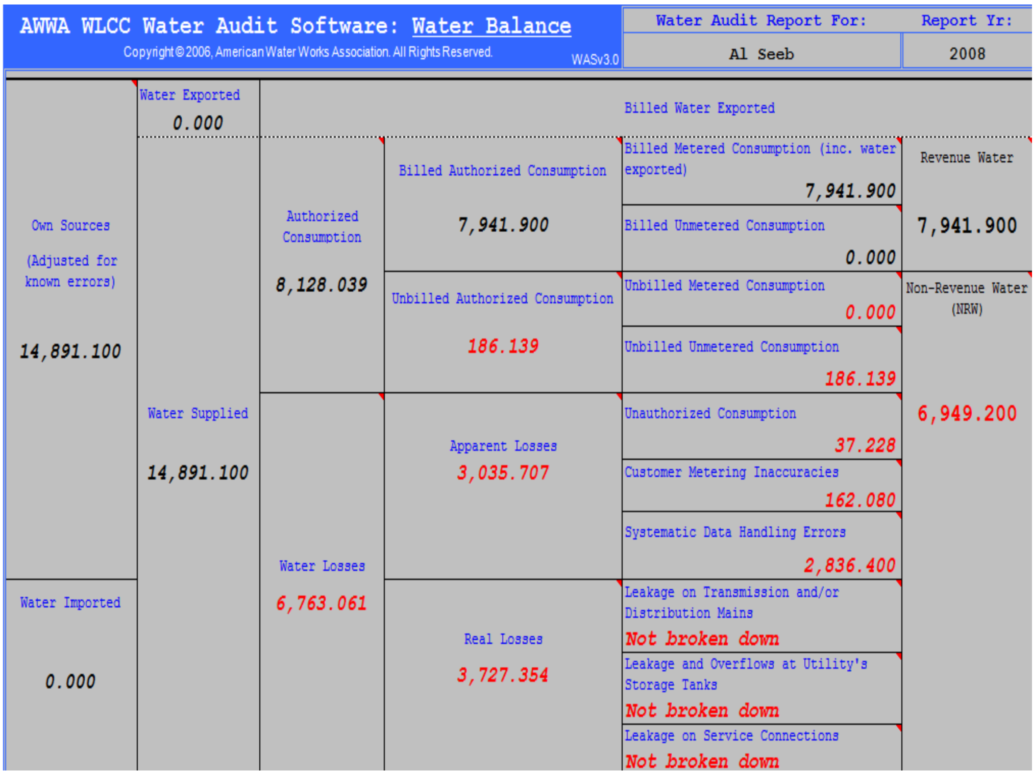

Figure C.5: Water Balance for Al Seeb Wilayat (Year 2008)

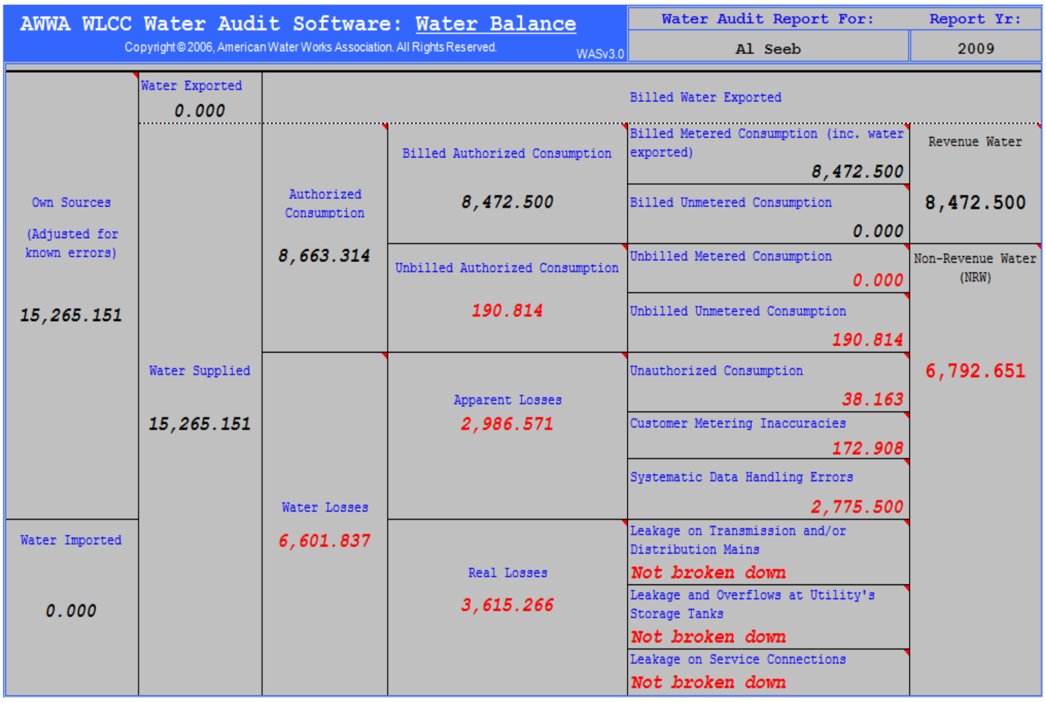

Figure C.6: Water Balance for Al Seeb Wilayat (Year 2009)

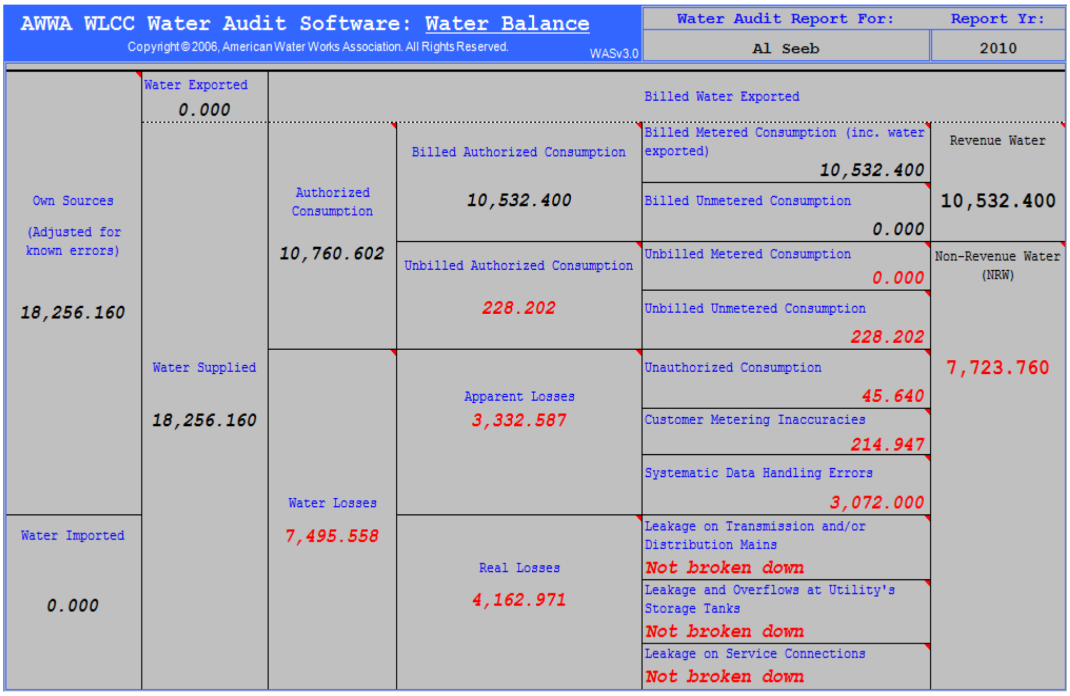

Figure C.7: Water Balance for Al Seeb Wilayat (Year 2010)

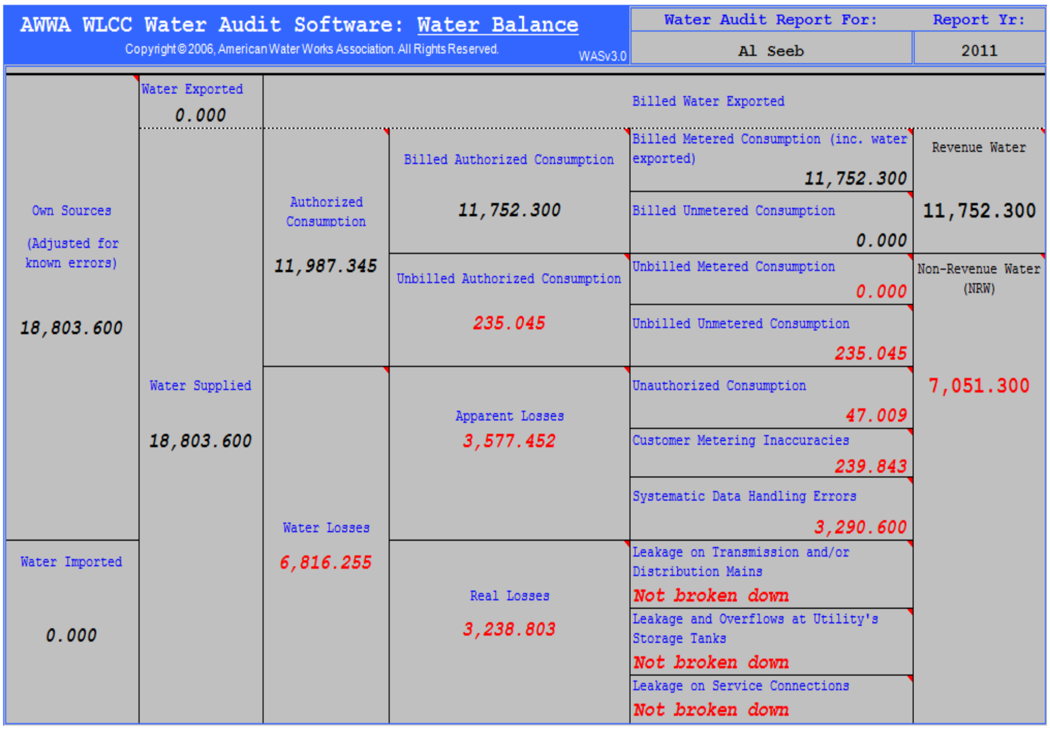

Figure C.8: Water Balance for Al Seeb Wilayat (Year 2011)

Table C.1: Al Seeb Water Balance for Year 2008

<table>
<tr><th colspan="3">AWWA Water Audit Software: Water Balance</th><th colspan="2">Report For: Al Seeb Wilayat</th><th>Report Year: 2008</th></tr>
<tr><td rowspan="7">**Own Sources**
(Adjusted for known errors)
93.7%</td><td>Water Exported
0.00</td><td colspan="4">Billed Water Exported
(0%)</td></tr>
<tr><td rowspan="10">**Water Supplied**
100%</td><td rowspan="4">Authorized Consumption
(54.6%)</td><td rowspan="2">Billed Authorized Consumption
(53.3%)</td><td>Billed Metered Consumption
(53.34%)</td><td rowspan="2">**Revenue Water**
(53.3%)</td></tr>
<tr><td>Billed Unmetered Consumption
(0%)</td></tr>
<tr><td rowspan="2">Unbilled Authorized Consumption
(1.3%)</td><td>Unbilled Metered Consumption
(0%)</td><td rowspan="8">**Non-Revenue Water (NRW)**
(46.7%)</td></tr>
<tr><td>Unbilled Unmetered Consumption
(1.3%)</td></tr>
<tr><td rowspan="6">**Water Losses**
(45.4%)</td><td rowspan="3">**Apparent Losses**
(20.4%)</td><td>Unauthorized Consumption
(0.3%)</td></tr>
<tr><td>Customer Metering Inaccuracies
(1.1%)</td></tr>
<tr><td rowspan="4">**Water Imported**
6.3%</td><td>Systematic Data Handling Errors
(19.0%)</td></tr>
<tr><td rowspan="3">**Real Losses**
(25.0%)</td><td>Leakage on Transmission and/or Distribution mains
Not broken down</td></tr>
<tr><td>Leakage and Overflow at Utility’s Storage Tank
Not broken down</td></tr>
<tr><td>Leakage on Service Connections
Not broken down</td></tr>
</table>

Table C.2: Al Seeb Water Balance for Year Year 2009

<table>
<tr><th colspan="3">AWWA Water Audit Software: Water Balance</th><th colspan="2">Report For: Al Seeb Wilayat</th><th>Report Year: 2009</th></tr>
<tr><td rowspan="7">Own Sources
(Adjusted for known errors)
87.9%</td><td>Water Exported
0.00</td><td colspan="4">Billed Water Exported
(0%)</td></tr>
<tr><td rowspan="10">Water Supplied
100%</td><td rowspan="4">Authorized Consumption
(56.8%)</td><td rowspan="2">Billed Authorized Consumption
(55.5%)</td><td>Billed Metered Consumption
(55.5%)</td><td rowspan="2">Revenue Water
(55.5%)</td></tr>
<tr><td>Billed Unmetered Consumption
(0%)</td></tr>
<tr><td rowspan="2">Unbilled Authorized Consumption
(1.3%)</td><td>Unbilled Metered Consumption
(0%)</td><td rowspan="8">Non-Revenue Water (NRW)
(44.5%)</td></tr>
<tr><td>Unbilled Unmetered Consumption
(1.3%)</td></tr>
<tr><td rowspan="6">Water Losses
(43.2%)</td><td rowspan="3">Apparent Losses
(19.6.0%)</td><td>Unauthorized Consumption
(0.3%)</td></tr>
<tr><td>Customer Metering Inaccuracies
(1.1%)</td></tr>
<tr><td rowspan="4">Water Imported
12.1%</td><td>Systematic Data Handling Errors
(18.2%)</td></tr>
<tr><td rowspan="3">Real Losses
(23.6%)</td><td>Leakage on Transmission and/or Distribution mains
Not broken down</td></tr>
<tr><td>Leakage and Overflow at Utility's Storage Tank
Not broken down</td></tr>
<tr><td>Leakage on Service Connections
Not broken down</td></tr>
</table>

Table C.3: Al Seeb Water Balance for Year 2010

<table>
<tr><th colspan="4">AWWA Water Audit Software: Water Balance</th><th>Report For: Al Seeb Wilayat</th><th colspan="2">Report Year: 2010</th></tr>
<tr><td rowspan="8">Own Sources

(Adjusted for known errors)

(100%)</td><td>Water Exported
0.00</td><td colspan="5">Billed Water Exported
(0%)</td></tr>
<tr><td rowspan="11">Water Supplied

(100%)</td><td rowspan="4">Authorized Consumption

(58.9%)</td><td rowspan="2">Billed Authorized Consumption

(57.7%)</td><td colspan="2">Billed Metered Consumption
(57.7%)</td><td rowspan="2">Revenue Water

(57.7%)</td></tr>
<tr><td colspan="2">Billed Unmetered Consumption
(0%)</td></tr>
<tr><td rowspan="2">Unbilled Authorized Consumption

(1.2%)</td><td colspan="2">Unbilled Metered Consumption
(0%)</td><td rowspan="9">Non-Revenue Water
(NRW)

(42.3%)</td></tr>
<tr><td colspan="2">Unbilled Unmetered Consumption
(1.2%)</td></tr>
<tr><td rowspan="7">Water Losses

(41.1%)</td><td rowspan="3">Apparent Losses

(18.2%)</td><td colspan="2">Unauthorized Consumption
(0.2%)</td></tr>
<tr><td colspan="2">Customer Metering Inaccuracies
(1.2%)</td></tr>
<tr><td colspan="2">Systematic Data Handling Errors
(16.8%)</td></tr>
<tr><td rowspan="4">Water Imported

(0%)</td><td rowspan="4">Real Losses

(22.9%)</td><td colspan="2">Leakage on Transmission and/or Distribution mains
Not broken down</td></tr>
<tr><td colspan="2">Leakage and Overflow at Utility’s Storage Tank
Not broken down</td></tr>
<tr><td colspan="2">Leakage on Service Connections
Not broken down</td></tr>
</table>

Table C.4: Al Seeb Water Balance for Year 2011

<table>
<tr><th colspan="3">AWWA Water Audit Software: Water Balance</th><th colspan="2">Report For: Al Seeb Wilayat</th><th>Report Year: 2011</th></tr>
<tr><td rowspan="7">Own Sources
(Adjusted for known errors)
(100%)</td><td>Water Exported
0.00</td><td colspan="4">Billed Water Exported
(0%)</td></tr>
<tr><td rowspan="10">Water Supplied
(100%)</td><td rowspan="4">Authorized Consumption
(63.8%)</td><td rowspan="2">Billed Authorized Consumption
(62.5%)</td><td>Billed Metered Consumption
(62.5%)</td><td rowspan="2">Revenue Water
(62.5%)</td></tr>
<tr><td>Billed Unmetered Consumption
(0%)</td></tr>
<tr><td rowspan="2">Unbilled Authorized Consumption
(1.3%)</td><td>Unbilled Metered Consumption
(0%)</td><td rowspan="8">Non-Revenue Water (NRW)
(37.5%)</td></tr>
<tr><td>Unbilled Unmetered Consumption
(1.3%)</td></tr>
<tr><td rowspan="6">Water Losses
(36.2%)</td><td rowspan="3">Apparent Losses
(19.0%)</td><td>Unauthorized Consumption
(0.2%)</td></tr>
<tr><td>Customer Metering Inaccuracies
(1.3%)</td></tr>
<tr><td rowspan="4">Water Imported
(0%)</td><td>Systematic Data Handling Errors
(17.5%)</td></tr>
<tr><td rowspan="3">Real Losses
(17.2%)</td><td>Leakage on Transmission and/or Distribution mains
Not broken down</td></tr>
<tr><td>Leakage and Overflow at Utility’s Storage Tank
Not broken down</td></tr>
<tr><td>Leakage on Service Connections
Not broken down</td></tr>
</table>

Appendix- D

Risks for Regional Water Supply Systems

D.1 Risks to Southern Batinah Transmission System

1) Transmission Mains

Currently there is adequate planned storage throughout the southern Batinah region to cover the expected outage times due to bursts in the mains. The current demand on the system is small in comparison to the storage, mainly because the distribution systems supplying the existing wilayats have not been connected to the transmission main. Plans to construct the distribution systems within the wilayats are in the concept design stage and expected to be installed in the next few years. A serious failure in the main from Barka to Musanaah may be compensated for by transfers from Sohar desalination plant through the emergency connection between Suwayq and Musanaah.

2) Pumping Stations

All the pumping stations have adequate standby and provided this standby capacity is maintained, there is a minimal risk of supply to consumers due to failure of the pumps.

3) Loss of supply from Barka Desalination Plant

Loss of supply from Barka desalination plant may be covered by a combination of transfers from Sohar and storage in the system. Only prolonged outages, longer than seven days, pose any risk to the supply to consumers.

4) Mitigation Measures

At present, pipeline bursts, pump failures, or outages at the desalination plant for less than 7 days do not pose a high risk. There is currently sufficient storage available within the system to mitigate these risks.

The risks to the southern Batinah water supply system are summarized in Table (D. 1).

Table D.1: Risks to the Southern Batinah Water Supply System

Transmission Mains												
Hazard	**Diameter (mm)**	**Length (km)**	**Material**	**Expected Nr of failures/yr**	**Cumulative Nr of failures**	**Expected Nr 1:x yr failures**	**Population**	**Likelihood**	**Consequence**	**L**	**C**	**Risk**
Burst Barka Res to Barka SR	900	8.6	Steel	0	0	9	254523	One in five to twenty years	Loss of supply to south Batinah	3	16	48
Burst Barka SR to Musanaah SR	800	31.2	Steel	0	1	2	130090	One in one to five years	Loss of supply to Al Musanaah, Rustaq, Al Awabi	4	16	64
Burst New Barka to Hubra Res	500	12.3	Steel	0	1	2	29893	One in one to five years	Loss of supply to Wadi Al Maawil and Nakhal	4	8	32
Burst Hubra Res to Nakhal Res	400	11.3	Ductile Iron	1	1	1	17776	More than one per year	Loss of supply to Nakhal	5	8	40
Burst Musanaah to Al Hazm Res	800	29.0	Steel	0	1	1	56708	One in one to five years	Loss of supply to Rustaq, Al Awabi	4	16	64
Burst Al Hazm to Rustaq	700	15.4	Steel	0	1	1	56708	One in one to five years	Loss of supply to Rustaq, Al Awabi	4	16	64
Burst Rustaq to Wadi Assan	400	12.7	Ductile Iron	1	2	1	15906	More than one per year	Loss of supply to Al Awabi	5	8	40
Burst Wadi Assan to Al Awabi	300	5.8	Ductile Iron	1	3	0	15906	More than one per year	Loss of supply to Al Awabi	5	8	40

Pumping Stations							
Hazard	**Standby Arrangement**	**Operational Capacity (m^3/d)**	**Likelihood (L)**	**Consequence**	**L**	**C**	**Risk**
Pump failure - Barka to Musanaah PS	1 operational + 1 standby	45000	One in one to five years	Loss of supply to south Batinah	4	16	64
Loss of power - Barka to Musanaah PS	None	45000	More than one per year	Partial loss of supply to south Batinah	5	8	40
Failure of control systems - Barka to Musanaah PS	-	45000	One in one to five years	Partial loss of supply to south Batinah	4	8	32
Pump failure - Barka to Hubra PS	2 operational + 1 standby	6739	One in one to five years	Loss of supply to Wadi Al Maawil and Nakhal	4	16	64
Loss of power - Barka to Hubra PS	None	6739	More than one per year	Disruption of supply to Wadi Al Maawil and Nakhal	5	8	80
Failure of control systems - Barka to Hubra PS	-	6739	One in one to five years	Disruption of supply to Wadi Al Maawil and Nakhal	4	8	32
Pump failure - Hubra to Nakhal PS	2 operational + 1 standby	6048	One in one to five years	Loss of supply to Nakhal	4	8	32
Loss of power - Hubra to Nakhal PS	None	6048	More than one per year	Disruption of Loss of supply to Nakhal	5	8	40
Failure of control systems - Hubra to Nakhal PS	-	6048	One in one to five years	Disruption of Loss of supply to Nakhal	4	8	32
Pump failure - Musanaah to Hazm PS	3 operational + 1 standby	25142	One in one to five years	Loss of supply to Rustaq, Al Awabi	4	16	64

Table D.1 - Cont.: Risks to the Southern Batinah Water Supply System

Hazard	Standby Arrangement	Operational Capacity (m^3/d)	Likelihood (L)	Consequence	L	C	Risk
Loss of power - Musanaah to Hazm PS	None	25142	More than one per year	Disruption of supply to Rustaq, Al Awabi	5	8	40
Failure of control systems - Musanaah to Hazm PS	-	25142	One in one to five years	Disruption of supply to Rustaq, Al Awabi	4	8	32
Pump failure - Hazm to Rustaq PS	2D+1S	14170	One in one to five years	Loss of supply to Rustaq, Al Awabi	4	16	64
Loss of power - Hazm to Rustaq PS	None	14170	More than one per year	Disruption of supply to Rustaq, Al Awabi	5	8	40
Failure of control systems - Hazm to Rustaq PS	-	14170	One in one to five years	Disruption of supply to Rustaq, Al Awabi	4	8	32
Pump failure - Rustaq to Wadi Assan PS	2D+1S	8294	One in one to five years	Loss of supply to Al Awabi	4	8	32
Loss of power - Rustaq to Wadi Assan PS	None	8294	More than one per year	Disruption of supply to Al Awabi	5	4	20
Failure of control systems - Rustaq to Wadi Assan PS	-	8294	One in one to five years	Disruption of supply to Al Awabi	4	8	32
Pump failure - Wadi Assan to Al Awabi PS	2D+1S	3283	One in one to five years	Loss of supply to Al Awabi	4	8	32
Loss of power - Wadi Assan to Al Awabi PS	None	3283	More than one per year	Disruption of supply to Al Awabi	5	4	20
Failure of control systems - Wadi Assan to Al Awabi PS	-	3283	One in one to five years	Disruption of supply to Al Awabi	4	8	40

Loss of Supply from Desalination Plant

Hazard	Operational Capacity (m^3/d)	Average Daily Flow (m^3/d)	Storage at Desalination Plant (m^3)	Storage (hours of supply capacity)	Potential loss of Supply (m^3)		Likelihood	Consequence	L	C	Risk
					Mini	Max.					
Loss of Supply from Barka DP	210000	13226	182400	21	0	0	One in one to five years	< 12 hours partial reduction in treated water production (>34% of design output)	4	1	4
Loss of Supply from Barka DP	210000	13226	182400	21	0	0	One in one to five years	<12 hours loss of treated water production	4	1	4
Loss of Supply from Barka DP	210000	13226	182400	21	0	14965	One in one to five years	12 – 48 hours loss of treated water production	4	16	64
Loss of Supply from Barka DP	210000	13226	182400	21	14965	81096	One in one to five years	2 – 7 days loss of treated water production	4	16	64
Loss of Supply from Barka DP	210000	13226	182400	21	81096	>>81096	One in five to twenty years	>7 days loss of treated water production	3	16	48

D.2 North Batinah and Buraymi Transmission System

1) Transmission Mains:

The most serious outstanding risks are bursts in the main from Sohar DP (IWPP) to the Sohar intermediate and service reservoirs, as well as along the main from the MPS2 reservoir to the Buraymi service reservoir.

The long single transmission mains will always be at risk from failure and it will be necessary to ensure provision of supplies whilst the main is repaired. At the present time the downstream storage in the system should these mains fail provides 1.4 days supply should failure occur along the Sohar IWPP to Sohar intermediate and service reservoirs. Similarly there is 1.8 days of downstream storage available in the event that there is a burst on the main from MPS 2 reservoir to Buraymi service reservoir.

The supply to the Batinah coast between Saham and Suwayq is protected by the emergency link that enables water from Barka desalination plant to be transferred to these towns from Musanaah.

2) Pumping Stations:

The main pumping station delivering water from the desalination plant to the Sohar intermediate and service reservoirs has three duty pumps and one standby. We estimate that such an arrangement could result in two pumps breaking down at the same time once in about 25 years. The remaining pumping stations all have adequate standby and provided this standby capacity is maintained, there is a minimal risk of loss of supply to consumers due to failure of the pumps.

3) Loss of Supply at Sohar IWPP:

The system currently has at least one day's emergency storage throughout. The supplies to Saham, Khabourah and Suwayq may be ensured by use of water from Barka desalination plant via the emergency link from Al Musanaah. There is, however, a potential risk of loss of supply to Sohar due to loss of power supply at the main pumping station or failure of the control system.

A combination of reserve storage and the emergency connection to the Barka desalination plant ensure security against the loss of supply from the Sohar desalination plant for at least 48 hours. Only more prolonged outages are likely to affect consumers.

4) Mitigating Measures:

Duplicating the existing 1200 mm main from Sohar IWPP to the Sohar intermediate and service reservoirs will ensure that if there is a failure along one of the mains that a supply to the southern areas of Sohar town, Saham, Khaburah and Suwayq is still maintained. However, this may be economic as demand within the wilayats south of Sohar can be met from Barka DP through the existing Suwayq to Al Musanaah connection.

As there is not sufficient downstream storage available to mitigate the risk of a pipeline failure along the transmission main from MPS 2 Reservoir to Buraymi Service Reservoir for longer than 2 days, duplicating the main will ensure security of supply. In all instances, ensuring that timely repairs to bursts are made will remove the risks immediately.

Providing additional stand-by pump capacity at the Sohar IWPP to Sohar IR will mitigate risks in the event that there is more than one pump failing at any time.

The risks to the North Batinah and Buraymi water supply system are summarized in Table (D.2).

Table D.2: Risks to the North Batinah and Buraymi Water Supply System

Transmission Mains												
Hazard	**Diameter (mm)**	**Length (km)**	**Material**	**Expected Nr of failures/yr**	**Cumulative Nr of failures**	**Expected Nr 1:x yr failures**	**Population**	**Likelihood**	**Consequence**	**L**	**C**	**Risk**
Burst in main from Sohar DP (IWPP) to Liwa Service Res	600	19.2	Ductile Iron	1	1	1.5	75596	One in one to five years	Loss of supply to Shinas and Liwa	4	16	64
Burst in main from Liwa SR to Shinas IR	600	15.8	Ductile Iron	1	1	0.8	50978	More than one per year	Loss of supply to Shinas	5	16	80
Burst in main from Shinas IR to Shinas SR	500	10.5	Ductile Iron	0	2	0.6	50978	More than one per year	Loss of supply to Shinas	5	16	80
Burst in main from Sohar DP (IWPP) to Sohar IR &SR	1200	18.8	Mild Steel	0	0	4.0	434739	One in one to five years	Loss of supply to Sohar, Saham, Al Khaburah, and Suwayq	4	16	64
Burst in main from Sohar IR & SR to Saham SR	1200	39.9	Mild Steel	1	1	1.3	280508	One in one to five years	Loss of supply to Saham, Al Khaburah, and Suwayq	4	16	64
Burst in main from Saham SR to Al Khaburah SR	1000	30.0	Mild Steel	0	1	0.9	151450	More than one per year	Loss of supply to Al Khaburah	5	16	80
Burst in main from Al Khaburah SR to Suwayq SR	900	44.9	Mild Steel	1	2	0.6	138122	More than one per year	Loss of supply to Suwayq	5	16	80
Burst in main from Sohar DP (IWPP) to MPS1 Res	700	30.7	Mild Steel	0	0	2.5	75023	One in one to five years	Loss of supply to Buraymi	4	16	64
Burst in main from MPS1 Res to MPS2 Res	700	13.9	Mild Steel	0	1	1.7	75023	One in one to five years	Loss of supply to Buraymi	4	16	64
Burst in main from MPS2 Res to Buraymi IR	700	24.9	Mild Steel	0	1	1.1	75023	One in one to five years	Loss of supply to Buraymi	4	16	64
Burst in main from Buraymi IR to Buraymi SR	600	15.5	Ductile Iron	1	1	0.7	75023	More than one per year	Loss of supply to Buraymi	5	16	80
Burst in main from Buraymi IR to Buraymi SR	500	23.5	Ductile Iron	1	2	0.4	75023	More than one per year	Loss of supply to Buraymi	5	16	80

Table D.2 - Cont.: Risks to the North Batinah and Buraymi Water Supply System

Pumping Stations

Hazard	Standby Arrangement	Operational Capacity (m^3/d)	Likelihood (L)	Consequence	L	C	Risk
Pump failure - Sohar to Shinas PS	2 operational + 1 standby	26112	One in one to five years	Loss of supply to Shinas and Liwa	4	16	64
Loss of power - Sohar to Shinas PS	None	26112	One in one to five years	Disruption of supply to Shinas and Liwa	4	16	64
Failure of control systems - Sohar to Shinas PS	-	26112	One in one to five years	Disruption of supply to Shinas and Liwa	4	16	64
Pump failure - Sohar DP to Sohar IR PS	3 operational + 1 standby	147744	One in one to five years	Loss of supply to Sohar, Saham, Al Khaburah, and Suwayq	4	16	64
Loss of power - Sohar DP to Sohar IR PS	None	147744	More than one per year	Disruption of supply to Sohar, Saham, Al Khaburah,Suwayq	5	16	80
Failure of control systems - Sohar DP to Sohar IR PS	-	147744	One in one to five years	Disruption of supply to Sohar, Saham, Al Khaburah, and Suwayq	4	16	64
Pump failure - Mountain PS1	2 operational + 1 standby	34896	One in one to five years	Loss of supply to Buraymi	4	16	64
Loss of power - Mountain PS1	None	34896	More than one per year	Disruption of supply to Buraymi	5	16	80
Failure of control systems - Mountain PS1	-	34896	One in one to five years	Disruption of supply to Buraymi	4	16	64
Pump failure - Mountain PS2	2 operational + 1 standby	34896	One in one to five years	Loss of supply to Buraymi	4	16	64
Loss of power - Mountain PS2	None	34896	More than one per year	Disruption of supply to Buraymi	5	16	80
Failure of control systems - Mountain PS2	-	34896	One in one to five years	Disruption of supply to Buraymi	4	8	32

Loss of Supply from Desalination Plant

Hazard	Operational Capacity (m^3/d)	Average Daily Flow (m^3/d)	Storage at Desalination Plant (m^3)	Storage (hours of supply capacity)	Potential loss of Supply (m^3)		Likelihood	Consequence	L	C	Risk
					Mini	Max.					
Loss of Supply from Sohar DP	151000	102727	135000	21.5	0	0	One in one to five years	< 12 hours partial reduction in treated water production (>34% of design output)	4	1	4
Loss of Supply from Sohar DP	151000	102727	135000	21.5	0	0	One in one to five years	<12 hours loss of treated water production	4	2	8
Loss of Supply from Sohar DP	151000	102727	135000	21.5	0	113612	One in one to five years	12– 48 hours loss of treated water production	4	4	16
Loss of Supply from Sohar DP	151000	102727	135000	21.5	113611.6	627245	One in one to five years	2 – 7 days loss of treated water production	4	8	32
Loss of Supply from Sohar DP	151000	102727	135000	21.5	627244.8	>>627245	One in five to twenty years	>7 days loss of treated water production	3	16	48

D.3 As Sharqiya Transmission System

1) Transmission Mains:

There is a medium risk in the system should a burst occur along the length of transmission mains in the Sharqiyah Region. The long single transmission main will always be at risk from failure and it will be necessary to ensure provision of supplies whilst the main is repaired. Currently there is sufficient storage available however in the reservoirs to meet the average demand in the event of a burst.

2) Pumping Stations:

The pumping stations all have adequate standby and provided this standby capacity is maintained, there is a minimal risk of loss of supply to consumers due to failure of the pumps. The system has at least one day's emergency storage throughout, which we expect to be adequate time to resolve any loss of power supply and control system failures. Only more prolonged outages are likely to affect consumers.

3) Loss of Supply at Sur Desalination Plant:

There is adequate storage in the system to cover for the loss of supply from the Sur desalination plant for up to 48 hours.

4) Mitigating Measures:

The risks associated with pipeline bursts and pump failures within the Ash Sharqiyah region is not high. Currently there is sufficient storage capacity within the system to cater for short term outages. In the event of longer term outages, increasing the capacity of storage will mitigate against loss of supply. This can be done either by increasing the volume of storage at the existing desalination plant or further downstream closer to the supply areas.

The Ash Sharqiyah Region is an isolated zone where the only other source of supply is from the Sharqiyah Sands wellfields. An interconnection between Izki in Dakhliyah to Lizq may prove to be a possible economic solution to providing security of supply.

The risks to Ash Sharqiyah water supply system are summarized in Table (D.3).

Table D.3: Risks to the As Sharqiya Water Supply System

Transmission Mains											
Hazard	**Diameter (mm)**	**Length (km)**	**Material**	**Expected Nr of failures/yr**	**Cumulative Nr of failures**	**Expected Nr 1:x yr failures**	**Likelihood**	**Consequence**	**L**	**C**	**Risk**
Burst in main from Sur to Al Fulayj	914	19.5	Steel	0	0	4	One in one to five years	Loss of supply to whole system	4	16	64
Burst in main from Al Fulayj to Ma'ayah Pass	914	24.2	Steel	0	1	2	One in one to five years	Loss of supply to Bidiyah, Al Qabil, Ibra and Mudaybi	4	16	64
Burst in main from Ma'ayah Pass to Al Kamil	914	22.7	Steel	0	1	1	One in one to five years	Loss of supply to Bidiyah, Al Qabil, Ibra and Mudaybi	4	16	64
Burst in main from Al Kamil to Shariq	800	52.0	Ductile Iron	1	2	1	More than one per year	Loss of supply to Al Qabil, Ibra and Mudaybi	5	8	40
Burst in main from Shariq to Al Qabil	700	21.2	Ductile Iron	0	2	1	More than one per year	Loss of supply to Ibra and Mudaybi	5	8	40
Burst in main from Al Qabil to Ibra	400	19.7	Ductile Iron	1	3	0	More than one per year	Loss of supply to Ibra	5	8	40
Burst in main from Al Qabil to Mudaybi	600	18.5	Ductile Iron	1	2	0	More than one per year	Loss of supply to Mudaybi	5	8	40

Pumping Stations							
Hazard	**Standby Arrangement**	**Operational Capacity (m^3/d)**	**Likelihood (L)**	**Consequence**	**L**	**C**	**Risk**
Pump failure - Sur PS	4 operational + 2 standby	68640	One in one to five years	Partial loss of supply to whole system	4	16	64
Loss of power - Sur PS	None	68640	More than one per year	Loss of supply to whole system	5	16	80
Control system	None	68640	One in one to five years	Loss of supply to whole system	4	16	64
Pump failure - Al Fulayj PS	4 operational + 2 standby	68640	One in one to five years	Partial loss of supply to whole system	4	16	64
Loss of power - Al Fulayj PS	None	68640	More than one per year	*Partial loss of supply to Bidiyah, Al Qabil, Ibra and Mudaybi*	5	16	80
Control system	None	68640	One in one to five years	Loss of supply to Bidiyah, Al Qabil, Ibra and Mudaybi	4	16	64
Pump failure - Al Kamil PS	1 operational + 1 standby	7104	One in one to five years	Partial loss of supply to Al Qabil, Ibra and Mudaybi	4	16	64

Table D.3 - Cont.: Risks to the As Sharqiya Water Supply System

Hazard	Standby Arrangement	Operational Capacity (m^3/d)	Likelihood (L)	Consequence	L	C	Risk
Loss of power - Al Kamil PS	None	7104	More than one per year	Loss of supply to Al Qabil, Ibra and Mudaybi	5	8	40
Control system	None	7104	One in one to five years	Loss of supply to Al Qabil, Ibra and Mudaybi	4	16	64
Pump failure - Shariq PS	2 operational + 2 standby	20717	One in one to five years	Partial loss of supply to Al Qabil, Ibra and Mudaybi	4	16	64
Loss of power - Shariq PS	-	20717	More than one per year	Loss of supply to Al Qabil, Ibra and Mudaybi	5	8	40
Control system	None	68640	One in one to five years	Loss of supply to Al Qabil, Ibra and Mudaybi	4	8	32
Pump failure - Al Qabil PS to Ibra	2 operational + 2 standby	5760	One in one to five years	Partial loss of supply to Ibra	4	16	64
Loss of power - Al Qabil PS		5760	More than one per year	Loss of supply to Al Qabil, Ibra and Mudaybi	5	8	40
Control system	None	5760	One in one to five years	Loss of supply to Al Qabil, Ibra and Mudaybi	4	8	32
Pump failure - Al Qabil PS to Mudaybi	2 operational + 1 standby	16752	One in one to five years	Partial loss of supply to Ibra	4	16	64
Loss of power - Al Qabil PS		16752	More than one per year	Loss of supply to Ibra	5	8	40
Control system	None	16752	One in one to five years	Loss of supply to Ibra	4	8	32

Loss of Supply from Desalination Plant

Hazard	Operational Capacity (m^3/d)	Average Daily Flow (m^3/d)	Storage at Desalination Plant (m^3)	Storage (hours of supply capacity)	Potential loss of Supply (m^3)		Likelihood	Consequence	L	C	Risk
					Mini	Max.					
Loss of Supply from Sur DP	80000	60868	164000	49.2	0	0	One in one to five years	< 12 hours partial reduction in treated water production (>34% of design output)	4	1	4
Loss of Supply from Sur DP	80000	60868	164000	49.2	0	0	One in one to five years	<12 hours loss of treated water production	4	1	4
Loss of Supply from Sur DP	80000	60868	164000	49.2	0	0	One in one to five years	12 – 48 hours loss of treated water production	4	1	4
Loss of Supply from Sur DP	80000	60868	164000	49.2	0	262076	One in one to five years	2 – 7 days loss of treated water production	4	16	64
Loss of Supply from Sur DP	80000	60868	164000	49.2	262076	>>262076	One in five to twenty years	>7 days loss of treated water production	3	16	48