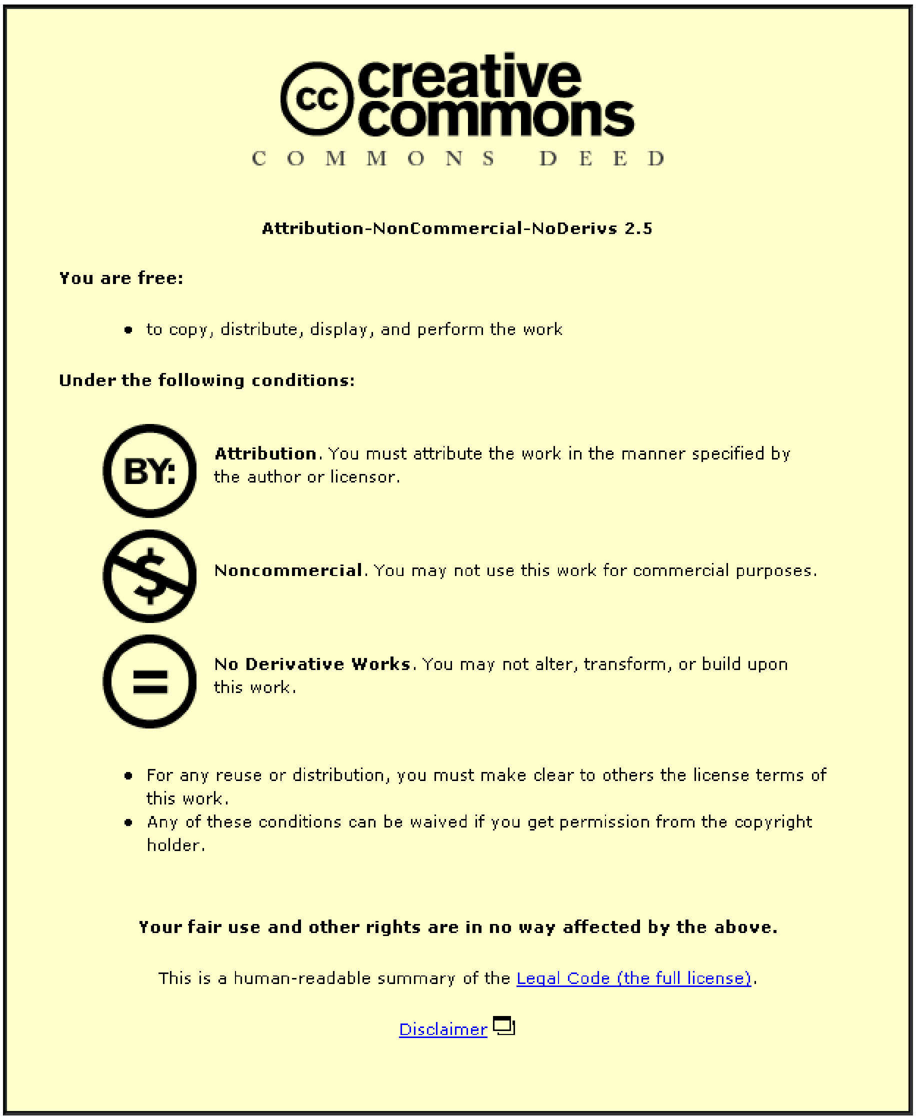

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INCLUSION OF ENERGY EXTERNALITIES IN THE ECONOMIC LEVEL OF LEAKAGE (ELL) MODEL

By
Camilo Muñoz-Trochez

Thesis

Submitted in partial fulfilment of the requirements for the award of Master of Philosophy of Loughborough University

October 2011

Loughborough
University

CERTIFICATE OF ORIGINALITY

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ABSTRACT

The Economic Level of Leakage (ELL) is the leakage level which minimizes the total of the present value cost of leakage management and the present value cost of the water lost through leakage. Reducing the leakage below the ELL would cost a water utility more than the benefits of the leak reduction. The overall aim of this research is to contribute to the reduction of carbon emissions associated with management of water leakages in water distribution networks. This study adapted an IWA methodology for the determination of an Economic Level of Leakage that incorporates energy externalities associated with active leakage detection, for a water distribution zone in the city of Zaragoza, Spain, which has no history of active leakage management.

The methodology used in this research divided the leakage into four components: Reported Burst Volumes, Estimated Background Leakage, Trunk Mains and Service Reservoir Leakage and Economic Unreported Real Losses. In the case of the Economic Unreported Real Losses, the calculation requires only three system-specific parameters: Cost of Intervention (CI), Variable Cost of Lost Water (CV), and Rate of Rise of Unreported Leakage (RR). Of these parameters, the most critical in the research was the RR due to the experimental nature.

The Estimated Background Leakage was calculated using the Burst and Background Estimate (BABE) method which requires field data such as the number of bursts, the average zone night pressure, length of mains, trunk-main losses, and number of billed properties that might not be available but that can be obtained by the water utility with a reasonable level of investment. According to the experience with the Water Utility in Zaragoza, the lack of a centralized depository of information in the Water Utility made the data collection process complicated for some data. It was noted that the main problem is not the lack of standardization between databases, but the lack of awareness of the information collected or considered by other teams in the water utility. This awareness can be improved by sharing the access to information between teams. Implementing a centralized information management system can solve the problem.

The utility in Zaragoza estimated non-revenue water (NRW) to the tune of 21 million m^3 (i.e. 34% of system input volume) in 2008 when the fieldwork was carried out. Approximately half of the NRW (about 9-12 million m^3) was estimated to be physical losses in the distribution network. The model developed as part of this study show that the estimated ELL was 1,638 $m^3 x10^3$/yr, based on only one approach for active leakage detection (using noise loggers). It can be seen that the physical losses are between 5.5-7.3 times bigger than the ELL. This shows that investment in Active Leakage Control would provide significant economic and financial benefits, and improve the performance of the water utility.

This research found that inclusion of energy externalities raised the ELL value by 0.4%, which appears insignificant. However, quantifying the emissions will be useful in future scenarios when various national legislations will make it compulsory to report on the energy emissions. Therefore, the model developed in this research can be adapted by utilities with limited data to quantify the effect of energy externalities in the water distribution systems. This has future important implications for policy and practice.

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List of Abbreviations

ABLPBL	Additional Background Leakage if ICF = Predicted Background Leakage
ARLSR	Allowances for Real Losses from Service Reservoirs
ARLTM	Allowances for Real Losses from Trunk Mains
ABI	Annual Budget for Interventions
CV	Assumed Variable Cost of Water
AVLDM@50m	Assumed Volume Lost per Reported Burst or Leak @ 50m Pressure in Distribution Mains
AVLSC@50m	Assumed Volume Lost per Reported Burst or Leak @ 50m Pressure in Service Connections
Lp	Average Length of Service Connections from Property Boundary to Meter
RR	Average Rate of Rise of Unreported Leakage
ASP	Average System Pressure
AZNP	Average Zonal Night Pressure
BL@50mM	Background Leakage @ 50m pressure and ICF = 1.0 for Mains
BL@50mSC	Background Leakage @ 50m Pressure and ICF = 1.0 for Service Connections
BEVCMI	Best Estimation Volume Customer Meter Inaccuracies and Data Handling Errors
CFEFDLK	Coefficient for Emission from Driving for Leakage Control
CEPL	Coefficient for Emission from pipe lying
DC	Connection Density
CELCA	Cost of Estimated Emissions from Leakage Control Activities
CI	Cost of One “Whole System” Intervention, Excluding Cost of Repairs
CARL	Current Annual Volume of Real Losses
DHEO	Data Handling Errors in the Office
Lm	Distribution and Transmission Pipe Length
EIF	Economic Intervention Frequency
EP	Economic Percentage of System to be Checked
EURL	Economic Unreported Real Losses
EBMRP	Effect of Bad Meter Reading Practices
EPL	Emission from Pipe Laying
EDLC	Emissions due to Driving for Leakage Control
ELCW	Emissions due to Labour, Commuting and Welfare
ECU	Emissions from Compressor Use
EGU	Emissions from Generator Use
ERE	Emissions from Repair Events
EBLPBL	Estimated Background Leakage for ICF= Predicted Background Leakage
ELCA	Estimated Emissions from Leakage Control Activities
ENAM	Estimated Number of Altered Meters
N1DM	FAVAD N1 for Distribution Mains
N1SC	FAVAD N1 for Service Connections
ICF	Infrastructure Condition Factor
ILI	Infrastructure Leakage Index
LWVEEI	Lost Water Volume in Each Economic Intervention
LWVV	Lost Water Volume Value
MANC	Meter Alteration Non Authorised Consumption
MLC	Minimum Legal Consumption
NRW	Non-Revenue Water
NTPC	Non-Traded Price of Carbon
NRBLDM	Number of Reported Burst and Leaks in Distribution Mains

NRBLSC	Number of Reported Burst and Leaks in Service Connections
Nc	Number of Service Connections
ONC	Other Non-Authorised Consumption
RDM%	Percentage of Rigid Distribution Mains
RSC%	Percentage of Rigid Service Connections
PI for Real Losses	Performance Indicators
PBL	Predicted Background Leakage
RR	Rate of Rise of unreported leakage
RTDM	Repair Time in Distribution Mains
RTSC	Repair Time in Service Connections
RBVDMSC	Reported Burst Volume in Distribution Mains and Service Connections
RBVSC	Reported Burst Volume on Service Connections
RBVDM	Reported Burst Volumes on Distribution Mains
SRLME	Service Reservoir Leakage at Margin of Error for ICF
SRELI	Short-Run Economic ILI
SRELL	Short-Run Economic Level of Leakage
DMA	The Concept of District Metered Areas
ILI	The Infrastructure Leakage Index
UARL	Unavoidable Annual Real Losses
UARLDM	Unavoidable Annual Real Losses per Metre of Pressure for Distribution Mains
UARLSC	Unavoidable Annual Real Losses per Metre of Pressure for Service Connections
UBLICF	Unavoidable Background Leakage for ICF=1.0
UBLperDay	Unavoidable Background Leakage per Day for ICF=1.0
UBNMC	Unbilled Non-metered Consumption
CV	Variable Cost of lost water
VCU	Volume of fuel in Compressor Use
VGU	Volume of Fuel in Generator Use
VEDM	Volume per Event in Distribution Mains
VESC	Volume per Event in Service Connections

1 INTRODUCTION

In July 2010, the General Assembly of the United Nations adopted Resolution 64/292 ("The human right to water and sanitation"), which not only acknowledged the importance of equitable access to safe and clean drinking water and sanitation as an integral component of the realization of all human rights" but also "recognized the right to safe and clean drinking water and sanitation as a human right that is essential for the full enjoyment of life and all human rights".

Scanlon et al (2004) mentions that for the concept of accessibility, water must be within safe physical reach for all (Physical accessibility), affordable (Economic accessibility) and accessible to all in law and in fact (Non-discriminatory). And one of the most important actors in that work are water utilities. Water utilities struggle to deliver water within the criteria previously described, 24 hours a day. But they also face challenges. Howe et al (2011) presents a list of challenges currently faced by the water utilities which include:

- Climate change. The water supply is directly affected by climate change. The water utilities must be aware of the effects and plan according to those effects.
- Population growth and urbanization. According to WHO/UNICEF Progress on sanitation and drinking-water 2010 update (WHO/UNICEF, 2010), 87% of the population gets their drinking-water from improved sources, and the corresponding figure for developing regions is also high at 84% While 94% of the urban population of developing regions uses improved sources, it is only 76% of rural populations. The water utilities must keep that level of service and consider the water supply needed for a future population growth.
- Governance and policies. This can affect not only the economic plans of the water utilities but the access to new water supplies due to new institutional frameworks, political regimes, global policies.
- Deterioration of infrastructure systems. In many cities the pipe networks are old and need to be replaced. The water utilities need to be aware of leakage problems and the consideration of maintenance versus replacement.
- Changes in public priorities. For example the consideration of new attitudes regarding environmental protection that affect the water utilities.
- Emerging technologies, energy costs and increasing complexity. The water utilities should consider the use of cutting edge technology to improve their service and economic performance.

As we can see, the challenges cover a very broad spectrum in very different fields. For this reason, this chapter will focus on the population growth, climate change, leakage and the consumption of energy in the water supply system, present those challenges and the structure of this research in the following sections.

1.1 The Population Growth and Urbanization Issue

There is a continuous increase in the world population. According the UN, the world population reached 6.7 billion in July 2007, 5.4 billion of whom will live in the less developed regions (United Nations, 2007). Assuming a declining fertility rate, the world population is projected to increase to 9.2 billion by 2050, and the biggest increment in population will be in developing countries (ibid).

This population increase has being reflected in an increased of population in urban areas. Now urban areas account for over half of the world's population. (UN-HABITAT, 2006). Between 2000 and 2030, it is projected that there will be an increase of urban population of 2.12 billion, with over 95% of this increase expected to be in low-income countries (UN-HABITAT, 2004). Those urban centres will require access to water.

However the supply of water for this urban areas would be complex considering that surface freshwater resources (river discharges, lake levels) are not adequately monitored and hydrographic networks are shrinking worldwide (Kundzewicz and Doll, 2009) and that the world's freshwater supply is not equally distributed across countries, within countries and between seasons (Shiklomanov, 2000). This issue will require a new perspective on the water management.

1.2 The Climate Change Issue

As Shiklomanov mentioned (ibid), there is a seasonal variation in the water supply. This is aggravated by the human impact on weather. In general, the negative impacts of climate change on freshwater systems outweigh any benefits (Kundzewicz and Doll, 2009).

Scientific evidence confirms that climate change is already taking place and that most of the warming observed during the past 50 years is due to human activities that increase the concentrations of greenhouse gases in the earth's atmosphere, that absorb infrared radiation. In particular, concentrations of carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) have increased over the last century as the result of emissions from fossil fuels and industrial processes (IPCC 2007). The climate change projections suggest increased variability in rainfall, more frequent extreme events and increased temperatures. (Mukheibir and Ziervogel, 2007). This can be translated in an increase of floods and reduction of water available during dry seasons. According to Stern, a temperature raise of 2°C may result in 1-4 billion people of developing countries experiencing water shortages (Stern, 2007) due to higher temporal flow variations that stem from increased precipitation variability and reduced summer low flows in snow-dominated basins (Kundzewicz and Doll, 2009).

The water supply systems themselves contribute to climate change through greenhouse gas emissions from the use of energy. Water producing consumes energy in pumping, treatment and distribution process, and these costs apply to water lost in leakage in the same way as they do to water delivered to consumers. This energy demand is growing not only for having a greater population but also because it becomes necessary to develop newer and more energy-intensive water sources for expanding cities and/or to meet higher service quality levels. Desalination is an example of a high energy water source which is becoming more widely used (Darwish et al, 2003).

However is important to stress that the energy cost is not only the financial cost of generation and distribution. There are externalities associated with the process of generation and distribution such as the impact of the construction of the infrastructure or the possible problems generated to the environment during the generation process. With the growth in energy use, an increase in energy costs for business and government will result in increased emissions of greenhouse gases from electricity generation, with the consequent impact on the climate change, and the additional strain on the existing power grid or energy source to meet the higher energy demand.

1.3 Leakage and the Leakage/Energy Relationship

The water industry understands how leakage control allows an improvement in performance and also represents a new source of water.

But leakage control also improves the water quality. During a leak, the intrusion of contaminants such as soil or waste water can generate a change in the taste, odour and colour of the water, decrease in the quality and introducing pathogens. This contaminants get into the pipe as a product of the back-siphonage of water due to the pressure reduction in the system, especially under conditions of intermittent supply as found in the cities of many developing countries. According to (Thornton et al, 2008) 24% of waterborne disease outbreaks reported in community water systems during the 90's where caused by contaminants that entered the distribution system and not by poorly treated water. A better control of the leakages can prevent this type of events.

The reduction of costs and expenses is another result of leakage control. As an example, the results of the UK water industry that, driven by a mixture of economic, political and social factors (WRc, 1994) and (Lambert et al. 1998), started working on the subject.

Figure 1.1 shows the UK water industry annual leakage estimates from 1994-95 and the targets until 2009-10. Each bar represents total leakage split between leakage on company pipes (distribution losses) and leakage on consumers' pipes (underground supply pipe leakage) (OFWAT, 2009).

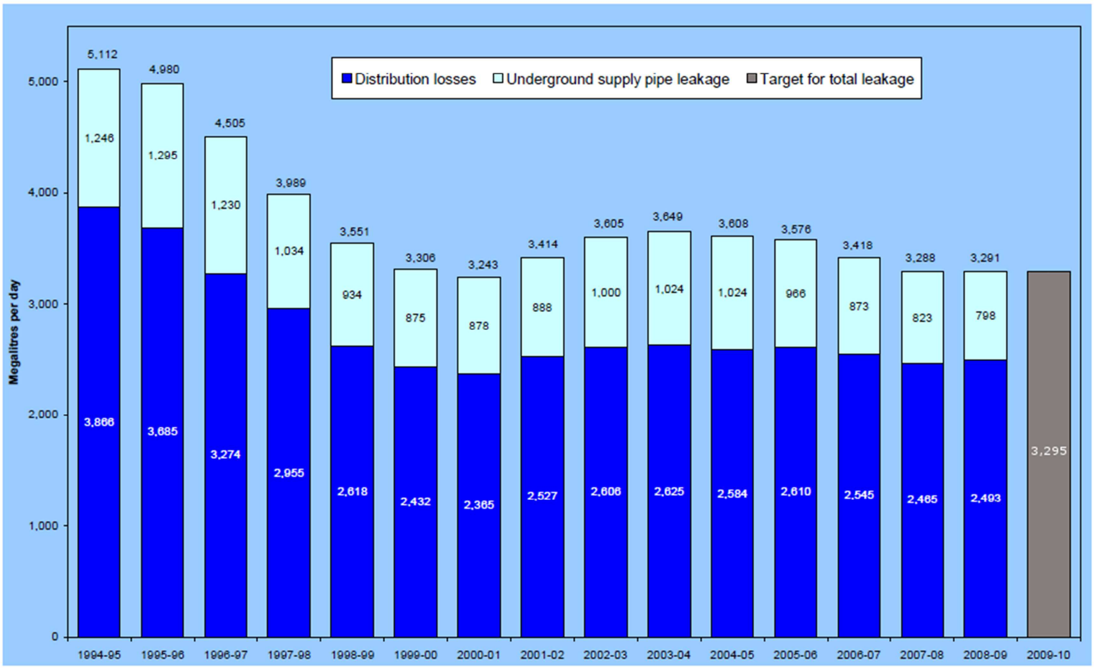


Figure 1.1: Total industry leakage 1994-95 to 2009-10
(Source: Adapted from OFWAT, 2009)

The reduction in leakage volumes can be reflected as a reduction in energy, chemicals and staff costs. If the focus is the energy component of leakage, it is found that, after staff costs, energy consumption is generally the second most important operating expense in the water utilities, and this might be more critical in developing countries. Increasing attention is being paid to the potential savings through increasing efficiency. For example, a 5% reduction in water distribution system leakage would save 270 million gallons per day of water and 313 million kWh of electricity annually, equal to the electricity use of over 31,000 homes. In addition, approximately 225,000 metric tons of CO_2 emissions could be avoided (Griffiths-Sattenspiel and Wilson, 2009).

The energy use and the relationship with the different approaches for leakage control in the "water distribution labyrinth" are represented in Figure 1.2. The figure shows the various factors that contribute to the total cost of the system and how they inter-relate with the capacity, demand and performance of the system. A system failure has a direct influence on the performance, which is related with the demand. A high demand and a bad performance will result in service problems with the users while a low demand and good performance allows the water utility to focus on the future development of the system since a lower water use will reduce the energy and chemicals used in water abstraction, treatment and pumping

That is the reason why the focus of the research is the sub-system shown shaded in Figure 1.2, which illustrates the interrelations between system failure, breaks, leaks, water use and energy use. The energy use on water treatment and distribution and on leakage control has an effect on the environmental impacts and climate change. The energy consumption, and the associated emissions, can be reduced when treating a lower water volume or improving the distribution conditions, resulting. A better understanding of these relationships then will be reflected in the total cost of system, performance and demand.

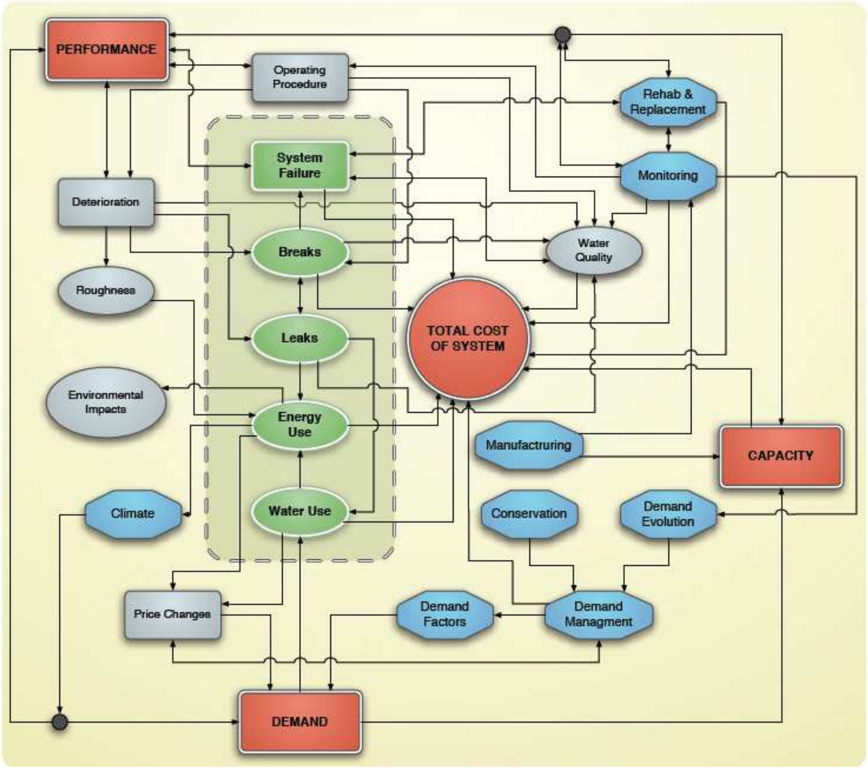


Figure 1.2: The water distribution system labyrinth
(Source: Adapted from Colombo and Karney, 2003)

(Colombo and Karney, 2002) have analysed how for pipe segments and distribution networks, leaks are shown to substantially increase energy costs. These costs depend on a variety of factors including demand regime, spatial distribution of leakage, and system complexity. In general, the percentage increase in energy cost appears to be a second-order polynomial function of leakage.

Considering the focus of this research, it becomes clear that with a future rise of either water or energy price, the importance of leak repair will become even more pronounced. But this repair has a cost and it would be pointless for the water utility if reducing leakage below would cost more than the benefits of the leak reduction. And that is where the concept of Economic Level of Leakage is useful.

The Economic Level of Leakage (ELL) is the leakage level at which the marginal cost of reducing leakage is equal to the benefit gained from further leakage reductions, that is the leakage level which minimises the total of the present value cost of leakage management and the present value cost of the water lost through leakage (OFWAT, 2008). *However the calculation of the ELL is information intensive and can be difficult for water utilities with no previous work on leakage control.* This research aims to make a contribution to solving this problem.

1.4 Aim and Objectives of the Research

1.4.1 Aim

The main aim is to contribute to the reduction of carbon emissions and control climate change through the development of a dynamic model for the determination of Economic Level of Leakage that considers changes in Energy Externalities associated with the Active Leakage Control activities. The use of a dynamic model is considered because some of the conditions, like the energy costs and resources availability, are constantly changing. This change has an impact on the performance of the leakage control activities.

1.4.2 Objectives

1) The main objective of this research is to develop a dynamic model for the determination of an Economic Level of Leakage considering the energy externalities associated with Active Leak Control, in a water distribution network.

2) That model will then be calibrated and then the validity and sensitivity will be tested.

3) The calibrated model will be used to perform the analysis of different scenarios strategies for water loss management in Economic Level of Leakage and study their effect on the active leakage control for the city of Zaragoza in Spain.

1.5 Scope of Research

This research will focus in the calculation of the Short Run Economic Level of Leakage, for urban water distribution systems with no previous implementation of Active Leakage Control, and the calculation of energy externalities associated with the leakage control tasks.

1.6 Justification of Research

As it was showed in Section 1.2 and Section 1.3, there is a nexus between leakage in water distribution systems and energy consumption. The increasing energy and water costs will demand for a better understanding of the relationship between these variables and, especially, to be able to quantify the relationships.

The ELL allows a quantification of the leakage level that can be attained with certain level of investment. This research looks for an application of an ELL calculation methodology that can be used by a water utility that has no history of active leakage control. This will be extended with the calculation of the Energy Externalities associated with leakage control to provide an insight into the relationship between leakage and energy. Quantifying these relationships will enable the prediction and comparison of costs and benefits associated with different options for Active Leakage Control. This will in turn provide justification for investments and priorities, given that availability of financial resources in many cities of the developing world cannot cope with their growth rates.

1.7 Thesis Structure

The thesis comprises seven chapters representing the development of the research. The following is a description of each chapter:

The current chapter mentions the background on leakage control and energy use. It also presents the aims and objectives of the research and the methodologies required to fulfil them.

Chapter 2 begins with a presentation of the concepts of Urban Water Balance and the different methods used for the management of Water Loses. This chapter is divided in two sections, according to the review of the cutting edge and bleeding edge literature in the Economic Level of Leakage area and Energy Externalities inclusion in the ELL.

A dynamic model for the calculation and inclusion of externalities in the ELL, implemented in Vensim, was developed during this research. Chapter 3 will describe the methodology involved and the reason for this implementation. This includes the presentation of the variables and equations that are part of the model, commenting on the sources and value ranges expected for them. The water leakage components considered in this analysis and the calculation of externalities are explained one by one.

Chapter 4 is about the verification and application of the model. To guarantee a high level of confidence and precision in the results, the model needs to be verified before analysing the current situation in Zaragoza. The verification process is presented in this chapter. This guarantees a model in working shape, allowing the use of the model to calculate the ELL in Zaragoza and the effect of energy externalities. This chapter starts with presenting the fieldwork location, the city of Zaragoza in Spain, and how the limited information available made a point for the use of a simplified model for the calculation and the inclusion of externalities in the ELL. The different available data sources are presented and analysed.

This chapter also will present the concept of Scenario Planning. This tool allows the exploration of different futures and the changes in the results for such futures. In this research three different scenarios for Zaragoza, in 2030, have been considered and the results are presented and discussed. However, since the implementation of this model assumes a start in the ELL process, the user needs to know what variables have a higher influence in the results. A sensitivity analysis allows the understanding of the effect of variables in the model, allowing the user to be aware of which variables require a higher level of precision and care during the data collection process.

Chapter 5 is the final chapter in this document. A summary of the results of this research, conclusions, recommendations and proposed future work in the Energy Externalities subject are presented in this chapter. Finally, the bibliography used in this research is consolidated in Chapter 6.

2 LITERATURE REVIEW

2.1 Introduction

Water loss occurs in all distribution systems - only the volume of loss varies (Farley, 2003). This depends on the characteristics of the pipe network and other local factors such as the level of technology and expertise applied to controlling it. These are the reasons why the volume lost varies widely from country to country, and between regions of each country.

One of the key steps of a water loss strategy is to understand the relative significance of each of the components, ensuring that each is measured or estimated as accurately as possible, so that priorities can be set via a series of action plans (ibid).

This chapter presents the standard terminology used in the water loss control, so the problem can begin to be understood, according to the reviews of the Water Losses Task Force of existing methodologies for international comparisons of Water Losses from water supply systems. The main objectives of this review were to prepare a recommended basic standard terminology for calculation of real and apparent losses and to review and recommend preferred performance indicators for the international comparisons of losses (Hirner and Lambert, 2000).

With this background, the next section is the description of the concept of IWA standard Water Balance, the different Water Loss Management Methods and Performance Indicators used in the water loss control. With this foundation, the chapter will present the concept of Economic Level of Leakage (ELL) and the calculation procedures, to finish with the energy use in the urban water utilities and the why it should be included in the calculation of the ELL using the concept of Energy Externalities.

This literature review was carried out by collecting and reading the state of the art papers from the database collection in Loughborough University. This was kept updated using RSS alerts with keywords such as "ELL", "Energy Externalities" and "water energy use". Other important sources of information were conference proceedings, official documents about the subjects stated and from interviews and email exchanges with field experts. This allowed a better understanding of the current state of the research and exposed the actual gaps in the ELL and Energy Externalities calculation.

2.2 The Urban Water Balance and NRW

The develop of a leakage control strategy, for any network, needs to ask some questions about the network and how it is operated, and then select the right tools to find the solutions. (Farley, 2001) presents the following questions and tools for finding the solution to those questions, which are summarized in Table 2.1

Question	Tool
HOW MUCH is being lost?	WATER AUDIT Measure components Check production /consumption Recalculate water balance Review records/operating procedures/skills
WHERE is it happening?	PILOT STUDIES Quantify total losses How much is leakage? — distribution network — transmission mains — reservoirs How much is non-leakage losses? Refine the water balance calculation
WHY is there water loss?	REVIEW NETWORK Investigate: Historical reasons Poor practice/poor QA (Quality Assurance) Poor materials/infrastructure Local influences Cultural/financial/social/political factors
HOW TO IMPROVE performance?	ACTION PLANS/STRATEGY DEVELOPMENT Update records systems/GIS Introduce zoning/DMAs Monitor water losses and leakage Prioritize areas Address non-physical losses Detect and locate leaks Initiate repair/rehabilitation policy
HOW TO MAINTAIN the strategy?	TRAINING/AWARENESS Improve awareness Increase motivation Transfer skills Introduce best practice/appropriate technology Give hands-on experience/continual reinforcement Monitor and follow-up action plans /implementation Involve community Consider demand management policy Initiate water conservation programme

Table 2.1: Questions and tools for the developing of a leakage strategy (Source: Farley, 2001)

The key to developing a water loss strategy is to gain a better understanding of the reasons for losses and the factors which influence them (Farley, 2003). This is the reason why the first step is to develop a Water Audit.

Water Audits are generally classified into comprehensive water audits and district flow audits (Hunaidi et al, 1999). A comprehensive water audit involves detailed accounting of water flow into and out of the distribution system. Normally, it is based on past meter records and flowmeter checks (ibid).

The district flow audits, on the other hand, are performed by first dividing the distribution system into District Metered Areas (DMA). The concept of DMA will be explained in the section 2.5 of this chapter but for the effect of current section, a DMA can be defined as hydraulically discrete part of the distribution network that is isolated from the rest of the distribution system. It is normally supplied through a single metered line so that the total inflow to the area is measured (Thornton et al, 2008).

The district flow audit measures the water flow into a district over a 24-hour period. The ratio between the night time minimum rate and average daily rate of water flow is then used to determine whether excessive leakage exists or not. Alternatively, if all service connections in the water system are metered, more accurate information about leakage can be obtained by monitoring water flow and usage in the isolated zone over an extended time period, e.g. one week. Meters are read at the beginning and end of the monitoring period to calculate water loss. District flow audits can be performed separately as needed or as an extension of comprehensive water audits (Hunaidi et al, 1999).

Water audits help to identify parts of the distribution system that have excessive leakage, and hence they are an important part of any effective leakage control program. Unfortunately, however, they do not provide information about the location of leaks (ibid).

2.2.1 Water Balance

The Water Balance summarizes the results of the water audit in a standardized format (Thornton et al, 2008). The terms "water audit" and "water balance" are often interchanged but when talking about a water audit it means the work related to tracking, assessing, and validating all components of water flow from the site of withdrawal or treatment, through the water distribution system and into customer properties.

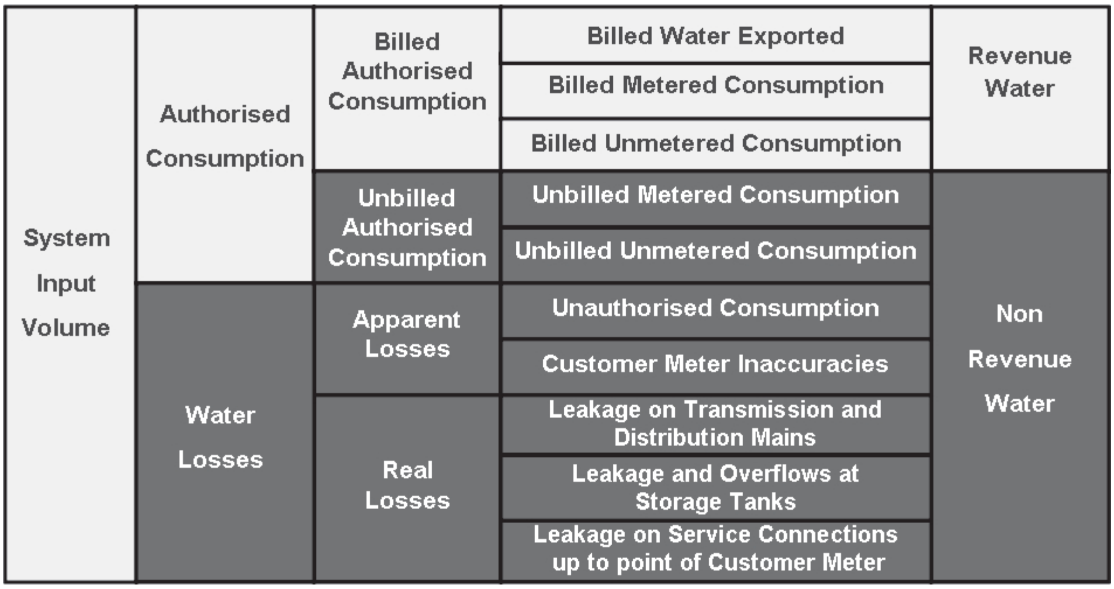
This concept has been developed during the last decade using Lambert's work as a framework (Lambert et al, 1999) and is defined by the IWA Task Forces on Performance Indicators and Water Losses as a summary of all the components of consumption and losses in a standardized form (Thornton et al, 2008). Figure 2.1 shows the standard IWA water balance.

The different components of the IWA standard water balance are defined as (Lambert, 2003):

- The System Input is defined as the volume input to that part of the water supply system to which the water balance calculation relates.
- Authorised Consumption is the annual volume of metered and/or non-metered water taken by registered customers, the water utility and others who are implicitly or explicitly authorised to do so, for residential,

commercial and industrial purposes. It also includes the Authorised Unbilled Consumptions, such as municipal uses, and the water exported to other systems.

- Water Losses is the difference between System Input Volume and Authorised Consumption. It consists of Apparent Losses (Unauthorised Consumption and all types of inaccuracies associated with metering) and Real Losses. In the Real Losses include the volume of water lost due to leaks, burst and overflows on mains, service reservoirs and service connections. This means the *physical* losses in the system.



System Input Volume	Authorised Consumption	Billed Authorised Consumption	Billed Water Exported	Revenue Water
			Billed Metered Consumption	
			Billed Unmetered Consumption	
		Unbilled Authorised Consumption	Unbilled Metered Consumption	Non Revenue Water
			Unbilled Unmetered Consumption	
	Water Losses	Apparent Losses	Unauthorised Consumption	
			Customer Meter Inaccuracies	
		Real Losses	Leakage on Transmission and Distribution Mains	
			Leakage and Overflows at Storage Tanks	
			Leakage on Service Connections up to point of Customer Meter	

Figure 2.1: IWA standard water balance
(Source: Hirner and Lambert, 2000)

So every unit of water supplied into the system is assessed and assigned to the appropriate component (Thornton et al, 2008). Once the authorized consumptions and losses (apparent and real) have been assigned, the cost impact of these components can be calculated. The water balance then allows the water utility to answer "How much water is being lost?" and "where is it being lost?" (Farley, 2003).

The answers will then allow the selection of the appropriate approach to control real and apparent losses. To integrate this with the usual budget structure, the water balance is calculated on an annual basis.

2.2.2 Non-Revenue Water (NRW)

Non-Revenue Water (NRW) is the difference between the System Input Volume and Billed Authorised Consumption. NRW consists of: Unbilled Authorised Consumption, Apparent Losses and Real Losses. According to (Liemberger, 2010), the Unbilled Authorised Consumption is those components of Authorized Consumption which are legitimate but *Unbilled* and therefore do not produce revenue.

All these three components add up a volume of water that is not generating profit for the water utility and that has to be identified and controlled. The Water Balance allows the identification of the critical components to prioritize their control. Also consider the use of the term “Non-revenue water”, instead of “Unaccounted for water”, since it avoids the misinterpretation and manipulation associated with the latter term (McKenzie and Lambert, 2004).

2.3 Water Loss Management Methods

Managing physical water losses in the distribution network is a critical aspect of water demand management. According to (Thornton et al, 2008), this gives an indication of the level of governance, autonomy, accountability and technical and managerial skills in a water utility. There are several benefits that will come out of effective and efficient water loss management by water utilities. Efficient water loss management will lead to lower production costs in terms of energy, materials and staff costs (Kayaga and Smout, 2007). This can result in a direct reduction of the costs that is equal the value of producing the amount of recovered water.

Section 2.2.1 presented the concept of Real Losses as the volume of water lost due to leaks, burst and overflows on mains, service reservoirs and service connections. (Thornton et al, 2008) goes a bit farther and introduces the concept of Current Annual volume of Real Losses (CARL). The CARL has two components: Unavoidable Annual Real Losses (UARL) and Potentially Recoverable Real Losses.

The Unavoidable Annual Real Losses (UARL) are composed of small but numerous background leakages from pipe joints and fittings that are difficult to detect using current technology, with no financial or economic constraints, and they are the lowest technically achievable volume of real losses at current operating pressure.

Potentially Recoverable Real Losses have higher leakage flows and pipe bursts, which require significant effort and investment on the part of the organisation to locate and repair them.

Since the CARL will increase as the distribution network grows older, the water utilities have four strategies that could be adopted to reduce water losses to a minimum and control the CARL. Figure 2.2 illustrate the four strategies as presented by (Liemberger and Farley, 2004).

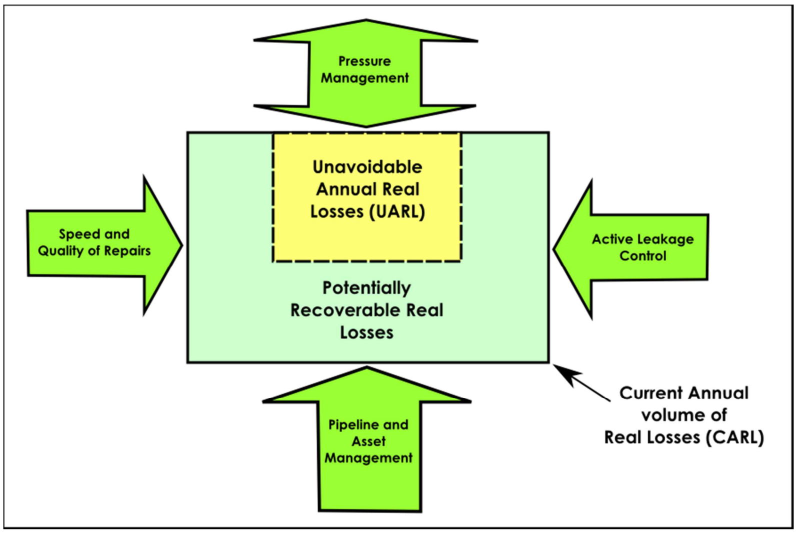


Figure 2.2: Components of water loss management strategy, as developed by IWA (Source: Liemberger and Farley, 2004)

The following sections will explain each approach: Section 2.3.1 will explain the concept of Active Leakage Control, Section 2.3.2 will explain Pipeline and Asset Management, Section 2.3.3 will explain Speed and Quality of Repairs and Section 2.3.4 will explain Pressure Management.

2.3.1 Active Leakage Control

Not all the leakages that develop in underground water pipes come up to the surface of the ground. Water from leakages and bursts follows a least resistance path, and can only appear on the surface if the flow rate and pressure reach a threshold value, which is dependent on several factors such as the ground conditions. Figure 2.3 shows how a leak can be classified in 3 types (Thornton et al, 2008):

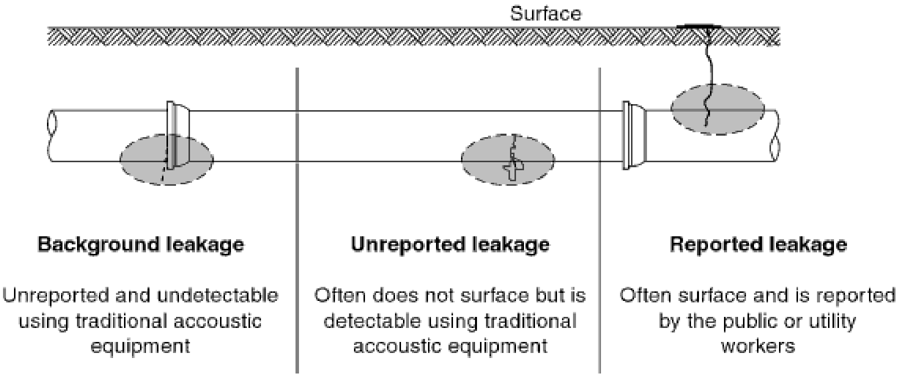


Figure 2.3: Components of Real Losses (Source: Thornton et al, 2008)

- Background leakage: They are the collective weeps and seeps in pipe joints and connections. They have flow rates that are typically too small (1 gpm (gallons per minute) or 250 L/hr) to be detected by conventional acoustic leak-detection equipment. They run continuously until they gradually worsen to the point when they can be detected. The only ways of reducing background leakage is through pressure management or infrastructure replacement.

• Unreported breaks and leaks: They are typically hidden from above-ground view, have moderate flow rates, and a long run time since utilities must seek out these leaks to become aware of them. They are located through active leak detection.

• Reported breaks and leaks: They typically have high flow rates, are visibly evident and disruptive, and have a short run time before they are reported to the utility by customers or utility personnel since they cause nuisance to the customer (pressure drop or supply interruption).

Therefore, many small and medium term leakages will manifest themselves as underground leakages for a long time, until when this threshold value is attained. In order to minimise overall leakage rates in a distribution network, a water utility needs to carry out active leakage management, which is (Liemberger and Farley, 2004) simply described as detection of leakages before they appear on the surface, using various technical equipment. Effective active leakage management requires high levels of technical and organisational capacities from the water utility side.

The usual approach to leak detection is the Leak Detection Survey (Hunaidi et al, 1999). In these surveys, the water distribution system is systematically checked for leaks employing acoustic leak detection equipment, that looks for the sound or vibration induced by water as it escapes from pressurized (ibid). This equipment includes listening devices and noise correlators (Muñoz-Trochez, 2006). Another option is the use of non-acoustic options for leak detection. This includes the use of tracer gas, thermography, ground-penetrating radar (GPR) and interferometry (ibid).

The effectiveness of existing acoustic leak detection methods and equipment has been demonstrated extensively in the past, at least in the case of metallic pipes (Hunaidi et al, 1999). The main problems for using of acoustic leak detection are (ibid):

- Interfering signals arising from heavy vehicle and pedestrian traffic, water flow in pipes themselves, and sounds from adjacent leaks.
- Signal attenuation along the pipe and in the ground.
- Insufficient sensitivity or frequency range of the measuring or listening equipment.

In the case of the non-acoustic methods, their use is very limited, and their effectiveness is not well established (Hunaidi et al, 1999).

Active Leakage Detection will be the water loss management approach where this research will focus.

2.3.2 Pipeline and Asset Management

The second strategy for minimising leakages in pipes and other assets in the distribution network is maintaining and replacing them as and when their economic life is reached. Although is the most costly and long term approach, the investment allows the improvement of leakage and water quality (Engelhardt et al, 2000).

Good asset management may be accomplished only when life cycles costs are well planned in the financial model, and when the technical team keeps an asset maintenance management information system.

(Thornton et al, 2008) describes some of the methods of Pipe Replacement and Rehabilitation and their advantages.

2.3.3 Speed and Quality of Repairs

The volume of water lost in a leakage is a function of the leak flow rate and the duration of the same, until is completely repaired. This duration involves a detection time, a localization time and a repair time. The longer the time, the bigger the volume of lost water. Therefore another strategy for leakage minimization shown in Figure 2.2 is to repair identified leakages and bursts in the shortest time possible, and to ensure that the quality of the repair work is beyond doubt (Thornton et al, 2008).

2.3.4 Pressure Management

Since the water distribution systems are designed considering a minimum pressure requirement and not a maximum pressure, certain areas of the system tend to be over pressured (Thornton et al, 2008).

In general terms, a higher system pressure results in a higher leakage flow rate, as shown in Equation 2.1. L_1 and L_0 are the leakages at pressures P_1 and P_0 respectively, and N1 varies between 0.5 and 1.5, depending on whether the cross-sectional area of the hole varies (1.5 is for the varying cross-sectional area). This means that the change in leakage rates with pressure is higher in small leaks found in pipe joints and fittings, which are normally increasing in surface area (Lambert, 2001). Furthermore, pressure fluctuations play an important role in generating fatigue failures, hence the need to have a water supply system with minimised pressure fluctuations.

$$\frac{L_1}{L_0} = \left(\frac{P_1}{P_0}\right)^{N1}$$

Equation 2.1: (Source: Lambert, 2001)

Pressure management may be the most cost effective approach to manage real losses, depending on the system pressures and topography of the service area. (Burn et al, 2002) analysed the effect of employing pressure management techniques on the operating cost of Australian water utilities and found an increase of 20-55% in the savings.

2.4 Performance Indicators (PI) for Real Losses

During the 90's, competition, drought—related water shortages and other factors generated an interest in England and Wales for the demand management and the wise use of water which required the development of Performance Indicators to evaluate water utilities.

As a result, the IWA published in 2000 "*Performance Indicators for Water Supply Services*" (Alegre et al, 2000). This document, and the second edition in 2006, is currently the best practice model for water auditing and performance measurement. The following sections discuss part of the PI considered in this document.

2.4.1 What's Wrong With Percentages?

Although the use of "percentage by volume" is the traditional PI for many components of the water balance, including non-revenue water, it can be very misleading as is strongly influenced by (McKenzie and Lambert, 2004):

- Differences and changes in the volume of consumption
- Intermittent supply
- The presence or absence of customer storage tanks

While "percentage by volume" is still recommended as a basic financial PI for non-revenue water, and a basic PI for real losses from a water resources viewpoint, it should definitely not be used for assessing any aspect of operational performance management of water losses (McKenzie, 2004). That is the reason why in addition to the standard water balance, the IWA Task Forces on Performance Indicators and Water Losses also proposed several key 'best practice' performance indicators (PI) for the different components.

In the case of real losses, the IWA Best Practice Report (ibid) clearly states that "%'s by volume" are unsuitable for assessing the efficiency of operational management of Real Losses. The main reason for this is that there are five other local factors which constrain performance in managing real losses, which can vary widely between individual distribution systems (Lambert et al, 1999):

- Continuity of supply
- Length of mains
- Number of service connections
- Location of customer meters on service connections
- Average operating pressure

This conclusion has been endorsed by many organisations throughout the world including: OFWAT in England/Wales, the national regulator in Malta, AWWA in N. America, WSAA in Australia, NZWWA in New Zealand and DWAF in South Africa (McKenzie, 2004).

(Lambert et al, 1999) also mentions that "number of service connections" should be used in PIs for real losses, rather than "number of properties". This is because there is no standard international definition of "properties"; real losses are calculated up to the first metering point, and in cities the service frequently splits into several separate pipes serving individual domestic or commercial properties after the first metering point.

2.4.2 The Infrastructure Leakage Index (ILI)

To address these deficiencies, a detailed operational PI for real losses was developed and is referred to as the Infrastructure Leakage Index (ILI). The ILI, described in Equation 2.2, is a measure of how well the three infrastructure management functions – repairs, pipelines and asset management, and active leakage control – are being undertaken. However, ILI is a purely technical performance indicator and does not take economic considerations into account.

$$\mathrm{ILI} = \cdot \frac{CARL}{UARL}$$

Equation 2.2: (Source: Lambert, 1999)

Although a well-managed system can have an ILI of 1.0 (i.e. CARL = UARL), this does not necessarily have to be the target. The greater the amount by which the ILI exceeds 1.0, the greater the potential opportunity for further management of real losses by infrastructure management and maintenance, more intensive active leakage control, or speed and quality of repairs (Lambert et al, 1999). The ILI will be discussed in a deeper way in the section 4.9.14 of this document.

2.4.3 The UARL Calculation Issue

The big issue with the ILI calculation is the UARL. The current annual real losses can be obtained from the standard water balance (Thornton et al, 2008) but there was no robust equation to determine the unavoidable losses.

To solve this, the IWA Water Loss Task Force elaborated a component-based formula and calibrated it with test results of utilities in a large number of countries. Assumptions for new leak frequency on mains (13/100 km/year) and service connections (5/1000 service connections/year) in good condition were based on published studies of repair statistics (notably the German water supply experts Hirner and Sattler, 2001).

The study uses a reference data set of 27 diverse water distribution systems in 20 countries - Australia, Brazil, Denmark, France, Finland, Germany, Gibraltar, Greece, Iceland, Japan, Maltese Islands, Netherlands, New Zealand, Singapore, Spain, Switzerland, Sweden, UK, USA, and West Bank (Palestine) – together with published data from other international sources listed in the references (Lambert et al, 1999). That data set allowed the discrimination of the different burst in different types. The classification of the bursts and the parameters required for the calculation of the UARL is presented in Table 2.2.

Component of Infrastructure	Background (undetectable) losses	Reported Bursts	Unreported Bursts
Mains	Length	Number/year	Number/year
	Pressure	Pressure	Pressure
	Min loss rate/km*	Average flow rate*	Average flow rate*
		Average duration	Average duration
Service Connections, Main to Edge of Street	Number	Number/year	Number/year
	Pressure	Pressure	Pressure
	Min loss rate/conn*	Average flow rate*	Average flow rate*
		Average duration	Average duration
Service Connections after Edge of Street	Length	Number/year	Number/year
	Pressure	Pressure	Pressure
	Min loss rate/km*	Average flow rate*	Average flow rate*
		Average duration	Average duration
* at some specified standard pressure			

Table 2.2: *Parameters required for calculation of Unavoidable annual real losses (UARL) (Source: Lambert et al, 1999)*

However, simply attributing the same average flow rate and the same average duration to every class of leak would not yield reliable predictions. Finally, the complex initial components of the UARL formula were converted to a more "user friendly" pressure-dependent format for practical use:

$$\mathrm{UARL\ (litres/day)} = (18 \cdot \mathrm{Lm} + 0.8 \cdot \mathrm{Nc} + 25 \cdot \mathrm{Lp}) \cdot \mathrm{P}$$

Equation 2.3: (Source: Lambert et al, 1999)

Where Lm = mains length (km); Nc = number of service connections; Lp = total length of private pipe, property line to customer meter (km); P = average pressure (m).

This equation will be discussed with more detail in Section 3.8 (Some Basic Concepts) but is important to mention that this equation involves not only the characteristics of the network but the pressure.

This is important because a continuous supply of pressurised water is the primary goal of a water supply system, the IWA Best Practice Manual (Alegre et al, 2000) has "Continuity of Supply" as a "Quality of Service" Performance Indicator (Qs10). However, since continuity of supply is not achieved in many countries, any Performance Indicators which are to be used internationally to compare average rates of Real Losses from systems must allow for the percentage of time the system is pressurised (Hirner and Lambert, 2000).

The length of mains and number of service connections are normally known, using the databases in the water utilities, but in the case of the value of Lp, the distance between property line and meter, seems to be a troublesome figure to obtain. Fortunately, according to (Liemberger and Farley, 2004) in some 50 per cent of situations, worldwide customer meters are located close to the property line and the Lp is effectively zero. In the remaining cases, it is relatively easy to estimate the average Lp-value by multiplying the average length obtained by random samples by the total number service connections.

The ILI measures how effectively a utility is managing real losses under the current operating pressure regime. However, it is important to note that this does not imply that the pressure management is optimal - it is usually possible to reduce the volume of real losses (but not the ILI) by improved active pressure management. This 'twin track' approach to leakage management directly addresses comments that the ILI somehow favours water utilities operating at high pressures and discriminates against those that implement strict pressure management measures (McKenzie and Lambert, 2004).

Once again, this is the subject of considerable debate. However, the speed at which water utilities throughout the world have adopted the ILI as their preferred PI for real losses is clear testament to its value in the water industry.
Theory and experience (McKenzie and Lambert, 2004) both show that it can be used with confidence for comparisons at international, national, state and within-system levels, for systems with:

- More than 5000 service connection
- More than 25m pressure, on average, throughout the system
- More than 20 service connections per kilometre of mains.

2.5 The Concept of District Metered Areas (DMA)

The calculation of the ILI requires the value of CARL. Section 2.4.3 presented the procedure for the calculation of the UARL. But, as it was mentioned in Section 2.3 (Water Loss Management Method), UARL is just one of the components of CARL. So the value of Potentially Recoverable Real Losses still needs to be found.

As was discussed in Section 2.1, there are two types of Water Audits and one of them is the district flow audits. A district audit is a reasonable alternative to a system wide approach to water loss management strategies, since the later would be time and money consuming. And this is where the concept of District Metered Areas (DMA) starts to be considered.

A DMA is a distribution network sector with a well-defined and permanent boundary, with a metered recording of the flow in the area (Farley, 2001). These zones are isolated by turning off the appropriate valves except at control points where portable flowmeters are installed (Hunaidi et al, 1999).

The establishment of DMAs will enable the current levels of leakage to be determined and to consequently prioritise the leakage location activities. By monitoring flows in the DMAs, it will be possible to identify the presence of new bursts so leakage can be maintained at the optimum level. The key to DMA management is the correct analysis of the flow, to determine whether there is excess leakage and identify the presence of new leaks (Morrison et al, 2007).

The DMA has also the advantage of allowing the pressure management. This allows an optimum level of pressure operation of the network (ibid).

2.5.1 The process of DMA setup

The setup process of a DMA is not limited to closing valves and meter installation. It needs to consider several conditions. Figure 2.4 describes the stages for the design and installation of a DMA.

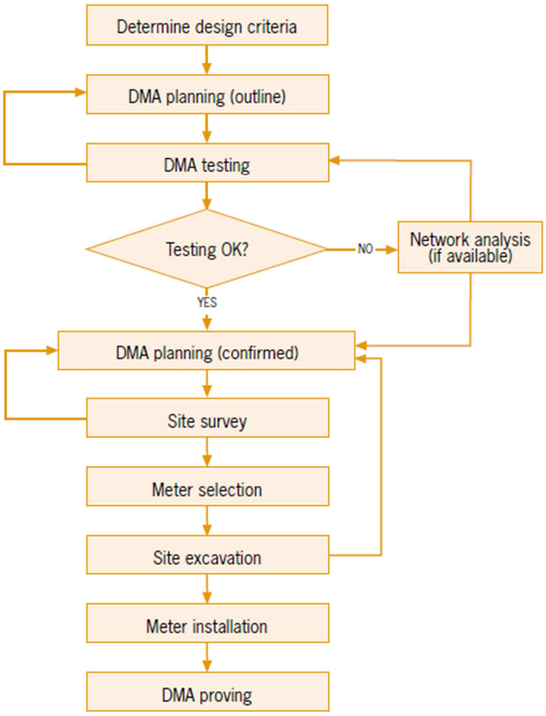


Figure 2.4: Stages in DMA design and installation
(Source: Farley, 2001)

2.5.2 Initial Design and Planning Considerations

According to (Morrison et al, 2007), the factors that should be taken into account in the Designing and DMA Planning stages are:

- *Size (geographical area and number customer connections)*

The size of DMAs has an impact on the cost of creating them: the smaller the DMAs, the higher the cost. This is because more valves and flow meters will be required. This will increase the maintenance cost. But smaller DMAs allow the reduction of the awareness and location time for new leaks and the reduction of detection costs. The recommend DMA size in urban areas varies between 500 and 3000 properties (ibid).

- *Housing type*

The idea is to keep a similar pattern of consumption in the DMA.

- *Water quality considerations*

Creating a DMA involves closing boundary valves. This creates more dead ends than the ones that would normally be found in a fully open system. Consequently complaints of poor water quality may occur. The greater number of valves in a DMA, the greater is the likelihood of this happening (Farley, 2001).

- *Pressure requirements*

A block of flats will require a pressure condition different from a single house which might complicate the pressure requirements. The variation in ground level has to be considered too. The idea is to optimise pressure to maintain customer standards of service and to reduce leakage. This includes the verification of the conditions of use for fire fighting.

- *Number of valves to be closed*
- *Infrastructure condition*
- *The required level of leakage*

2.5.3 Implementation

The planning stage is the process of dividing the distribution system into suitably sized DMAs (Morrison et all, 2007). Outline planning is the first step, using small-scale distribution mains maps to draw provisional boundaries. This step uses local knowledge of the network and available hydraulic data (pressure and flow) to identify potential trouble spots, which could be made worse by closing in DMAs.

Where the DMA boundary crosses a main, a meter is installed (or a valve is closed) so that any flow at the boundary crossing, either into the DMA or out into an adjacent DMA, is continuously monitored. This allows the net night flow to be calculated. The net night flow, taken at a time when demand is at its lowest, provides the basis for the operation of the DMA, and helps to prioritize each DMA for leak detection and location activity.

Before any further work is carried out, a test closure of DMA boundary valves should be made. This is to check that DMA pressures are maintained up to the standard of service (Farley, 2001).

2.6 Economic Level of Leakage

Leakage control can be expensive, due to the investment in technology and workforce, and water utilities need to achieve an economic balance between the costs of leakage control and the benefits obtained. (Pilcher et al, 2007) suggest that the cost of the leak shouldn’t be only measured in the water volume wasted and the price of repair. It should also include factors like:

- Administration,
- Traffic management
- Customer disruption
- Reputation of the water company
- Cost of repeat repairs (e.g. on same service pipe)
- Addition storage required
- Increased treatment costs
- Increased pumping costs
- Drain on natural resources

The cost can be related to a law of diminishing returns where the greater the level of resources employed the lower the additional marginal benefit which results (Thornton et al, 2008). This is the reason why every activity is analysed in a similar way to compare its marginal cost with that of other interrelated activities, and with the marginal cost of water in that supply zone (ibid).

The Economic Level of Leakage (ELL) is the leakage level at which the marginal cost of reducing leakage is equal to the benefit gained from further leakage reductions, that is the leakage level which minimises the total of the present value cost of leakage management and the present value cost of the water lost through leakage (OFWAT, 2008). A first approach to the concept can be presented in an adaptation of Figure 2.2 showed in Figure 2.5:

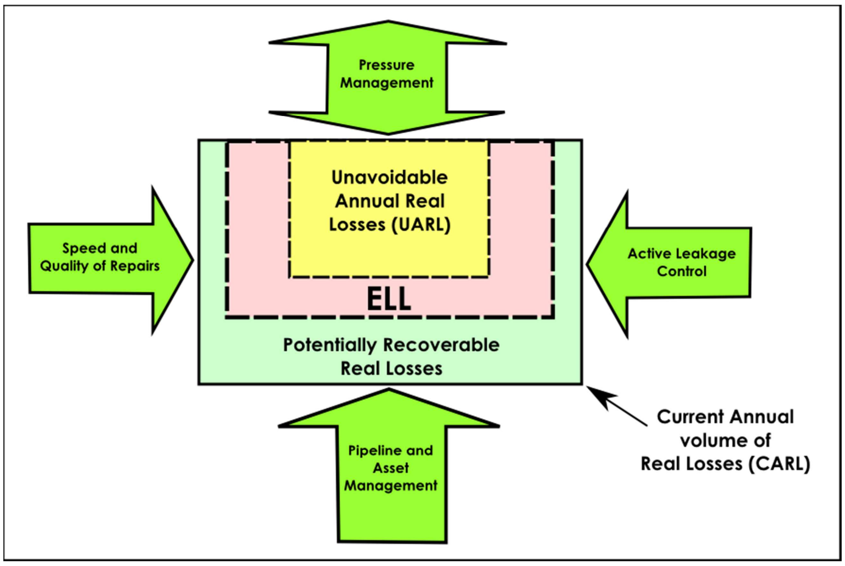


Figure 2.5: A first Approach to ELL
(Source: Adapted from Liemberger and Farley, 2004)

The ELL will be a leakage level within the Potentially Recoverable Real Losses but that will never be lower than the UARL. But what is the reason?

In Section 2.3.1 (Active Leakage Control), the concept of Reported Leaks was introduced. If an Active Leakage Control approach is implemented, Unreported Leaks will be located which, ideally, will be repaired and the leakage level will be maintained. An increase in the Active Leakage Control frequency will result in a lower level of leakage. So there is a relationship between the average leakage level and the survey frequency. Figure 2.6 illustrates this relationship as a Detection and Repair Cost curve.

The graph in Figure 2.6 shows present value costs of leakage management and water lost through leakage, varying with the leakage level (Ml/day). The cost of lost water refers to the *costs of actually producing and distributing water of an acceptable quality*. The costs of leakage management are those associated with detecting and repairing the leaks. The leakage detection and repair cost increases when the leakage level decreases since is easier to detect bigger leaks, and the effect of detection and repair is more visible. The graph also shows background leakage as an asymptote – this is the sum of all the leakages in all fittings in the network, which are too small to be detected and for this reason will be accumulated in the system and represented as an asymptote.

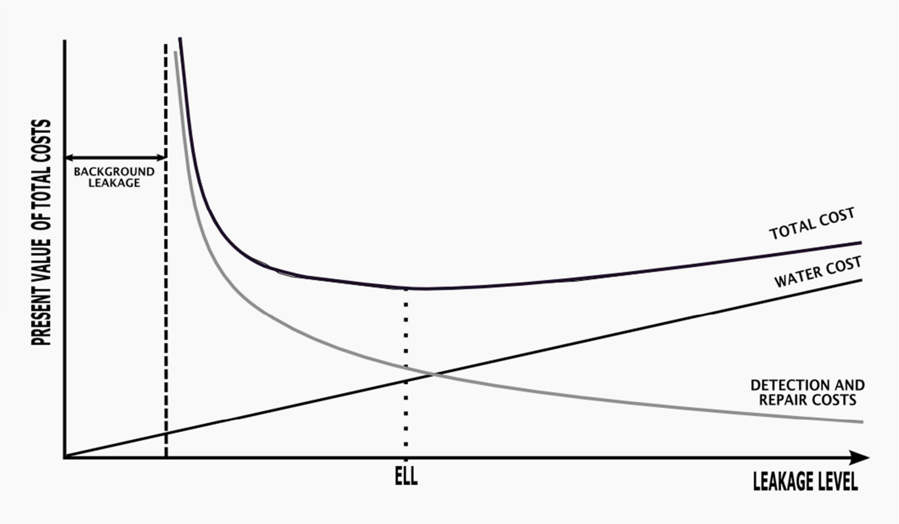


Figure 2.6: Economic Level of Leakage Calculation
(Source: Adapted from Pearson and Trow, 2007)

The background leakage is a function of the leakage detection methods employed by the utility and is generally defined as the leakage below the level of detection (with current technology) (Thornton et al, 2008). This means that the level of background leakage is a function of the extent and method of leakage detection employed, which itself will have different operating costs associated with different levels of leakage. Therefore, a matrix of leakage detection costs versus level of background leakage can be derived, to obtain a perspective on the appropriate economic method of detection, and the associated level of background leakage.

If the cost of the water lost at different levels of leakage is plotted on the same graph this would be represented by the Water Cost line. The slope of the water cost line is the marginal cost of water. If the marginal cost of water is constant, the line will be a single straight line. If not, the line will be made up of a number of straight lines; usually increasing in slope with higher leakage as more expensive water is used. This cost can be (and now usually is) more widely defined than simply costs of production and distribution - it could include bulk supply charges, or deferred capital investment or even be as high as sale price of water (where water saved from leakage could be sold to other customers) (Personal communication with Allan Lambert, 2010).

The Total Cost Curve is the total cost of operation and is defined as the cost of leakage control plus the cost of water production. This curve will be high initially due to the high cost of leakage detection required to achieve very low levels of leakage. The total cost then reduces before increasing again as the cost of water production increases with increasing levels of leakage. The point at which the total cost is lowest will be the Short-Run ELL. At this point, the marginal cost of leakage detection activity will be equal to the marginal cost of water. This point will also define the economic Level of resources to he deployed on (Thornton et al, 2008). As shown in Figure 2.6, reducing leakage below the ELL would cost more than the benefits of the leak reduction. And also different supply zones have different base levels of leakage (due to differing pressures, infrastructure condition, etc.) and different operating costs; therefore a company-wide economic level of leakage can only be evaluated as an aggregate of economic levels of leakage for individual supply zones.

The issue of individual supply zones allows us to discuss how the first nationwide study and report on the ELL subject in the UK was the "Leakage Control Policy and Practice" by the National Water Council in 1985. This study set down a methodology for the assessment of ELL and it identified the benefits of pressure control and sectorization in managing leakage.

This led to the DMA implementation in most companies in England and Wales. The findings of this report were updated by a major national research programme that resulted in the "Managing Leakage" report by the Water Research Centre in 1994. This allowed the ELL to be included in the reports that water utilities have to deliver to the regulators. In the UK, a water utility has to report annual leakage figures to the regulators each year. These figures are audited by independent assessors. Every 5 years the companies have to develop business plans for the following 20 years, which include a full engineering assessment of their assets and a financial model of forecast income and expenditure. The objective is to set the prices for the next 5 years. Part of this report includes the assessment of the ELL. Most companies are operating at or close to their assessed ELL (Thornton et al, 2008).

However, the international situation is really different form the UK situation. Sectorization is very rare and Active Leakage Control is limited. The benefits of pressure management are not widely appreciated and there is generally no assessment of the ELL. Only limited data is available and there are generally very few hydraulic models. There is therefore the need for advice on the application of ELL in a staged manner in the situation of limited data (ibid). This is one of the conditions this research is tackling.

2.6.1 Plotting the Detection and Repair Costs Curve

In the UK, the annual leakage report delivered to the regulators allows the investment on a very high level of monitoring which translates in data availability. This data includes for example 15 minutes flow and pressure data on each sector. Most companies now have fully calibrated hydraulic models of their networks (Thornton et al, 2008). A water utility with enough information about the activities and costs can easily plot the Detection and Repairs Cost Curve. This approach requires (Howarth, 2007):

- Keeping records of all Active Leak Control activities and costs at supply zone level
- The determination of a base level of leakage for each supply zone
- Calculation of the marginal cost of supply for each zone

The difficulty with this approach is that the current position on the curve represents a static situation of the balance between average leakage over a number of years, at a constant resource level. It may take years to reach stability when detection resources are changed. That means that is a long process to develop a number of points on the curve. Or consider the example of this data in Table 2.3, from Wessex Water, presented in Environment Agency Science Report – SC070010/SR:

Item	Details	Volume saved (Ml/d)
Repair detected leaks	386 leak repairs per year	4.125
Leaks detected	700 leak repairs per year	1.000
Repair reported leaks	1,206 leak repairs per year	15.717
Renewal of main pipes		1.000
Renewal of service pipes		1.000
Pressure management		17.000

Table 2.3: Water volumes saved by different leakage control strategies (Source: Environment Agency, 2008)

There is information about the volumes of water saved but there is no information about costs. Or also the case of the fieldwork developed in Zaragoza, Spain, for this research.

The city lacked an active leakage control squad, so part of the fieldwork involved detection of leakages in a sector. The value of repairing the leaks detected was calculated to be 30,062.80 Euros (See Section 3.2.3 Burst Frequencies). However there is no information about the volume of water that will be saved with that investment. Since the water utilities look for a specific investment, the common case is to have only one point of the Detection and Repair Cost curve since there is only one value of saved volume and one of cost.

The curve will then have to be drawn based on two further assumptions: The estimation of the base level of leakage, and the estimation of the leakage level with no detection and control, the so called "passive" level. The equation of this curve is given in the Report C: "Setting Economic Leakage Targets" of the UKWIR (UKWIR, 1994)

$$C = \frac{-1}{\delta} \times \frac{\ln(L - L_P)}{(L_P - L_b)}$$

$$\delta = \frac{-1}{C_a} \times \frac{\ln(L_a - L_b)}{(L_P - L_b)}$$

Equation 2.4: (Source: UKWIR/WRc,1994)

Where:

C = cost associated with a program of leakage control (£/conn/a);
L = level of leakage associated with a program of leakage control (m3/conn/a);
L_a = actual level of leakage for the area (m3/conn/a)
L_b = base level of leakage (m3/conn/a)
L_p = passive level of leakage (m3/conn/a).
C_a = actual cost of leakage control for the area (m3/conn/a)

It can be observed that Equation 2.4 does not consider the pressure as a variable of leakage level. For this reason, a theoretical model such as the Burst and Background Estimate (BABE) is implemented for the calculation of the curve. The BABE methodology is used in the UK and accepted as best practice for assessing and managing leakage in water distribution systems all over the world. Chapter 3 of this document will describe with more detail the issues of the BABE methodology. But initially it can be mentioned that in a BABE analyses, the total losses are separated into real and apparent losses and real losses are classified as:

- Background leakage at joints with very small leak volume that makes them invisible to detection.
- Reported leaks and bursts of very short duration but with high leak volumes.
- Unreported leaks and bursts with moderate flow rates and average duration that depend on the active leakage control method used by the water utility.

The influence of pressure on leakage is adjusted using the concept of N1 exponent and the use of component analysis is applied to determine unexplained leakage from a minimum night flow.

By calculating the average duration of detectable leaks considering Awareness, Location and Repair times, these concepts can be used to model any utility policy, increasing or decreasing the detection effort with its consequent effect on the time for leaks to be located and repaired. The use of the BABE methodology requires field data such as the number of bursts, the average zone night pressure, length of mains, trunk-main losses, and number of billed properties that might not be available but that can be obtained by the water utility.

Howarth (2007) mentions the importance of stressing that each and every of the curves associated to leakage control approaches are different. The shape of the curve is related to the efficiency and motivation of the staff. Also the repair costs vary with the degree of leakage-detection activity, the leakage level at which unit costs are infinite and the natural rate of rise in leakage.

Having those variations in mind, the best option is to find out the current Detection and Repair Costs Curve analysing the results of actual operations, and then estimate the shape of the curve at increased or decreased levels of Active Leakage Control activity using a component based approach. The level of background leakage can be assessed using current methodologies (DEFRA et al, 2003). As it was mentioned previously in this section, the level of background leakage is a function of the extent and method of leakage detection employed, which itself will have different operating costs associated with different levels of leakage. Therefore, a matrix of leakage detection costs versus level of background leakage can be derived, from which a view on the appropriate economic method of detection, and the associated level of background leakage can be obtained.

The normal approach to solving this problem is to choose a small increment of activity in each area and work out the cost/benefit. These are ranked and the one with the best benefit is "implemented" (Trow and Farley, 2003). Figure 2.7 shows the variation in returns from different approaches to leakage control and the differences in investment required.

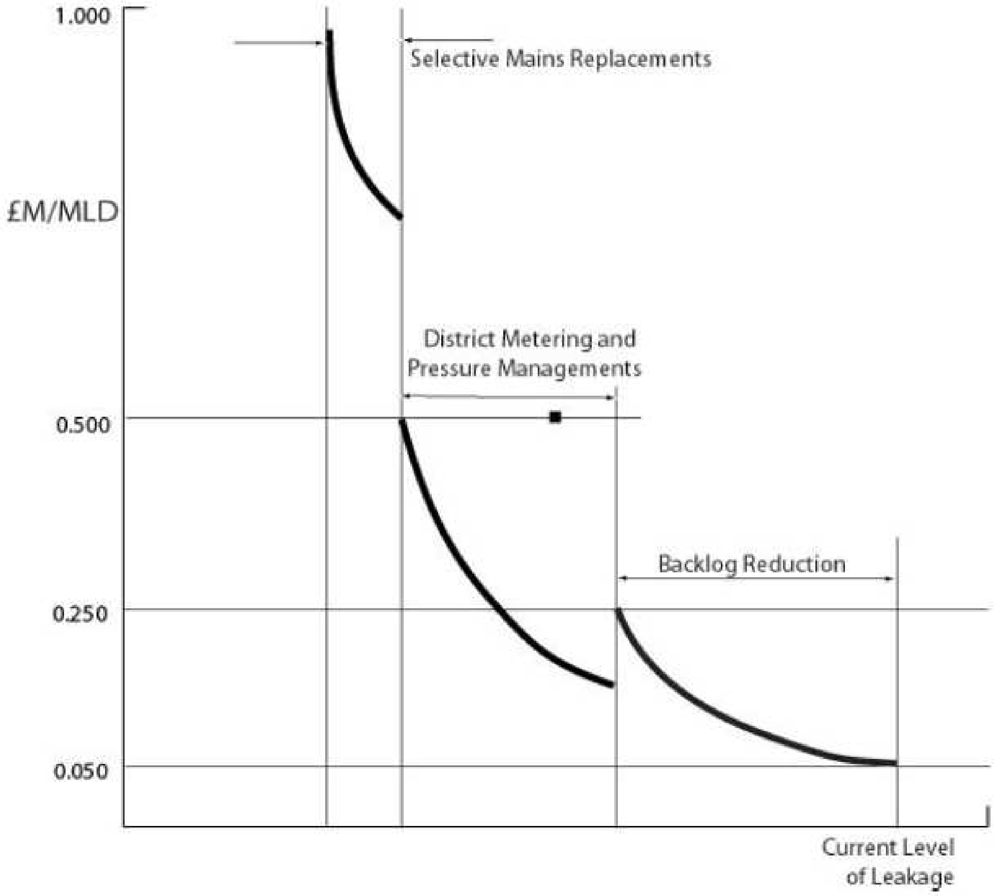


Figure 2.7: Diminishing Returns from Leakage Management Measures (Source: Trow and Farley, 2003)

The leakage benefit for the other approaches are then reassessed due to the change that this approach imposes and compared again. Then another scheme is then chosen and the leakage benefits reassessed etc. This process is continued until the marginal cost of any activity is equal to or greater than the marginal cost of water. This then establishes the economic level of leakage and the list of approaches and associated costs that will be implemented to achieve this level (ibid).

2.6.2 Short and Long Term ELL

Section 2.6 described the Short Run or Short Term ELL. In the case of the short term ELL, the quantity of at least one input is fixed and the quantities of the other inputs can be varied. The long term is a period of time in which the quantities of all inputs can be varied, and other new inputs can be introduced. (Pearson and Trow, 2005)

This means that approaches like active leakage control and speed and quality of repairs can be affected by changes in labour and shall be considered in the short term while pressure management and asset management would require an investment decision, and be considered in the long term. Once the investment has been made, there will be a new (lower) short-run economic level of leakage, which has to be re-calculated.

As an example, values of ELL for Bristol Water in the short run for 2008/09 and 2009/10 are 54.6 and 55.0 Ml/d respectively. The calculated ELL for long run for 2008/09 and 2009/10 is 53.6 Ml/d (Bristol Water, 2007). Considering that the distribution input for the water utility during 2006/07 was 286 Ml/d, the ELL values corresponds to 19.1%, 19.2% and 18.7% of the total supply.

As was mentioned earlier, the situation in other parts of the world is quite different from the UK. Water utilities are keen on controlling leakage but not on calculating the ELL. Since there are no official entities such as OFWAT that command the development of the ELL for the local municipal authorities, the estimation of the ELL is not a priority for the water utilities. Also the lack of information and hydraulic models make difficult the calculation of the ELL, even using theoretical models due to the amount and quality of the data used.

2.7 Energy Use in Urban Water Supply

In December 2009, the IWA presented the "IWA Water and Energy Declaration". This document was a result from the First IWA Water and Energy Conference in Copenhagen and it states that as a part of their responsibility, the IWA has to tackle water issues associated with global warming and subsequent climate change.

A list of points was mentioned as important for consideration toward a treaty on world climate management:

1. Water and energy are indivisible and equally important for society

2. Water and energy policies must be integrated in order to meet basic requirements of people and nature

3. The requirement to deliver water for basic needs must not be compromised by the need to cut greenhouse gas (GHG) emissions

4. Behavioural changes must be initiated in order to facilitate prudent use and consumption of water and energy

5. Recovery of water and energy must be put high on the agenda of policy formulation and technology development

6. Technological solutions do exist – and more will be developed – to improve the water and energy efficiencies in both the energy and water sectors

7. Development and use of fiscal instruments will accelerate the implementation of behavioural changes and of sustainable technologies in households, industry and supply sectors

8. Novel professional platforms must be established to help balance competing interests of water and energy needs, and to develop appropriate legislative and regulatory frameworks.

The document not only stressed how water and energy are physically linked and cannot be separated, but also how the development of new policies and technologies, which reduce the use of water and energy, are required and may also stimulate economies. This means the water policy influences energy choices, and vice versa, creating a need for the integration of policies for emission control.

2.7.1 Policies for Emission Control

The UK government started to consider the energy emission nexus with the Climate Change Act 2008. This was the world's first long-term legally binding framework to tackle the dangers of climate change and became law on 26 November 2008.

The Climate Change Act has as a main objective to "establishing an economically credible emissions reduction pathway to 2050, by putting into statute medium and long-term targets and a system of carbon budgets which will constrain the total amount of emissions in a given time period providing greater clarity and predictability for UK industry to plan effectively for, and invest in, a low-carbon economy".

This can be compared with the agreement in 2007 by the EU Heads of State and Government on climate and energy targets to be met in the mid-term (2020) (Ranci et al, 2011):

- A reduction of EU greenhouse gas (GHG) emissions by at least 20% with respect to 1990 levels
- Meeting at least 20% of EU energy consumption using renewable resources (RES)
- The reduction of EU primary energy use by at least 20% compared with projected levels.

The "climate and energy package" supporting the achievement of these targets came into law in 2009 (ibid) and was complemented with the "Analysis of options to move beyond 20% greenhouse gas emission reductions and assessing the risk of carbon leakage" which revisits the analysis of the implications of the different levels of ambitions (20% and 30% targets) and assesses the risk of carbon leakage.

These policies are important since they delimit the approach on the energy emission subject on the water utilities. According to the Office for National Statistics (Office for National Statistics, 2010), in 2008 energy consumption was the highest in the electricity, gas and water industries, which accounted for 28.6 per cent of all energy used from fossil fuels. The manufacturing and transport and communication industries accounted for a further 15.8 per cent and 15.0 per cent respectively of energy from fossil fuels. Households were the second largest direct users of energy accounting for 27.1 per cent of the total. This means that there is a lot of opportunities for emission reduction in the water industry.

This can relate how the recovery of water and energy is high on the agenda of policy making and technology development. The need for planning tools to quantify an "eco-footprint" of the sustainable alternative technology or management scenarios, including policy measures for driving more sustainable investment decisions is clear.

Finally, the "IWA Water and Energy Declaration" states that "Saving water means saving energy in the extraction, treatment and distribution of water and the collection and treatment of wastewater". This section will present the different energy consumptions present in the Leakage Management approaches and will show how certain technology developments, will offer an impact on the total energy use. The externalities will be explained with a higher level of detail in the Methodology and Model Description chapters of this document.

2.7.2 Energy Use in Active Leakage Control

The first item to consider is the fuel consumption used for transportation during the detection campaigns. A secondary item is the energy consumed in the process of detection and the transmission of the information to a centre. The information obtained from the campaigns should be stored and managed to be used. Data obtained, such as pressure and flow rate, can be used for modelling, to achieve a better understanding of the system or to verify or calibrate the same. The simulation of different scenarios is another use of this information. This allows system optimization and identification of possible problems such as low pressure zones or zones with high leak presence.

Since the 80's the shift from telemetry, to measure quantities from a remote site and transmit them to a data collection point for recording and processing, to Supervisory Control and Data Acquisition (SCADA) systems has allowed a more accurate, versatile, and cost-effective use.

A SCADA system compiles data about the operation of a distribution system and allows the automated control of system components (Jentgen and Wehmeyer 1994). The "supervisory" part alludes to the need of a person to supervise and make decisions about the operation of the distribution system.

For the leak detection in water distribution systems, the interest is measuring flow rate and pressure, but the SCADA system can also measure temperature, pH, chlorine residual, turbidity, and conductivity. This depends on the sensors used, just like the energy consumption. It might not seem like a high consumption but is just a problem of scale. Bigger water distribution systems are going to need a bigger coverage and are going to have a bigger consumption. However, is also interesting to see the potential of open-source hardware such as the Arduino microcontroller for development of low consumption sensors and data transmission systems (Thompson, 2008).

Information is then collected in a centre. This centre has very special energy consumption characteristics. Table 2.4 shows the increase in energy consumption in data centres during 2000-2006 in the United States.

According to construction process electricity use, Defra, 2007 gives the following values: 0.263 kgCO2e for each kWh of power derived directly from fossil fuel (diesel) and 0.523 kgCO2e for each kWh of grid electricity. It might seem paradoxical that onsite generation has lower emissions but actually grid electricity has to be transported from a long distance, a process that has a considerable level of losses.

So the information needed for this approach will be:

- SCADA records
- Fuel used in transport
- Data processing records
- Electricity consumption by data centres

End use component	2000		2006		2000 – 2006 electricity use (compound annual growth rate)
	Electricity use (billion kWh)	% (total)	Electricity use (billion kWh)	% (total)	
Site infrastructure	14.1	50%	30.7	50%	14%
Network equipment	1.4	5%	3.0	5%	14%
Storage	1.1	4%	3.2	5%	20%
High-end servers	1.1	4%	1.5	2%	5%
Mid-range servers	2.5	9%	2.2	4%	-2%
Volume servers	8.0	29%	20.9	34%	17%
Total	28.2		61.4		14%

Table 2.4: Energy consumption in data centres, 2000 to 2006
(Source: US Environmental Protection Agency 2007)

2.7.3 Energy Use in Improved Speed and Repair of Leakages

Using control systems it is possible to monitor the incidents, time taken for response, and time taken to complete a job. This allows the monitoring of the staff, keep the standards of work and the identification of possible problems. This means that again there is a need for data centre associated consumptions.

Also consider the following OFWAT guideline in page 23 of "Setting price limits for 2010-15: Framework and approach – a consultation paper":

"Where a company makes proposals for large-scale mains replacement of water mains primarily to reduce leakage it must justify these using Cost Benefit Analysis – including evidence of the carbon balance of the proposal and alternatives, and consider the links with its capital maintenance strategy." (Ofwat, 2007)

It basically states the avoidance of high energy consumption associated with the repair process and the traffic delays product of this repairs. This allows the consideration of the use of less invasive technologies for the repair of leaks such as trenchless systems.

Usual procedure for installing a pipe involves digging of a trench, pipe installation and excavation filling. However this also means the repair of the streets or sidewalks that were damaged during the trench excavation. This repair process also involves extra crews and extra energy consumptions.

The trenchless technology is not a replacement for the trenchers or excavators. They still need to cut a hole in the ground, which is smaller than a trench and is easier to repair, and trenchless methods can't work in all kinds of soils. But they are a good option in difficult places and the range of savings are cited between 30 to 50% (Griffin, 2004) from reducing the size of excavation, reduced restoration costs and, in most cases, the elimination of traffic obstructions. This technology can also be used for rehabilitation and repair of pipes.

Consider the values for overall emissions for laying polyethylene pipelines in fields and roads in Table 2.5.

Diameter (mm)	Location	Trench depth to pipe invert (m)					Pipe density (tonnes/m)
		<1.5	1.5 – 2	2 – 3	3 – 4	4 – 5	
125	Field	106	122	145	174	203	0.003
	Road	319	358	416	494	571	
250	Field	112	128	150	180	209	0.011
	Road	336	375	433	510	588	
450	Field	123	138	161	190	220	0.035
	Road	385	424	482	559	636	

Table 2.5: Emissions for laying polyethylene pipelines in fields and roads (kgCO2e/m length of pipe)
(Source: UKWIR, 2008)

All this values assume open-cut construction and include the emissions embodied in the pipeline material, any imported backfill and allowances for temporary works, trench excavation and, where appropriate, backfill compaction and road reinstatement. Considering that the trenchless technology avoids the backfill, compaction and road works, it shows the considerable amount of savings in emissions implementing this option.

The value of emissions from the use of labour is estimated to be approximately 1 kgCO2e/person/hour. This is based on the assumptions: i) that site workers travel an average distance of 25 km each day from their lodgings to site and then back again by car or van (2 persons to a vehicle); and ii) that each labourer makes use of site welfare facilities (large heated portacabins). Table 2.6 describes the calculation of this value, assuming an 8 hour working day.

Item	Quantity	Number	Conversion factor	$kgCO_2e$/ Person day	$kgCO_2e$/ Person hr
Travel to site	2 x 25 km per day	2 persons per vehicle	0.210 $kgCO_2$/km	5.3	0.66
Energy use on site	5 kW per portacabin for 8 hours per day	8 persons per portacabin	0.523 $kgCO_2$/kWh	2.6	0.33
Total				**8**	**1**

Table 2.6: Emissions for1 hour of labour
(Source: UKWIR, 2008)

The combination of GIS data and trenchless technology can help to avoid the possible problems with other pipes during the work.

It is important to mention that no account is taken of any recycle or reuse of construction waste. It is assumed that it was already accounted for in the materials selected for the task. The same goes for the demolition and disposal emissions. For the transport of equipment, a value of 0.05 kgCO2e/tonne of plant or waste should be added to embodied carbon totals of relevant construction items for each km travelled by road. For other modes of transport allow 2.63 kgCO2e/litre of diesel fuel used.

So the information needed for this approach will be:

- Repair logs
- Fuel used in transport and equipment

2.7.4 Energy Use in Pressure Management

A reduction in pressure reduces the leakage rates, the frequency of bursts and the energy consumptions. However, this also reduces the consumption volume of the users. The studies on energy and pressure management has gained a lot of attention in the research field going from optimizing the pumping schemes (Mackle et al, 1995), (Baran et al, 2005) to developing new control technologies (Rao and Salomons, 2007). (Mackle et al, 1995) mentions that theoretical studies and practical implementation of optimal pump scheduling in various types of supply system suggest that 10% of the annual expenditure on energy and related costs may be saved if proper optimisation methods are used.

Table 2.7 shows several payback periods for different approaches to the pressure management.

Function	**Typical Payback Period (years)**
Avoid the unnecessary operation of pumping equipment	0 – 1 it implies level automatic
To optimize the electromechanical efficiencies of the pumping systems	0.5 – 1.5
Control of pressure and output in the networks	1.5-3
Use of highly efficient motors	2 -3

Table 2.7: Typical payback periods for pressure management technologies and practices (Source: Alliance to Save Energy, 2005)

So far, the information required for the Pressure Management approach will be:

- SCADA records
- Generators: ratings, fuel consumption, annual running hours, other support services
- Air compressors: type, ratings, controls, operating set points, operating profiles, annual running hours
- Heating systems: types, ratings, controls and set points, operating patterns and annual running hours, fuel type, actual energy / fuel consumption
- Lighting: types, ratings, controls and operating patterns, annual operating hours, purpose
- Pump performance curves.
- Pump log book, detailing the maintenance history of the pump and any changes to its performance.
- Pump and pumping system design data, including design duty information and pump performance curves
- Actual pump operating data: duty information including flow rates, operating pressures, power absorbed, operating speeds, electricity and diesel consumption
- Operating profiles: number of pumps run and hours run
- Site electricity consumption, including monthly billing information and half hourly electrical readings.

This is a very detailed information and the reason is that the studies on energy and pressure management has gained a lot of attention in the research field going from optimizing the pumping schemes to developing new control technologies. If this information is compared with the required information for Asset Management, Active Leakage Detection and Proper Repair Times, that is basically the type of equipment used for process and fuel & energy consumption logs, a big gap in the identification of energy externalities in the leakage management activities step of energy cost inclusion will be found.

2.8 Estimation of Carbon Emissions and the Economic Externality Costs of Energy Use

OFWAT (2008) has produced guidance for the UK water industry on the process of including externalities in this model of ELL. It defines, in page 1, an externality as "any positive or negative impact arising from an activity that is not normally considered in the decision of the agent (in this case the Water Service Provider) undertaking the activity".

These externalities arise because the positive impacts or the avoidance of negative impacts have a value but there is no obvious market price (or cost) which reflects third parties' willingness to pay. These externalities include social and ecological variables. However the inclusion of carbon valuation in this field is recent, to take account of the cost of climate change and emissions of greenhouse gases, as a product of including the cost of climate change and emissions of greenhouse gases.

When talking about the costs of producing water, is the amount of energy used during the treatment and distribution process. The amount of energy consumed worldwide in water supply is more than 6552 Petacalories (26 Quads; 1 Quad = 10 ^15 BTU), is roughly equivalent to the amount of energy used by Japan and Taiwan together, about a 7% of the total energy consumption. (Alliance to Save Energy, 2003). The efficient use of water and energy is the most economically profitable way to achieve those objectives. For example, according to the Confederation of Indian Industry, the energy consumption on water distribution systems could be reduced at least in 25% using high efficiency energy measures. (ibid)

After obtaining the necessary information to develop the ELL is necessary to also consider new policy & technological options. This involves to identify the potential impacts of a new policy (or policies) on key parameters such as leakage level, policy minimum, bursts, NRR (natural rate of rise) etc and then modelling the impact of the new policy/technology over 10 years.

It is important to stress that the ELL shouldn’t be considered only as a financial, technological or economical target. This target leakage level depends on the current and future physical characteristics of the water distribution system, population, population growth, economic and financial condition of the water utilities, existing policy by official entities, works in the water distribution network, in leakage management and water source management, and many other variables.

Using information from ELL a baseline is defined and obtain Relations between Leakage & Costs that allow quantification of reduction in operating costs and possible reduction in future capital investment requirements (and associated operating costs). This then can be used in the elaboration of a Least Cost Plan and to find the Marginal Cost of Water and Marginal Cost of Leakage vs. Water.

This illustrates another result of this research: The prediction of the costs, benefits and results of different options for ELL, to justify investments and priorities, since the financial resources can be very low or just can't keep with the grow rate of the cities.

2.8.1 Incorporating Energy In The Economic Level Of Leakage

Incorporating the economic costs of carbon emissions in the ELL model can be considered in 5 stages:

1. Identification of energy externalities in water supply and leakage management activities.
2. Data collection and assessment of emissions in water supply and leakage management activities.
3. Evaluation of the carbon externalities in the water supply and leakage management activities
4. Inclusion of values of carbon externalities in the economic analysis.
5. Post-analysis monitoring.

As the Final Report on Leakage Methodology Review: Alternative Approaches to Leakage Target Setting (OFWAT, 2007:15) stresses:

"A best practice framework is provided for including environment and social costs in the report. However, this is probably the weakest area of the current practice for deriving an ELL. The issue of environment and social costs is subject to a new review (being led by Ofwat), which will be starting shortly"

That review was carried out in 2008 with the Providing Best Practice Guidance on the Inclusion of Externalities in the ELL Calculation document that will be discussed in the next section.

2.9 Previous Work on Energy Use in the ELL

The UKWIR Report Ref No 08/CL/01/6 (Carbon Accounting In The UK Water Industry: Guidelines For Dealing With 'Embodied Carbon And Whole life Carbon Accounting) covers measuring and costing carbon emissions, but not other externalities, such as the one that appear in the Asset management approach. This then will be one of the products of this research: Clear guidelines for the inclusion of energy externalities associated with the Active Leakage management approach in the ELL model. Table 2.8 shows the externalities considered by the UKWIR report.

Activity	Externality	Potential impacts	
		Carbon	Environmental
Leak detection	Transportation energy/fuel use	*	
Detected leak repair	Road traffic delays/disruption and diversions	*	*
	Pedestrian diversions		*
	Commercial and domestic disruption/disamenity due to excavation		*
	Noise impact of street works		*
	Transportation energy/fuel use	*	
	Work site energy/fuel use	*	
	Embodied materials	*	
Asset renewal	Road traffic delays/disruption and diversions	*	*
	Pedestrian diversions		*
	Commercial and domestic disruption/disamenity due to excavation		*
	Noise impact of street works		*
	Transportation energy/fuel use	*	
	Work site energy/fuel use	*	
	Embodied materials	*	
Reported (unplanned) leak repair	Avoided costs of discolouration		*
	Road traffic delays/disruptions and diversions	*	*
	Pedestrian diversions		*
	Commercial and domestic disruption/disamenity due to excavation		*
	Noise impact of street works		*
	Transportation energy/fuel use	*	
	Work site energy/fuel use	*	
	Embedded materials	*	
Reported mains burst events (externalities are potential benefits attributable to asset renewal and pressure management)	Commercial and domestic cost of flooding		*
	Cost of unplanned interruptions to supply/pressure reduction		*
	Transportation energy/fuel use	*	
	Work site energy/fuel use	*	
	Sewer flooding (water only companies)		*
Pressure management	Road traffic delays/disruptions and diversions		*
	Cost of unplanned interruptions to supply/pressure reduction		*
Transportation of potable water to sites where supply has been disrupted	Extraordinary fuel use	*	

Table 2.8: Emissions for Leakage Management Externalities
(Source: UKWIR, 2008)

According to OFWAT (OFWAT, 2008) it is necessary to establish the relationships between leakage control costs and leakage for each of the 3 principal leakage management options: Active leakage control (ALC), pressure management and asset renewal. This means that the asset management is just considering the renewal part. Any active leakage control, leak detection and repair, is associated with carbon related and social disruption externalities. However this research will focus on the energy externalities associated and not on the social externalities.

In the case of leakage maintenance, earlier discussion of ALC modelling approaches has indicated that some water utilities exclude leak repair costs from the calculation of the maintenance cost elements so for this water utilities, only the carbon impacts of leak detection activities will be relevant. For other water utilities the social and carbon impacts of leak repairs should be included as part of maintenance costs.

But still there are no clear guidelines on how to involve the energy externalities.

2.9.1 Economic inclusion of the emissions

After identifying energy externalities in the leakage management activities, is necessary to measure them and then to find a way to monetise the emissions and the energy consumed because after all an economic model is in developing.

However, limitations of data and the absence of detailed guidance on appropriate valuation methods may in some instances have resulted in inadequate or inappropriate valuation of external costs and benefits, particularly with respect to carbon-related impacts. If, for example, the environmental benefits of leakage reduction are understated, the ELL assessment will be higher than is socially optimal. In this case, top-level willingness to- pay surveys may indicate customers' preferences for greater leakage reduction expenditure and/or environmental improvements in the form of flow alleviation schemes. In recent years, methodologies for valuing external costs and benefits have become both better grounded in economic theory and more accepted by non-specialists.

The basic approach in UK until 2009 was to express emissions as carbon dioxide equivalent (CO2e), priced at £25 per tonne of carbon dioxide equivalent (CO2e) in 2007 prices (DEFRA, 2007). However DEFRA also recommended until 2009 the use of the concept of Shadow Price of Carbon (SPC), applied consistently, in all areas of government decision-making. The concept of SPC is based on the work of the Stern Review on the Economics of Climate Change, which assessed cost and risk associated and estimated the damage caused by climate change. The SPC was defined (in page vii) as

"The government preferred method of incorporating carbon emissions in cost-benefit analysis and impact assessments. The SPC captures the damage costs of climate change caused by each additional tonne of greenhouse gas emitted, which is converted into CO2e for ease of comparison. It is different to the Social Cost of Carbon (SCC) as it takes more account of uncertainty, is based on a stabilisation trajectory and is in line with the marginal abatement costs of reaching the stabilisation goal" (OFWAT, 2008)

The effect of the SPC is to rise the net present value (NPV) of options with low carbon impacts relative to those with larger carbon impacts. Therefore is the current maximum value that should be given to mitigation or abatement.

The SPC value rises by 2% per year to account for observed (and assumed) inflation; and due to the rising damage costs from higher greenhouse gas concentrations. So the SPC for a policy beginning in 2007 was £25.4/tCO2. For 2009 the SPC was £27.1/tCO2 and £30.5/tCO2 for 2015.

However, in July 2009, as a part of the UK Low Carbon Transition Plan the Department of Energy and Climate Change (DECC) announced that the shadow price of carbon has been replaced with the Non-Traded Price of Carbon (NTPC).

According to (DECC, 2009:57): "A carbon trading system, like EU ETS, places a cap on the total emissions of participants, divides that cap into rights to emit or 'allowances', and allows participants to trade those allowances".

This means that each participant must surrender allowances proportional to the number of tonnes of carbon dioxide they emit. This encourages them to reduce their emissions if they can do so for less than the cost of allowances (ibid).

Allowances are initially distributed either freely to participants, or through an auction. Once distributed allowances can be traded between participants. The trading of allowances gives them a value, or price, which is the same for all participants. This common price creates the same incentive for all participants to reduce their emissions which keep the costs down by incentivising the least cost options to reduce emissions across the whole of the system.

The EU Climate and Energy Package (December 2008), introduced separate emissions reduction targets for the traded sector, that is those emissions covered by the EU Emission Trading System (EU ETS), and for the non-traded sector, that is those emission not covered by the EU ETS). The EU ETS (EU, 2009) states in page 13:

"In the first trading period, from 2005 to 2007, the scheme covered CO_2 emissions from high-emitting installations in the power and heat generation industry and in selected energy-intensive industrial sectors: combustion plants, oil refineries, coke ovens, iron and steel plants and factories making cement, glass, lime, bricks, ceramics, pulp and paper.

In the second trading period, from 2008 to 2012, emissions of nitrous oxide from the production of nitric acid are also included. In addition, from 1 January 2008 the geographical coverage of the EU ETS has been extended beyond the 27 EU Member States to include Iceland, Liechtenstein and Norway.

In some cases, a size threshold based on production capacity or output determines which individual plants in the sectors covered must participate in the system. At present some 11,000 installations in the EU are included, accounting for around 50 % of the EU's total CO_2 its overall greenhouse gas emissions".

DECC (2010) clarifies that changes in emissions which occur in the traded sector are valued at the Traded Price of Carbon (TPC), whereas changes in emissions in the non-traded sector are valued at the Non-Traded Price of Carbon (NTPC). This means that the water utility sector is included in the Non-Trade sector and for that reason a NTPC should be in the economic calculations. These traded and non-traded prices are currently different, but will converge, becoming equal in 2030 and subsequently following the same trajectory. This is based on the assumption that there will be a functioning global carbon market by 2030. The last update for the Trade and Non-Trade values was on June 2010. The new NTPC is £51 for 2009. It is almost double the SPC set out in previous guidance from the DEFRA. The NTPC also considers a Low, Central and High values with a range of +/- 50% (DECC, 2009).

There is also the concept of social cost of carbon (SCC), which measures the full global cost today of an incremental unit of carbon (or equivalent amount of other greenhouse gases) emitted now, summing the full global cost of the damage it imposes over the whole of its time in the atmosphere. It measures the externality scale. However, the SCC is not used for policy assessment because it can't be adjusted for the estimation of factors that affect the willingness to pay for carbon emission reductions or for the marginal abatement cost (MAC), which is related with the cost of emission reduction rather than the damage imposed by creating emissions, required to take the world onto the stabilisation goal. The SCC is determined purely by our understanding of the damage caused and the way is valued, the SPC can adjust to reflect the policy and technological environment. And is this policy and technological side that will be analysed in this research.

This SPC costs will be added to the operating costs (including capital maintenance) of monitoring leakage, detecting and locating leaks and repairing leaks. There are two approaches for these operating costs:

- Total costs are split into steady state costs (the cost of maintaining leakage at a given level) and transitional costs.

- Unit costs and estimates the cost of reducing leakage assuming a natural rate of rise.

Figure 2.8 shows a comparison of the carbon cost of water saving options. And it shows how the report of leaks saves a higher water volume but with a high carbon cost when compared to the active leak detection. However the active leak detection is more economical than the renewal of assets. Asset renewal has a relative constant level of saved water but the carbon cost is higher for the renewal of mains.

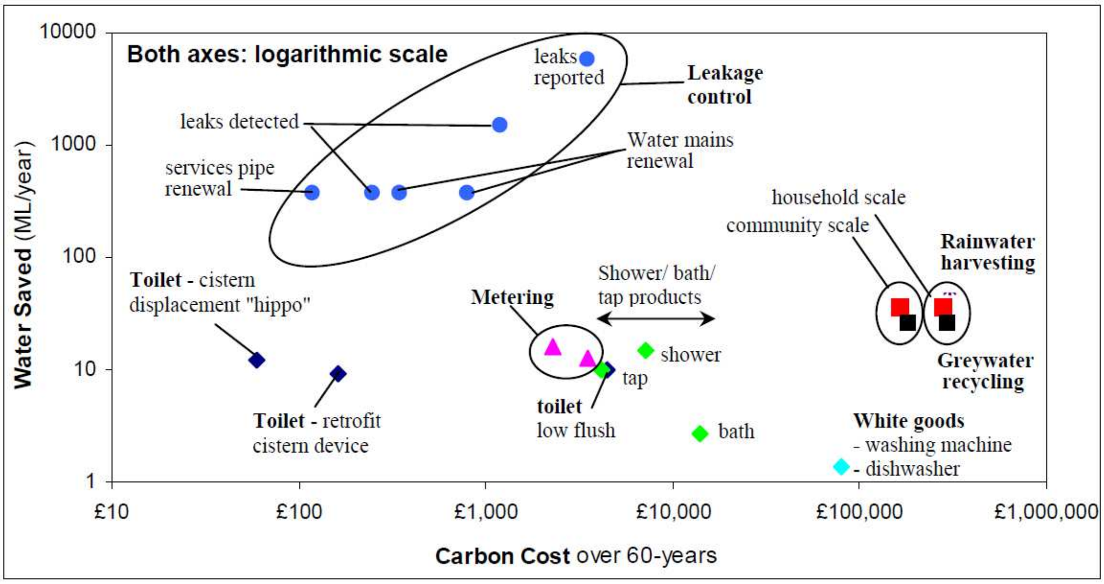


Figure 2.8: Carbon Cost Model Results - Water Efficiency Options (Source: Environment Agency, 2008)

2.10 Chapter Conclusions

For a Water Utility, leakage control is a challenge that will always be present. However, to achieve a control of the problem is possible. The water utility should be aware of the level of investment needed to achieve this control and to know this, they need to know the current levels of leakage.

This chapter presented the different Leakage Management Options available and the Performance Indicators used. But leakage control can be expensive, due to the investment in technology and workforce, and water utilities need to achieve an economic balance between the costs of leakage control and the benefits obtained.

The concept of ELL allows the Water Utility to know the leakage level at which the marginal cost of reducing leakage is equal to the benefit gained from further leakage reductions, that is the leakage level which minimises the total of the present value cost of leakage management and the present value cost of the water lost through leakage. However not all the Water Utilities have the data to calculate the ELL. Also the literature review showed that the data required for the ELL calculation makes quite difficult the start of the implementation in the case of a Water Utility with no previous Active Leakage control. This was the first gap found by the literature review.

The literature review has showed a nexus between leakage and energy. Considering the critical issues of global warming and water management, this nexus is a great opportunity for the Water Utilities to improve their service and their performance. But there is a lack of guidelines on the inclusion of Energy, and the externalities associated to the energy use, in the ELL calculation. That is the second gap found by the literature review and this research will contribute to the extension of the ELL calculation with the inclusion of the energy externalities associated with the Leakage Control activities.

The next chapter will present the methodology used in the research, the fieldwork developed and how the gaps in data and methodology were faced during the research process.

3 METHODOLOGY AND MODEL DEVELOPMENT

3.1 Overview

The previous chapters increased the awareness of what is the research problem. This is called in the Artificial Intelligence field as the frame problem (Hayes and McCarthy, 1969). The problem is started with a set of assumptions about what is relevant and what is not. To deal effectively with a problem or for bigger problems for which they may be a model, there is a need for operate on two or more simultaneous levels. One level works on the problem while another, higher-level thread monitors the progress.

The use of a correct methodology, described in this chapter, will assess if the approach is working, the likeness of an answer and if there are other possible options to try. If one approach is not working, you need to step back, take a look at the big picture, and question some of the assumptions you have been making.

In the case of this research, the problem is to develop a dynamic model for the determination of an Economic Level of Leakage (ELL) considering the energy externalities associated with the components of water loss management, as developed by IWA, and apply this in a water distribution network where limited data are available.

The following steps where used to solve the problem stated

1) Literature review and gap identification.

2) Development of a dynamic model.

3) Application of the dynamic model to Zaragoza including:

   - Collection of documents
   - Interviews

   To verify the model

The main idea of a literature review is to increase the knowledge on the research subject and to contextualize the findings. According to Kumar (2010), there are four steps in literature review:

- Search for existing literature in your area of study: Journals and conference proceedings from Loughborough University library were the main source of information.

- Review literature selected: This was done during the complete development of the research and not only focusing in the current cutting edge of the subject.

- Develop a theoretical framework: This was developed during the first year and complemented during the rest of the research to complete the Chapter 2 of this document.

- Develop a conceptual framework: The result was the model that will be explained in this Chapter 3.

The literature review in Chapter 2 showed gaps in:

- Application of the ELL concept in situations where DMA's have not been established and limited data are available.

- Incorporation of energy externalities in the ELL model. The development of a model to address these gaps is described in this chapter. The application of the model to Zaragoza is described in Chapter 4.

3.2 Model Development

To develop an ELL, is necessary to start obtaining information about the leakage control activities in the study area and to collect all the possible information about the subject. However, as it was mentioned in the Section 2.6. (ELL), some study zones lack active leakage control programs. The use of the Burst and Background Estimate (BABE) (UKWIR/WRc, 1994) method can help overcome this lack of information and allows the development of the ELL model. This method will be discussed on this chapter, as it was mentioned in the Section 2.6.1 (Plotting the Detection and Repair Cost Curve).

Information required for the model will be covered with data obtained from the technical literature. The reason behind this is to adapt an IWA methodology for the determination of an Economic Level of Leakage, for a water distribution zone with no history of active leakage management.

After the initial analysis of the resulting short run ELL, the energy related externality costs will be included. The resulting model will calculate the ELL for different leakage management approaches and allow the review of energy related emissions and their relation with the leakage volumes. Also the energy externalities to be studied in this research do not include the asset management approach or the social externalities, only the externalities associated with leakage control in the water distribution system, from the meter at the exit of the water treatment plant to the meter at the service connection. The externalities in the cost of water extraction and treatment will be considered using the values in the literature since the water utility shall be responsible for knowing this values since the water cost has to be a total cost.

The model used in this research is a Dynamic Model based on relationships found in the literature. The first step for the calculation of the ELL is to guarantee the proper quality of the data sources. The following paragraphs describe the data sources for the ELL. It is important to understand that, assuming that the backlog of leaks has been removed; there are two possible methods for analysing costs in the ELL (Tripartite Group, 2002.):

- Method A: Split current costs into steady state costs (the cost of maintaining leakage at a given level) and transitional costs (the cost of moving from one level of leakage to another)

- Method B: Estimate the cost of reducing leakage and determine a natural rate of rise (NRR)

In the Method A, the split into steady state and transitional costs should be based on the number of leakage repairs and leakage levels over a number of years and considers the weather conditions, changes in infrastructure condition and pressure management. The Method B, in which unit costs are used, requires the determination of a Natural Rate of Rise of leakage (NRR) that must be determined accurately for individual areas.

For example, it is necessary to identify that the NRR can be expressed as total NRR (NRRt) and detected NRR (NRRd: the NRR of detected leaks). The difference between them arises from higher rates of flow from reported bursts than detected bursts (the higher flow rates show at the surface). NRR from the bottom up analysis of changes in leakage can be very variable and it is difficult to isolate NRRd from NRRt. NRR rates can also be estimated from flow rates from bursts but again flow rates are difficult to assess. Appendix C of The Tripartite Group (2002) explains this issue with an example.

According to The Tripartite Group (2002), the best practice approach under Method A is currently more reliable than Method B because is straightforward and requires fewer input data. Also the theory used in Method B assumes smaller leaks at lower levels of leakage and therefore the NRR increases with the level of leakage. However, due to the difficulties associated with determining the NRR this assumption has not been verified from the data analysis carried out. Figure 3.1 describes the process map for the Method A and Figure 3.2 describes the procedure of Method B.

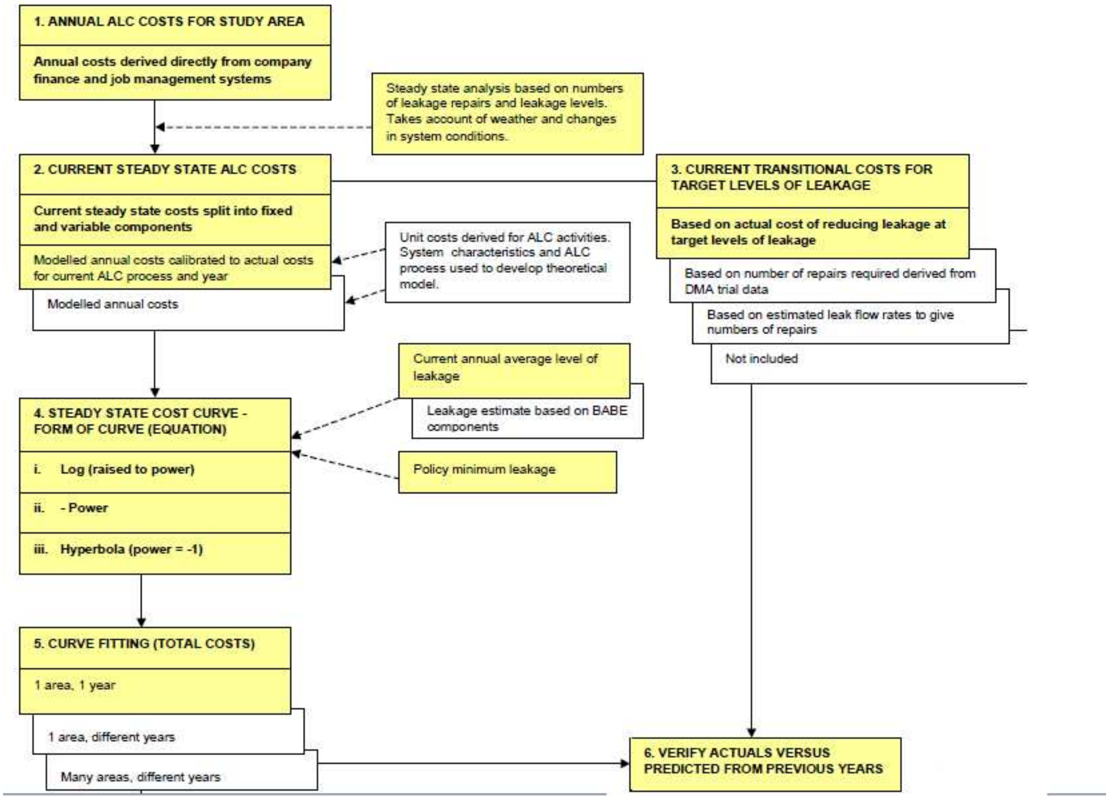


Figure 3.1: Process map for best practice development of leakage costs relationships – Method A
(Source: Adapted from The Tripartite Group, 2002)

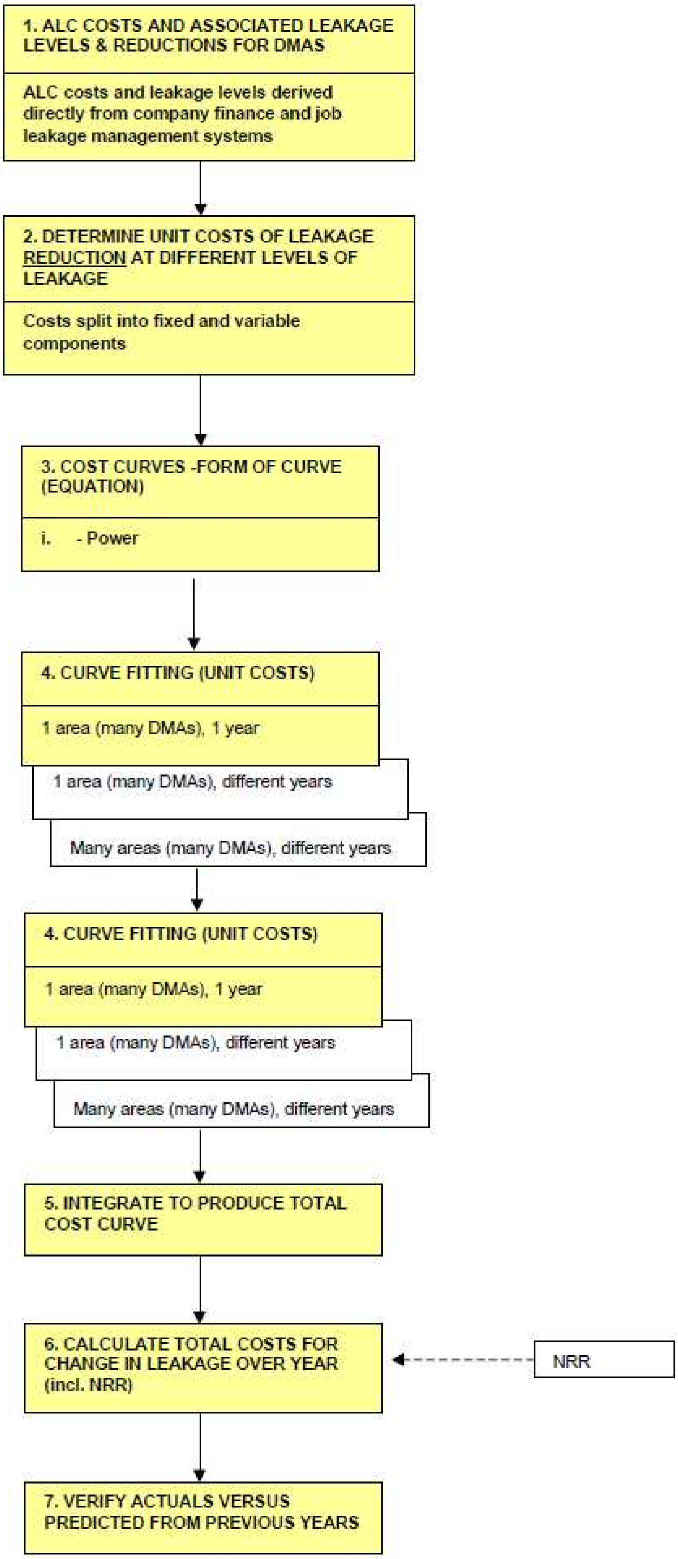


Figure 3.2: Process map for best practice development of leakage costs relationships – Method B
(Source: Adapted from The Tripartite Group, 2002)

Since this research applies the splitting of current costs into steady state costs and transitional costs, the Method A will be used. Also (ibid) mentions that the BABE Methodology is included in this category. Having this in mind, the next step is to list the different data sources available in Zaragoza.

3.3 Verification and Application

This research involves the developing of a dynamic model. This dynamic model will be verified by comparison with a case study in literature (Wide Bay Water) and check the applicability in real conditions via fieldwork in Zaragoza.

The data collection tools used in the fieldwork includes documents and interviews

3.3.1 Documents

In this case the work involves with field notes and data from the fieldwork in Zaragoza, Spain (Section 4.2.1). This data includes data collected from forms developed by the author, the analysis of logbooks and leak detection tests.

The Logbooks included:

- The leak repair database, kept by the "Guardallaves" team. The access was given by the chief of "Guardallaves".
- The monthly vehicle pool use database, kept by the drivers team. The access was given by the chief of drivers and it included.
- GIS system kept by the water utility. The access was granted by the chief of service. This GIS is very organized, updated often and that was very convenient for the research.
- Monthly reports of costs and payments in Zaragoza's water utility, kept by the city council. The data was given by the Revenue Service of the city council.

The access to data and databases was usually given after an interview with the person in charge. In these interviews the research objective was described and the information requirement was transmitted.

The work involves Secondary data since the information required was already available (Kumar, 2010) by the water utility or the city council. Data from earlier researches was used for the process of model calibration (Section 4.1). All the data was kept as private and confidential and was obtained under the consent of all the stakeholders.

The repair log books and databases provided in the case text book example of how the water utilities tend to store information but it is not making the most out of it. The use of repair codes is a common practice, but sometimes they are vague. To standardize these codes can be helpful for the analysis process.

3.3.2 Interviews

This research also included interviews with:

- Alfonso Narvaiza, the Head of the Service of Exploitation of Systems and Cartography for Zaragoza's Water Utility. The interviews allowed the authorization of works and the discussion of the access to different types of information. Also interviews allowed giving feedback on the state of the research. These interviews were carried out in Zaragoza, Spain on 01/10/08, 15/10/08, 11/11/08, 24/02/09, 03/03/09, 13/11/09 and 27/05/10.

- Guardallaves chiefs and team. The research involved a close work with them and that was carried out from September to December/08 and from 09/03/09 to 13/03/09 in in Zaragoza, Spain. The interviews were a direct source of data on the team repair practices.

- Plumbing chiefs and team. The research involved a close work with them and that was carried out from September to December/08 and from 09/03/09 to 13/03/09 in in Zaragoza, Spain. The interviews were a direct source of data on the team repair practices.

- Chief of drivers. This interview allowed the access to the driver database. It was on 27/05/10 in Zaragoza, Spain.

- Alan Lambert, an international expert in the field. This interview clarified the implementation of the BABE methodology in the ELL calculation. This interview was carried out in Llandudno, North Wales on 26/08/09. This interview was followed by several email exchanges.

- Jose Maria Pina, from the Economic Studies unit of Zaragoza's city council Revenue Service. This interview allowed the access to reports of costs and payments in Zaragoza's water utility. This interview was carried out on 28/05/10 in Zaragoza, Spain.

3.4 The Concept of Dynamic Model

The primary modelling and analysis tool used in this research is the System Dynamics (SD) methodology developed by Forrester (Forrester, 1961) as a modelling and simulation methodology for long-term decision-making in dynamic industrial management problems. According to Forrester, a Dynamic Model deals with time-varying interactions and uses feedback to convert conditions to information that will later be used as a basis for the decision making to control actions to alter the surrounding conditions in a continuous cycle (ibid). He stresses that this process is a closed loop.

A Dynamic Model should have the following characteristics (ibid):

- Be able to describe any statement of cause-effect relationships that we may wish to include.
- Be simple in mathematical nature.
- Be closely synonymous in nomenclature to industrial, economic and social terminology.
- Be extendable to large number of variables (thousands) without exceeding the practical limits of digital computers.
- Be able to handle "continuous" interactions in the sense that any artificial discontinuities introduced by solution time intervals will not affect the results. It should, however, be able to generate discontinuous changes in decisions when these are needed.

Focusing on the 4th characteristic is clear that Dynamic Models were designed to be used with digital computers. This research uses Vensim as an engine for the model. The next section will explain the reason of choosing Vensim and not tools like spread sheets.

3.5 Vensim Vs Spread sheets

Burnett et al (2001) states that the spread sheet paradigm is probably the most popular programming paradigm in use today. This is because spread sheets allow a direct manipulation interface makes it easy to view, navigate, and interact with the data. This style of interaction is common in ad hoc spread sheets that a user creates for a specific goal (Chi et al, 1997). Also they provide a flexible and easy-to learn programming environment since spread sheet developers create templates that enable end-users to reliably repeat often-needed computations without the effort of development or coding (ibid). On top of that they provide a convenient tabular layout for presenting information.

This has allowed the spread sheets to be highly successful tools for interacting with numerical data, such as applying algebraic operations, manipulating rows or columns, and exploring "what–if" scenarios (Chi et al, 1997). This research uses Vensim instead of spread sheets.

Vensim is a visual modelling tool that allows conceptualizing, documenting, simulating, analysing, and optimizing models of dynamic systems. Vensim provides a simple and flexible way of building simulation models from causal loop or stock and flow diagrams (Eberlein, 2002). Vensim is distributed by Ventana Systems Inc (http://www.vensim.com) from Harvard, Ma. In this research, the Professional version of Vensim was used since it supported the sensitivity testing and Montecarlo simulations. However a free "Personal Learning Edition" is available for download at the Ventana Systems Inc website and it can be used to develop and run models just like the ones developed with the Professional version.

The use of the graphical conceptualization and documentation tools of Vensim allows an easy way to illustrate the cause-effect relationships. Since this research is not working with row-column references or addresses, like in a spread sheet but with variable names, that possibly cryptic issue of equation structure is solved. For example: The propagation of equations from cell to cell is prone to errors when a model involves a large number of variables.

Another characteristic of Vensim is that data and model are not mixed, so it's difficult to break the chain of causality by accidentally replacing an equation with a number. Vensim also verifies in an automatic way the dimensional consistency of equations, a task that also can be difficult with complex spread sheets. And the variables with high levels of connections can be identified very easy and the relationships discriminated since more connections mean more impact. The graphic interface is also an easier way to update or expanded the model.

On the simulation part, Vensim has internal calibration and optimization algorithms that facilitate the scenario and sensitivity analysis which require the use of several spread sheets, macros or add-ins to be run in a spread sheet model. These internal tools are also quicker because they are already implemented in the software. This can come very handy in the case of the Montecarlo Simulation that will be discussed in the next chapter.

In the case of this research, spread sheets were used as an interface for data collection and for the data input.

3.6 A Simplified Model for the Calculation of the ELL

After defining the model, the next step is to consider the variables that will be used in the calculations.

It was stated back in Section 2.6.1 (Plotting the Detection and Repair Costs Curve) that if the water utility has no active leakage control or a very poor one, the calculation of the ELL will require the assumption of a large quantity of data. This is the reason why the Water Losses Task Force has developed a simple methodology to assess the economic annual volume of real losses from unreported bursts, for a policy of regular survey, using only three system-specific parameters. The methodology was first presented by Lambert and Fantozzi (2005), then in a more user-friendly format at the Leakage 2005 Conference (Lambert and Lalonde, 2005). The Lambert and Lalonde paper also presents application examples of this methodology in a Canadian and an Australian water distribution system.

The two reasons to develop this simpler methodology were the lack of data and the absence of a methodology that allows the inclusion of the influences of pressure management on Short Run ELL.

3.6.1 Lack of Data

The data-intensive methods developed in the UK for economic intervention frequency could not readily be applied in systems where DMAs did not exist, or where there were major seasonal variations in night use. This issue calls for the developing of a simpler methodology to assess the economic intervention frequency for active leakage control, and the corresponding annual volume of real losses from unreported bursts.

This methodology requires only three system-specific parameters: Cost of Intervention (CI), Variable Cost of Lost Water (CV), and Rate of Rise of Unreported Leakage (RR) and can be used to quickly assess the Short Run ELL for any size of system or sub-system (Lambert and Lalonde, 2005).

3.6.2 Absence of a methodology

There was an absence of a methodology to allow the calculation of the influences of pressure management on Short Run ELL. Changes in leak flow rates could be modelled using Fixed And Variable Area Discharges (FAVAD) concepts, that describe water leakage flow rates as proportional and sometimes increase variably with increases in pressure (May, 1994), but no method existed for predicting changes in burst frequencies on mains and services, and associated cost savings. This deficiency has been remedied through recent developments by the Pressure Management Group (Thornton & Lambert, 2006), (Thornton & Lambert 2007). This research is an extension of this methodology, with the inclusion of the energy externalities associated with the Leakage control activities.

3.6.3 Results of the use of a simplified model

With the economic intervention concept, the three components of short-run economic leakage level (SRELL) can be quickly calculated, for a policy of regular survey, at current operating pressure. Real losses from reported bursts are calculated from number of reported burst repairs, with a pressure-dependent 'per burst' volume allowance. Background (undetectable) leakage is calculated as a multiple of Unavoidable Background Leakage. Economic annual volume of unreported real losses is calculated using Economic Intervention theory, which will be discussed in the Section 3.7 (Some Basic Concepts). This approach can be used to investigate how the SRELL is influenced by the interaction between cost and efficiency of different intervention methods, and the undetected and unrepaired leakage that remains after an intervention. The model description and the connection with the energy externalities will be explained with more details on the Section 3.15 (Calculation of Externalities) in this current chapter.

3.7 Some Basic Concepts

If referred to the IWA Components of water loss management strategy in the Figure 2.2 in the Section 2.3 (Water Loss Management Methods), the Current Annual Real Losses (CARL, represented by the largest box) exceed the Unavoidable Annual Real Losses (UARL, the smallest box), and there is an Economic Level of Leakage (ELL) somewhere between the two. The ratio of the CARL to the UARL is known as the Infrastructure Leakage Index (ILI).

The calculation of an ELL require the assessment of each relevant infrastructure component, such as mains and service connections, background leakage, reported leaks and unreported leaks. In the UK, it is assumed that there are continuous night flows for the different sectors in the network. They usually also require data on the average number and types of reported and unreported leaks and bursts that occur, on average, each year, under normal conditions, when the number of new bursts occurring equals the number of bursts repaired. As most Utilities internationally undertake little or no active leakage control, this information is rarely available.

Assuming a basic active leakage control policy of regular survey, the three parameters RR, CI and CV can be used to quickly assess, for any size of system or sub-system. According to Fanner and Lambert (2009), If unreported leakage is rising at a rate RR, then the minimum total cost of lost water and intervention costs occurs when the accumulated value of the lost water (the volume in the red triangle in Figure 3.3, multiplied by the variable cost of water CV) equals the cost of an intervention (CI). The intervention brings the leakage from Q_1 to Q_0.

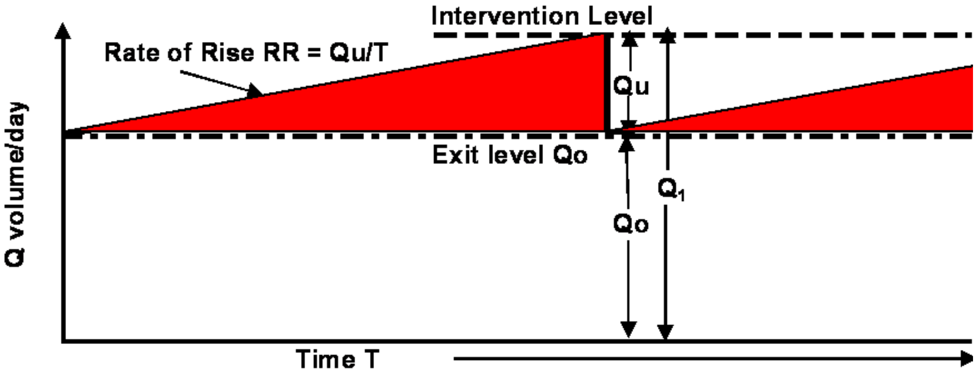


Figure 3.3: Economic Intervention level
(Source: Adapted from Fanner and Lambert, 2009)

This can be expressed as:

$$\text{Volume of water lost at time T} = \frac{1}{2}\cdot T\cdot(RR\cdot T) = \frac{1}{2}\cdot RR\cdot T^2$$

$$\text{Value of water lost at time T} = CV\cdot\frac{1}{2}\cdot RR\cdot T^2$$

Equation 3.1: (Source: Adapted from Figure 4.2, 2011)

The Economic Intervention theory will state that the value of the water lost must be equal to the Cost of Intervention:

$$CV \cdot \frac{1}{2} \cdot RR \cdot T_e^{\,2} = \text{Cost Of Intervention} = \text{CI}$$

$$T_e^{\,2} = \frac{2 \cdot \text{CI}}{CV \cdot RR} \rightarrow T_e = \sqrt{\frac{2 \cdot \text{CI}}{CV \cdot RR}}$$

Equation 3.2: (Source: Lambert and Lalonde, 2005)

Lambert and Lalonde (2005) expressed the concept of Economic Intervention Frequency as a time. If the Intervention Cost CI is in \$, the Variable Cost CV is in $\$/m^3$, and the Rate of Rise RR is in m^3/day/year:

$$\text{Economic Frequency of Intervention (EIF)} = \sqrt{\frac{0.789 \cdot \text{CI}}{CV \cdot RR}}$$

Equation 3.3: (Source: Lambert and Lalonde, 2005)

In this case, the 0.789 coefficient is used to express the EIF in months. The EIF allows the definition of an Economic Percentage of system to be surveyed annually (EP), considering a monthly distribution:

$$\text{Economic Percentage of system to be surveyed annually EP (\%)} = \frac{100 \cdot 12}{\text{EIF}}$$

Equation 3.4: (Source: Lambert and Lalonde, 2005)

This EP means that is not necessary to survey the whole system but only part of it. An Annual Budget for Intervention (ABI) can be calculated considering this EP and the Cost of Intervention:

$$\text{ABI (\$)} = \text{EP} \cdot \text{CI}$$

Equation 3.5: (Source: Lambert and Lalonde, 2005)

The Economic Unreported Real Losses (EURL) can be expressed as:

$$\text{EURL (m}^3\text{)} = \frac{\text{ABI}}{\text{CV}}$$

Equation 3.6: (Source: Lambert and Lalonde, 2005)

Equation 3.6 relates the Annual Budget for Intervention with the Variable Cost of water (CV). There must be a volume of lost water with a cost that is equal to the cost of the ABI. If the cost of water is know, that volume can be calculated easily.

As these equations include square root functions, confidence limits for calculating each of the above parameters are relatively insensitive to errors in RR, CI and CV. Methods of intervention range from simple (listening on hydrants) to complex (noise loggers and night flow measurements), and have different costs. In general, the more expensive the method the higher the CI and CI/CV ratio, leading to less frequent intervention and higher Economic Unreported Real Losses, and a higher efficiency in detection.

Lambert (2005) states than allocating a nominal volume allowance, per reported burst repaired with an appropriately short run time, multiplied by an appropriate average flow rate and adjusting for actual pressure can be used for defining the leak volume. Table 3.1 shows the volume allowances for 50 m of pressure according to Lambert et al (1999) using the UARL calculation which will be explained in the next paragraphs.

Infrastructure Component	Unavoidable Background Leakage	Detectable Reported Leaks and Bursts	Detectable Unreported Leaks and Bursts
Mains	20 l/km/h	12.4 bursts/100 km/yr at 12 m^3/h for 3 days = 864 m^3/burst	0.6 bursts/100 km/yr at 6 m^3/h for 50 days = 7200 m^3/burst
Service connections, main to property line	1.25 l/conn/h	2.25 /1000 conn/yr at 1.6 m^3/h for 8 days = 307 m^3/burst	0.75 /1000 conn/yr at 1.6 m^3/h for 100 days = 3840 m^3/burst
Service connections, property line to meter, if customer meter is not located at the property line	0.50 l/conn/h*	1.5 /1000 conn/yr* at 1.6 m^3/h for 9 days = 346 m^3/burst	0.50 /1000 conn/yr* at 1.6 m^3/h for 101 days = 3878 m^3/burst
	* For 15 m average length		

Table 3.1: Volume allowances for reported burst and leaks for a pressure of 50 m (Source: Lambert et al, 1999)

The values were obtained from the statistical analysis of the AQUA 1999 data set from 27 different water supply systems in 20 countries (Lambert et al, 1999).

These values take account of different durations of the leak incidents. For example a 1 day incident in a main will have a flow of 36 m^3/h and a 2 days a 18 m^3/h compared to 12 m^3/h for 3 days in Table 3.1, since the bigger leaks tend to be repaired quicker than the smaller leaks. For a different system pressure, a lineal relationship between leakage and pressure can be assumed as shown in Table 3.2.

Item	Volume per event @ 50m of pressure (m^3)	Volume per event @ 30m of pressure (m^3)
Mains	864	518
Service connections (Utility side)	307	184

Table 3.2: Volume allowances for reported burst and leaks for a pressure of 30 m based on Table 3.12 values
(Source: The Author, 2008)

With these volumes and the number of reported burst and the pipe length, a figure of annual loss from reported burst in l/conn/day or m^3/km of main/day can be obtained.

The formula to calculate Unavoidable Annual Real Losses UARL, the technical minimum, assumes that a well-managed system with infrastructure in good condition will have a specified frequency of mains (13 /100 km/year, 95% reported), service pipe bursts (3 per Utility side connection/year, 75% reported) and background leakage equal to Unavoidable Background Leakage (UBL), for infrastructure in good condition, assuming all unreported leaks are detected and repaired (Lambert and Lalonde, 2005).

The data in Table 3.1 contains the values from published international data used to calculate the coefficients in the basic equation for the calculation of UARL:

$$\mathrm{UARL\ (l/day)} = (18 \cdot \mathrm{Lm} + 0.8 \cdot \mathrm{Ns} + 25 \cdot \mathrm{Lp}) \cdot \mathrm{P}$$

Equation 3.7: (Source: Lambert, 1999)

Where Lm is the mains length (km), Ns is the number of service connections (main to property line), Lp is total length of underground pipes (property line to meter) and P is the average 24-hour pressure (metres). The 18, 0.8 and 25 values, that remain the same no matter if the UARL is calculated in different units as long as consistent units are used for all the parameters, were obtained from the statistical analysis of the AQUA 1999 data set from 27 different water supply systems in 20 countries (Lambert et al, 1999). See Section 2.4.3 (The UARL Calculation Issue).

This equation can also be used for the analysis of the components of night flow where the Unavoidable Background Leakage on mains and service connections up to the property line is:

$$\mathrm{UBL\ (l/h)} = (20 \cdot \mathrm{Lm} + 1.25 \cdot \mathrm{Ns}) \cdot \left(\frac{\mathrm{AZNP}}{50}\right)^{1.5}$$

Equation 3.8: (Source: Lambert, 1999)

Where Lm is the mains length (km), Ns is the number of service connections (main to property line) and AZNP is the Average Zone Night Pressure (m). The linear relationship between pressure and leakage has been studied (UKWIR, 2002) and proven right for the data used. (Lambert, 2001) describes the process of deduction of the value of 1.5 exponent using data from:

- Laboratory tests on holes in pipes (actual failures, or artificially created leaks).
- Tests on sectors of actual distribution systems, with customers supply turned off.
- Night tests on sectors of actual distribution systems, including customer night use.

Results from the analysis will be processed as relationships between leakage control activities and leakage cost. The establishment of current and future supply demand balance and alternative investments will be defined according with the plans that the government from Zaragoza have.

3.7.1 Background leakage level

Background leakage levels need an historical analysis of the night flow data for at least 4 years. The background leakage is identified as the minimum leakage level sustained for a significant period. In the case of night flow, the background leakage level is the best achieved night flow losses, based on a rolling 7- day minimum night flow.

In the case of not having night flow data, the background leakage level (LB) can be calculated applying the BABE methodology (Farley, 2001) where the level of background losses is dependent on the size (number of connections and length of mains) and condition of the system (ICF), and the average system pressure (Average Zone Night Pressure and Hour to Day Factor) applying the following equation:

$$\text{LB} = \text{ICF} \times \text{PCF} \times (4 \times \text{Number of Connections}) + (0.04 \times \text{Metres of Main})$$

Equation 3.9: (Source: Lambert, 1999)

The PCF is a Pressure Correction Factor that depends on the average zone night pressure.

3.7.2 ICF

The condition of the infrastructure is characterized by the Infrastructure Condition Factor (ICF). The ICF is the ratio between actual background leakage and the unavoidable amount of background leakage. Its value normally lies between 0.5 and 2.0, depending on the condition of the mains so 0.5 for mains that are considered to be in good condition, or 2.0 if they are considered to be in poor condition from a water tightness point of view (Farley, 2001). The ICF can be obtained by:

- Determine from leak detection and repair work within District Metered Areas (DMA) and extrapolate for whole system

- Determine from N1 pressure step tests and extrapolate for whole system

- Estimate from ILI

If there is no information available, an ICF value can be assumed. With the use of an average condition for the pipes (ICF = 1.0), the background losses are underestimated and consequently the recoverable losses are overestimated, which balances both conditions. This is the condition that will be used for this research. This research will consider the effects described by Fanner and Thornton (2005) on assuming an ICF value on these calculations in Section 3.13 (Estimated Background Leakage).

3.7.3 Natural rate of rise of leakage

The Natural Rate of Rise (NRR) is defined as the rate at which leakage will rise due to unreported bursts if no active leakage control takes place. The method for calculating it is described in UKWIR (1999). It involves the analysis of timesequences of minimum night flow data, and calculation of regression relationships for periods between consecutive unreported leak repairs. Short periods below a minimum duration are discarded, and the final NRR calculation is the average of the results from each regression period, weighted by the duration of each.

The NRR is a data that must be obtained if the Method B (Estimate the cost of reducing leakage and determine a natural Rate of Rise), described in Section 3.2 (Model Development), of analysing costs is used. Since this research is applying the splitting of current costs into steady state costs and transitional costs (Method A), this value will not be obtained for Zaragoza.

3.7.4 Unit costs of leak detection staff and leakage survey costs

These marginal costs include the direct costs of all leak detection technicians, both direct labour and contractors. The rates also include costs of supervision and support of these staff, as well as the equipment and vehicles required to carry out the work.

The survey costs can be calculated using information from different survey procedures and relating the number of man hours required to the number of properties and length of mains using regression analysis. It is important to consider in the analysis the possibility of a more detailed second leakage survey that might be needed in some sectors of the area under analysis.

This information has been obtained from Zaragoza's Water Utility and is presented in Table 4.24, Section 4.2.11 (ELL Calculation).

3.7.5 Reported leakage

The reported leakage component of the ELL is calculated from reported burst frequencies, reported burst flow rates and awareness, location and repair times.

Burst flow rates are derived as part of the calibration process for the natural rate of rise study. The numbers of each type of reported burst with appropriate burst flow rates are calibrated against the overall natural rate of rise. The awareness, location and repair times are obtained from the repair logs database or from comparison with the case studies in literature and are presented in Table 4.24, Section 4.2.11 (ELL Calculation).

3.7.6 Variable Cost of lost water (CV)

The cost of water is the financial benefit to a company which results from a reduction in the level of leakage and can be divided into (Farley, 2001):

- Operating costs: The savings in power and chemicals due to reducing the volume of water which is lost as leakage. The power costs are based on average flows with the electricity tariffs and include both raw water and treated water pumping costs.

- Capital costs: The savings which can be realized by deferring or downsizing demand related capital schemes. This may include the provision of resources, treatment capacity, and supply and distribution capacity. The timing of the schemes must consider the minimum headroom requirement, i.e. the margin of safety between drought-related resource yields and peak annual demands.

The cost of leaking water should be based on the leakage level in each DMA and the corresponding operating and capital costs of water (Farley, 2001). The consideration of capital costs is important during the Long Term ELL calculation.

The CV can be more widely defined than simply costs of production and distribution - it could include bulk supply charges, or deferred capital investment or even be as high as sale price of water (where water saved from leakage could be sold to other customers) (Personal communication with Alan Lambert, 2010). In the case of this analysis, this value is obtained from the water utility costs database in $\$/m^3$.

This information has been obtained from Zaragoza's Water Utility and is presented in Table 4.23, Section 4.2.11 (ELL Calculation).

3.7.7 Cost of an Intervention (CI)

This is obtained from the repair and detection logs using the costs of workforce and materials. The CI doesn't include the cost of repairing the unreported leaks found since there is no active leak detection. There can be different CI for different strategies. The units are $, or $/service connection, or $/km of mains. Section 4.2.11 (ELL Calculation) describes the calculation of the CI for Zaragoza.

3.7.8 Rate of Rise of unreported leakage (RR)

This data can be obtained in several ways (Lambert, 2005):

One is to use Measured Night Flows, in this case the measurement of flow over several nights is suitable for small and medium sized systems within a single pressure zone. The night flow measurement facilities do not have to be continuous or permanent. The Rate of Rise in m3/hour/year is the difference in adjusted night flows, divided by the time period. Multiply by a suitable Night-Day Factor NDF to allow for diurnal variation of leak rate with pressure (use NDF = 24 hrs/day as default). It is important to consider than this method should use data from times of the year with a minimum effect by the irrigation and industrial uses.

If a water utility lacks information about night flow measurements but can have water balances for several years where there has been no active leakage control. The Rate of Rise RR will be:

$$RR = \frac{(RL1 - RLN)}{N}$$

Equation 3.10: (Source: Adapted from Lambert, 2005)

Where RL1 is the annual volume of Real Losses in year 1, RLN is the annual volume of Real Losses a number N of years before. If the number of service connections or average pressure has changed, RLN shall be adjusted to number of connections and pressure in Year 1. Since there have been no active leakage control during the last year in the Actur test sector, the RR will be obtained by comparison of water balances using the information of the water balance calculated for 2007-2008 and a new water balance that will be calculated for 2008-2009 period.

It is necessary to consider a survey frequency and an analysis period. From 3 to 5 years is a recommended analysis period since is a SRELL.

If there are no measurements of night flow but there are any single active leakage control intervention in all or part of the system, the first step is to classify the detected leaks by typical average flow rate and by which part of the infrastructure they occurred on, for example mains and service connections. This can be done using the repair database from the water utility.

The annual Rate of Rise will be calculated as the division of the aggregate flow of all of the leaks found and the number of years over which they may have accumulated. This annual rate is expresses as per service connection or per km of mains for the part of the system surveyed and is assumed that it applies to the whole system.

If there are no measurements of night flow but there have been active leakage control interventions with a known interval in between, the annual Rate of Rise will be calculated as the division of the aggregate flow of all of the leaks found and the time period between the interventions to get the Rate of Rise.

It is important to mention that an approximate assessment of the Rate of Rise is acceptable to get started on Economic Intervention calculations. The results obtained can be refined in a later stage. The Rate of Rise is discussed in Section 3.14.3 (Average Rate of Rise of Unreported Leakage (RR)) and Section 4.2.11 presents the current value.

3.8 Use of the BABE Methodology in the Model

To develop an estimated Economic Level of Leakage, physical losses can be analysed in the following categories using the Bursts and Background Estimates (BABE) methodology and empirical relationships developed by the IWA Water Loss Task Force:

- Trunk mains and service reservoir leakage
- Real losses from reported leaks and bursts of very short duration but with high leak volumes
- Background leakage at joints with very small leak volume that makes them invisible to detection.
- Unreported real losses from unreported leaks and bursts with moderate flow rates and average duration that depend on the active leakage control method used by the water utility.

Categories considered by this methodology are showed in Figure 3.4.

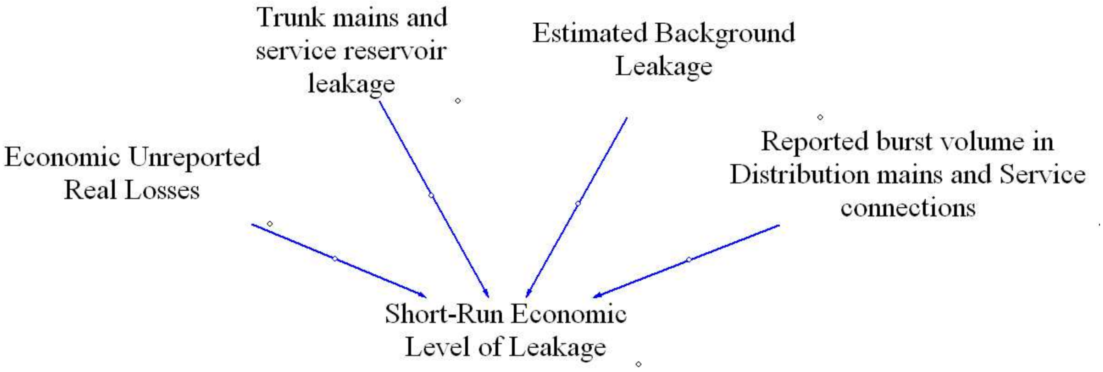


Figure 3.4: Representation of the leakage involved in the Short-Run Economic Level of Leakage
(Source: The Author)

Sections 3.11 (Reported Burst Volume in Distribution Mains and Service Connections), 3.12 (Estimated Background Leakage), 3.13 (Trunk Mains and Service Reservoir Leakage) and 3.14 (Economic Unreported Real Losses) describe the variables and outputs for each leakage type. The total addition of the calculated volumes will give the ELL for the system.

3.9 Inclusion of Externalities

After achieving the calculation of the ELL, it is necessary to include the energy externalities on the model. Section 3.15 will describe this procedure. The model will require the input of a combination of leakage control strategies, specified by the user, with the same time frame or with different time frames. Considering the historical data provided, it will calculate the volume of water saved by the strategy and the cost of that saved leakage, the cost of the implementation and the amount of emissions associated with each strategy. From the amount of emissions, the model will calculate a cost of the energy externalities applying the concept of Shadow Price of carbon.

This research considers the externalities only in the detection and repair stages of the leakage control. Considering the possibility of a "whole life carbon cost", where emissions are a function of: the embodied emissions from initial construction and periodic asset maintenance; annual operational emissions; and asset design life (UKWIR, 2008), this research will determine the net present value of carbon emissions using the shadow price of carbon (adjusted for year on year increased damages) and an appropriate discount rate (UKWIR, 2008). This research will not consider the social externalities associated with leakage management activities such as disruption to traffic and pedestrians or noise pollution.

Since investment decision-making for water industry assets is based on whole life assessment, a life cycle analysis (LCA) approach to carbon accounting is required. However the scope of a LCA approach is wider than the current research and it will not be considered. The Inventory of Carbon & Energy (Hammond, 2007) can be used to obtain the given values if needed.

As mentioned in Section 2.7.3 (Energy Use in Improved Speed and Repair of Leakages), no account is taken of any re-use or recycling of construction waste.

Instead it is assumed that this is accounted for in selecting materials for initial construction

The inclusion of externalities in the model will consider the fuel consumption used in the transport of the detection and repair crews. Using the millage of the vehicles and the fuel consumption (Both registered in current databases by the water utility) can be used to obtain a reference for the fuel consumption per event and per unit of time. This will be divided in the different types of vehicles used by the water utility. A similar approach will be used with the pumps, generators and illumination consumption.

In this case one of the objectives is to present the Greenhouse Gas (GHG) in a unit of volume from the leakage and from the water saved by the intervention. In this way, a lower value of GHG per cubic metre or litre will indicate a lower level of emissions and a better option when compared with a higher one. This will quantify the impact on emissions in tonnes of CO2. The Non-Traded Price of Carbon (NTPC), described in Section 2.9.1 (Economic Inclusion of the Emissions) and explained in Section 3.15.9 (Non-Traded Price of Carbon) will turn this GHG emissions into monetized values that are related to the volume of water so they can be included in the ELL calculation process as a extra curve.

3.10 Water Balance

Section 2.2.1 (Water Balance) described the IWA standard Water Balance and how the Water Balance allowed the water utility to answer "How much water is being lost?" and "where is it being lost?". This makes the Water Balance an important part of the model to allow the Water Utility to diagnose the current status of the water distribution system. The developed model contains a Water Balance calculation section that can be used to calculate the Rate of Rise as described in Section 3.14.3 (Average Rate of Unreported Leakage (RR)). The CARL can also be used for the calculation of the Infrastructure Leakage Index as showed in Section 3.12.18 (Infrastructure Leakage Index (ILI)).

Table 3.3 is a list of the Water Balance section of the model variables and outputs. An output in this chapter is defined as the result of the operation of a variable or the operation of previous level outputs. So a Level 2 output is the result of the equation of a Level 1 output or of a variable.

Variables	Outputs Level 1	Outputs Level 2	Outputs Level 3	Outputs Level 4
System Input Volume				
Billed Metered Consumption				
Billed Unmetered Consumption				
	Billed Authorised Consumption			
Unbilled Metered Consumption				
Unbilled Unmetered Consumption				
	Unbilled Authorised Consumption			
		Authorised Consumption		
			Water Losses	
Estimated Number of Illegal Domestic Connections				
Persons Per House				
Consumption				
	Unauthorized Illegal Domestic Consumption			
Other Unauthorized Consumption				
Estimated Number of Altered Meters				
Minimum Legal Consumption				
	Meter Alteration Unauthorised Consumption			
		Unauthorised Consumption		
Billed Metered Consumption (Without Bulk Supply) Percentage of Error in Measurement				
Billed Metered Consumption (Without Bulk Supply)				
Metered Bulk Supply (Export) Percentage of Error in Measurement				
Metered Bulk Supply (Export)				
Data Handling Errors in the Office				
Effect of Bad Meter Reading Practices				
Best Estimation Volume Customer Meter Inaccuracies and Data Handling Errors				
Unbilled Metered Consumption (Without Bulk Supply) Percentage of Error in Measurement				
Unbilled Metered Consumption (Without Bulk Supply)				
	Best Estimation Volume Customer Meter Inaccuracies and Data Handling Errors			
		Apparent Losses		
				Real Losses
				Current Annual Volume of Real Losses (CARL)

Table 3.3: List of the variables and outputs used in the Water Balance section of the model. (Source: The Author)

The Level 2, Level 3 and Level 4 outputs are showed in Figure 3.5. This is a simplification of the Water Balance section of the model.

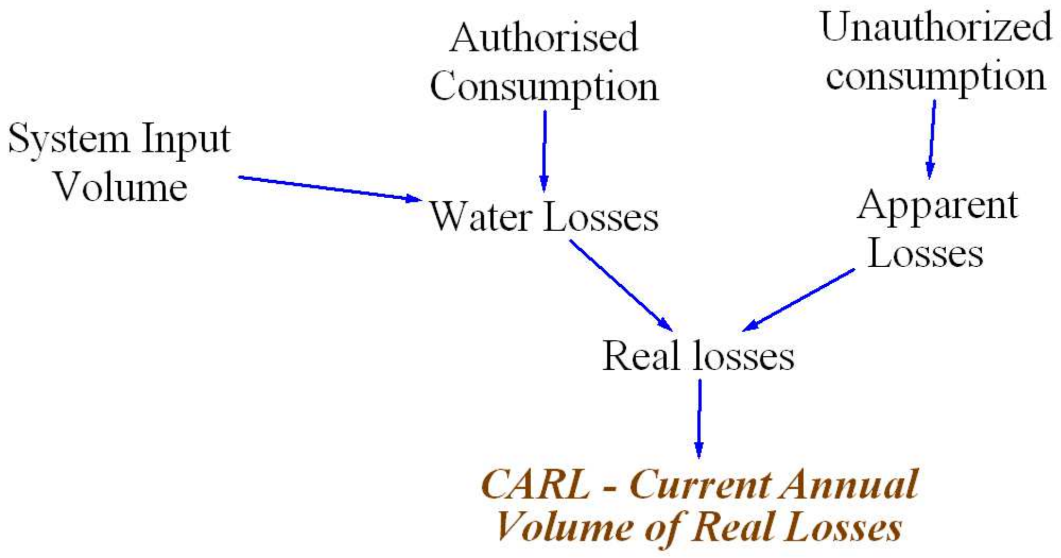


Figure 3.5: Simplification of the Water Balance section of the model (Source: The Author)

3.10.1 System Input Volume

When the entire system input is metered, the calculation of annual system input should be a straight forward task. It is recommended to verify input meters using portable flow measuring devices. If any discrepancies between meter readings and the temporary measurements are discovered, the problem has to be investigated and, if necessary, the recorded quantity has to be adjusted to reflect the real situation.

If there are some unmetered sources, Liemberger (2004) recommends that the annual flow has to be estimated by using any (or a combination) of the following: (i) temporary flow measurements using portable devices, (ii) reservoir drop tests or (iii) analysis of pump curves, pressures and average pumping hours.

Units: m^3.
Equation: This value is an input for the model.

3.10.2 Billed Metered Consumption

All metered consumption which is also billed. This includes all groups of customers such as domestic, commercial, industrial or institutional and also includes water transferred across operational boundaries (water exported) which is metered and billed. This information is obtained and analysed from the Water Utility billing system (Liemberger, 2004). The analysis of this data goes hand in hand with the detection of possible billing and data handling errors, information later on required for the estimation of Apparent Losses. It’s recommended (ibid) to pay special attention to the group of very large consumers.

The meter readings must be corrected for adjust for lag time in meter readings. While production meters, are usually read on the same day of every month, customer meters are read over the full month. Also there is generally a lag of up to 30 days between the time when water is consumed and when meter is read (Farley et al, 2008).

The best way to account for changes in the number of customers and in consumption patterns is to prorate water consumption for the first and last billing periods within the water audit period (Thornton, 2008). This can be used when all customer meters are read on the same day. In the case of existence of different meter reading routes, a meter lag correction should be used for each meter reading route.

Units: m^3.
Equation: This value is an input for the model.

3.10.3 Billed Non-metered Consumption

All billed consumption which is calculated based on estimates or norms but is Non-metered (Liemberger, 2004). This might be a very small component in fully metered systems (for example billing based on estimates for the period a customer meter is out of order) but can be the key consumption component in systems without universal metering. This component might also include water transferred across operational boundaries (water exported) which is unmetered but billed. This value can be obtained from the utility’s billing system. To analyse the accuracy of the estimates, unmetered domestic customers should be identified and monitored for a certain period, for example by measuring a small area with a number of unmetered customers.

Units: m^3.
Equation: This value is an input for the model.

3.10.4 Unbilled Metered Consumption

Metered Consumption which is for any reason unbilled. This might for example include metered consumption by the utility itself or water provided to institutions free of charge, including water transferred across operational boundaries (water exported) which is metered but unbilled (Liemberger, 2004). This value can be obtained from the utility’s billing system.

Units: m^3.
Equation: This value is an input for the model.

3.10.5 Unbilled Non-metered Consumption (UBNMC)

Any kind of Authorized Consumption which is neither billed nor metered. This value traditionally includes water used by the water utility for operational purposes.

This component typically includes items such as:

- Fire fighting and fire fighting training
- Flushing of water mains, storm inlets and sewers
- Street cleaning
- Landscaping and irrigation of public areas
- Decorative water facilities
- Frost protection

- Swimming pools
- Construction Sites: water for mixing concrete, dust control, trench setting, others
- Water consumption at public buildings not included in the customer billing system

In a well-run utility it is a small component which is very often substantially overestimated due to simplifications (a certain % of total system input) or overestimates on purpose to "reduce" water losses. For this reason, components of this value must be identified and estimated individually. Theoretically this value might also include water transferred across operational boundaries (water exported) which is unmetered and unbilled - although this is an unlikely case (Liemberger, 2004).

Units: m^3.
Equation: This value is an input for the model.

3.10.6 Billed Authorised Consumption

According to Liemberger (2010), the Billed Authorised Consumption is the components of Authorized Consumption which are billed and produce revenue (also known as Revenue Water). Alegre et al (2000) defines the Billed Authorised Consumption as the sum of Billed Metered and Billed Non-metered Consumption.

Units: m^3.

3.10.7 Unbilled Authorised Consumption

According to Liemberger (2010), Unbilled Authorised Consumption is those components of Authorized Consumption which are legitimate but Unbilled and therefore do not produce revenue. Alegre et al (2000) defines the Unbilled Authorized Consumption as the sum of Unbilled Metered and Non-metered Consumption.

Units: m^3.

3.10.8 Authorised Consumption

The volume of metered and/or unmetered water taken by registered customers, the water supplier and others who are implicitly or explicitly authorized to do so by the water supplier, for residential, commercial and industrial purposes. It also includes water exported across operational boundaries. Authorized consumption may include items such as fire fighting and training, flushing of mains and sewers, street cleaning, watering of municipal gardens, public fountains, frost protection, building water, etc. These may be billed or unbilled, metered or unmetered. Defined by Alegre et al (2000) as the sum of Billed and Unbilled Authorized Consumptions.

Units: m^3.

3.10.9 Water Losses

As stated in Section 2.2.1 (Water Balance), the Water Losses are the difference between the System Input Volume and the Authorised Consumption.

Units: m^3

3.10.10 Persons per House

This information is obtained using a house-to-house survey or city census data.

Units: Number
Equation: This value is an input for the model.

3.10.11 Consumption

This value is obtained from consumption studies by the water utility.

Units: litres per person per day.
Equation: This value is an input for the model.

3.10.12 Estimated Number of Illegal Domestic Connections

This information is obtained from the commercial database or anecdotal evidence of inspectors, or by a house-to-house survey of a sample zone (checking that each connection has a billing reference) estimate the number of broken or by-passed meters (Farley, 2001).

Units: Number
Equation: This value is an input for the model.

3.10.13 Non Authorised Illegal Domestic Consumption

To obtain the NIDC, the Estimated Number of Illegal Domestic Connections is multiplied by the Persons per House and the Consumption. This value is expressed in m^3 in a yearly basis.

Units: m^3/year

3.10.14 Minimum Legal Consumption (MLC)

This value is the volume of water that the national legislation sets as a minimum resource requirements for certain human and ecological functions (Gleick, 1999).

Units: litres per capita per day (lpcd).
Equation: This value is an input for the model.

3.10.15 Estimated Number of Altered Meters (ENAM)

This information is obtained from the commercial database or anecdotal evidence of inspectors, or by a house-to-house survey of a sample zone (checking that each connection has a billing reference) estimate the number of broken or by-passed meters (Farley, 2001).

Units: Number
Equation: This value is an input for the model.

3.10.16 Meter Alteration Non Authorised Consumption (MANC)

From the product of the Estimated Number of Altered Meters and the Minimum Legal Consumption, a yearly figure in m^3 is obtained. This value refers to meters reading zero or bypasses.

Units: m^3/year
Equation:

$$\mathrm{MANC} = \frac{\mathrm{MLC} \cdot \mathrm{ENAM} \cdot 365}{1000}$$

Equation 3.11: (Source: The Author)

3.10.17 Other Non-Authorised Consumption (ONC)

This value can be used to consolidate a different type of unauthorized consumption.

Units: m^3.
Equation: This value is an input for the model.

3.10.18 Non Authorised Consumption

This value includes water illegally withdrawn from hydrants, illegal connections, bypasses to consumption meter or meter/meter reading equipment tampering. Calculated as the sum of Meter Alteration Non Authorised Consumption, Non Authorised Illegal Domestic Consumption and Other Non Authorised Consumption.

Units: m^3

3.10.19 Effect of Bad Meter Reading Practices (EBMRP)

It is important to mention that while the estimation of water consumption using historic consumption trends might seem a reasonable approach, multiple cycles of meter estimates without an actual reading greatly increase the prospect of inaccurate estimates (Thornton et al, 2008). This value is estimated by the Water Utility.

Units: Percentage
Equation: This value is an input for the model.

3.10.20 Billed Metered Consumption (Without Bulk Supply) (BMC)

BMC is the total billed metered consumption by the users, excluding the bulk supply. The bulk supply is defined as "water supplied in bulk, usually in treated form, from one water company to another" (DWI, 2004).

Units: m^3
Equation: This value is an input for the model.

3.10.21 Billed Metered Consumption (Without Bulk Supply) Percentage of Error in Measurement (BMC%)

Mutikanga et al (2010) mentions the use of data-capturing audits to compare the input data used for billing and the readings on the meter reading sheets submitted by meter readers. The readings that were wrongly captured in the billing database were established and their corresponding total volume was computed (x m^3). If water sales for assessment period were y m^3, the percentage data handling errors were computed as (x/y *100).

Units: Percentage.
Equation: This value is an input for the model.

3.10.22 Data Handling Errors in the Office (DHEO)

Apparent water losses caused by data handling errors in the meter reading and billing system. This value is estimated by the Water Utility.

Units: m^3
Equation: This value is an input for the model.

3.10.23 Metered Bulk Supply (Export) (MBS)

This is the actual volume of bulk supply the water utility exported.

Units: m^3
Equation: This value is an input for the model.

3.10.24 Metered Bulk Supply (Export) Percentage Of Error in Measurement (MBS%)

The use of data-capturing audits can help in the calculation of this value.

Units: percentage
Equation: This value is an input for the model.

3.10.25 Unbilled Metered Consumption (Without Bulk Supply) (UMC)

This value is estimated by the Water Utility.

Units: m^3
Equation: This value is an input for the model.

3.10.26 Unbilled Metered Consumption (Without Bulk Supply) Percentage of Error in Measurement (UMC%)

Units: Percentage
Equation: This value is an input for the model.

3.10.27 Best Estimation Volume Customer Meter Inaccuracies and Data Handling Errors (BEVCMI)

Alegre (2000) warns that the over-registration of customer meters, leads to under-estimation of Real Losses while the under-registration of customer meters, leads to over-estimation of Real Losses. In this model, the BEVCMI is presented as the sum of the Effect of Bad Meter Reading Practices, Billed Metered Consumption (Without Bulk Supply), Data Handling Errors in the Office, Metered Bulk Supply (Export) and Unbilled Metered Consumption (Without Bulk Supply). Some of the variables are affected by a percentage of error in measurement.

Units: m^3/year
Equation:

$$\mathrm{BEVCMI} = E\mathrm{BMRP} + (\mathrm{BMC} \cdot \mathrm{BMC\%}) + \mathrm{DHEO} + (\mathrm{MBS} \cdot \mathrm{MBS\%}) + (\mathrm{UMC} \cdot \mathrm{UMC\%})$$

Equation 3.12: (Source: The Author)

3.10.28 Apparent Losses

Includes all types of inaccuracies associated with customer metering as well as data handling errors (meter reading and billing), plus unauthorized consumption (theft or illegal use) (Liemberger, 2010). In this case the Apparent Losses are defined as the sum of the Best Estimation Volume Customer Meter Inaccuracies and Data Handling Errors and the Non Authorised Consumption.

Units: m^3/year

3.10.29 Real Losses

The volume of current annual Real Losses represents the average picture over a 12-month period in which the natural rate of rise of leakage is constrained, to a greater or lesser degree, by leakage management activities (Lambert and McKenzie, 2002). Real losses are called "Physical Losses" by the World Bank and in some countries the misleading term "Technical Losses" is used (Farley, 2008). (Liemberger, 2004) recommends verifying the real loss figure using Component Analysis or Bottom-up real loss assessment.

Units: m^3/year
Equation:

$$\mathrm{Real\ Losses} = \mathrm{Water\ Losses} - \mathrm{Aparent\ Losses}$$

Equation 3.13: (Source: Alegre et al, 2000)

3.10.30 Current Annual Volume of Real Losses (CARL)

If the analysis is not done on a yearly basis, the CARL should be adjusted to express it as such.

Units: m^3/year
Equation:

$$\mathrm{CARL} = \mathrm{Real\ Losses}$$

Equation 3.14: (Source: Thornton et al, 2008)

3.11 Reported Burst Volume in Distribution Mains and Service Connections

After defining the Water Balance, the model estimates the volume of real losses from reported bursts in distribution mains and service connections using data on the number of reported bursts and the average system pressure, together with empirical relationships developed by Lambert et al (1999) that was mentioned in Section 3.7. Table 3.4 shows the variables and outputs in this section of the model.

Variables	Outputs Level 1	Outputs Level 2	Outputs Level 3
Average System Pressure			
Percentage of Rigid Service Connections			
	FAVAD N1 for Service Connections		
Number of Reported Burst And Leaks In Service Connections			
Volume per Event in Service Connections			
Repair Time in Service Connections			
	Assumed Volume Lost per Reported Burst or Leak @ 50m Pressure in Service Connections		
		Reported Bursts Volumes on Service Connections	
Number of Reported Burst and Leaks in Distribution Mains			
Percentage of Rigid Distribution Mains			
	FAVAD N1 for Distribution Mains		
Volume per Event in Distribution Mains			
Repair Time in Distribution Mains			
	Assumed Volume Lost per Reported Burst or Leak @ 50m Pressure in Distribution Mains		
		Reported Bursts Volumes on Distribution Mains	
			Reported Burst Volume in Distribution Mains and Service Connections

Table 3.4: List of the variables and outputs used in the Reported burst volume in Distribution mains and Service connection section of the model.
(Source: The Author)

The Level 1, Level 2 and Level 3 outputs are showed in the Figure 3.6. This is a simplification of this section of the model.

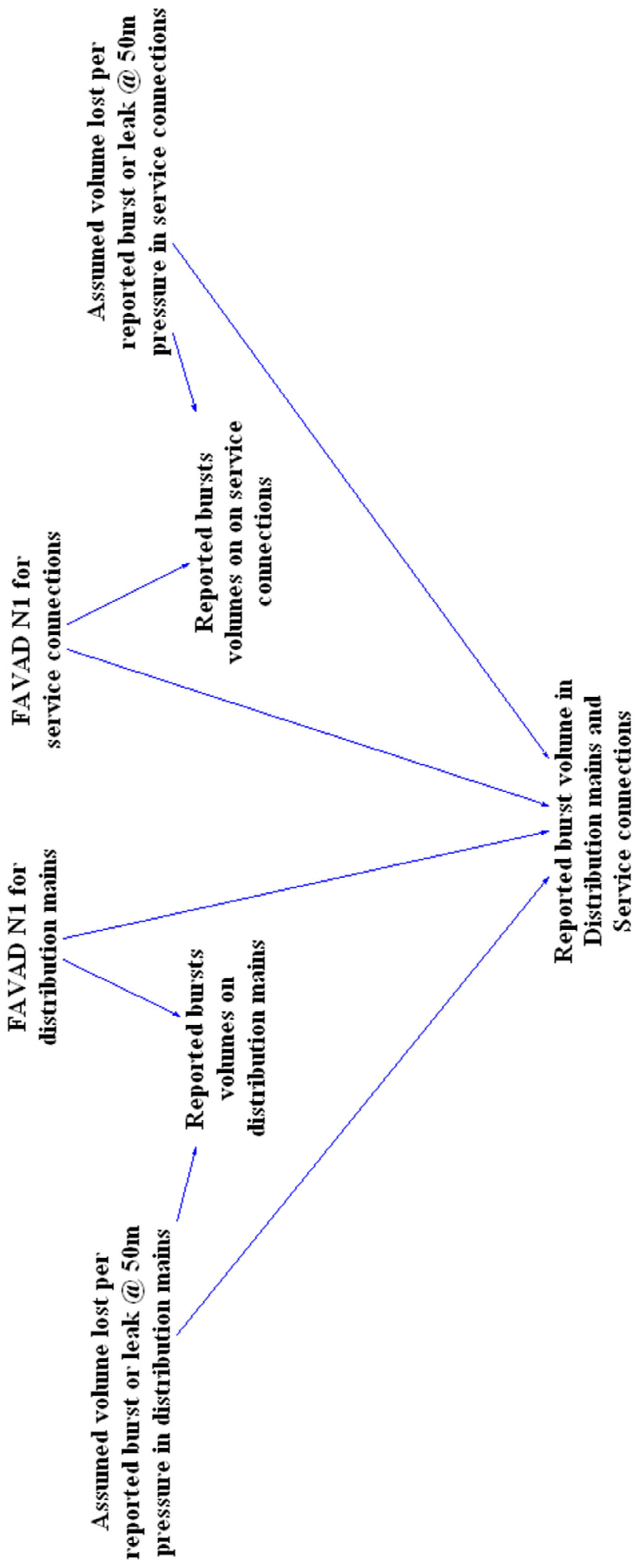


Figure 3.6: Simplification of the Reported burst volume in Distribution mains and Service connection section of the model
(Source: The Author)

In a very general way, this section of the model calculates a FAVAD N1 for Distribution Mains and Service Connections using the percentage of rigid service connections and distribution mains and the number of reported leaks.

This N1 exponent is used to calculate leakage:pressure relationships. (Lambert, 2001) mentions that the most appropriate general equations to use for this calculations are

$$L \text{ varies with } P^{N1}$$

Equation 3.15: (Source: Lambert, 2001)

And Equation 2.1

$$\frac{L_1}{L_0} = \left(\frac{P_1}{P_0}\right)^{N1}$$

Equation 3.16: (Source: Lambert, 2001)

Where L is the leakage rate (volume/unit time) and P is pressure.

The higher the N1 value, the more sensitive existing leakage flow rates will be to changes in pressures. Undetectable small 'background' leaks from joints and fittings in distribution systems are quite sensitive to pressure, with N1 values typically close to 1.5 where larger detectable leaks from plastic pipes typically have N1 values of 1.5 or even higher. In the case of larger detectable leaks in metal pipes the N1 value is usually close to 0.50 (Lambert, 2001).

3.11.1 Average System Pressure (ASP)

ASP pressures should be calculated as average 24-hour values; night pressures at the ASP point are known as AZNP's (Average Zone Night Pressures). The calculation of the average system pressure is described by McKenzie et al (2004):

If a network model is available, it is relatively easy to calculate the weighted average pressure for all nodes in the model (or any defined part of it) since each node of a Network Analysis Model will normally have a datum ground level, and an average pressure value. It's useful to ensure that a weighted average ground level, and an AZP point are defined for each zone/sector, as these might be required for test measurement.

If network models are not available, the first step is to calculate weighted average ground level for each sector or DMA. Using a contour map, preferably with 2-metre intervals, locate in each contour band one of the following infrastructure parameters (parameters are in order of preference):

- Number of service connections;
- Number of hydrants;
- Length of mains.

Using the midpoint value in each band and the number of infrastructure parameters, the Weighted Average Ground Level can be estimated.

The second step is to measure or calculate the average zone pressure either using measurements over a period of one year or preliminary estimations based on average Inlet pressure adjusted for difference in ground levels between Inlet Point and AZP.

Finally, the weighted average pressure for aggregation of zones is obtained by calculating a weighted average for all the zones. If possible, the number of service connections should be used as the weighting parameter (if not available, use length of mains or number of hydrants).

The assumption of a linear relationship between pressure and leakage is reliable considering a combination of factors (Lambert and McKenzie, 2002) especially for large systems with mixed metal and non-metal pipework, with average pressure in the range 30 to 70 metres. This is based in an UKWIR study of some 70 mixed-pipework sectors in the UK (ibid)

Equation: This value is an input for the model.
Units: m.

3.11.2 Percentage of Rigid Service Connections (RSC%)

This information is available from the water utility databases.

Units: Percentage.
Equation: This value is an input for the model.

3.11.3 FAVAD N1 for Service Connections (N1SC)

According to Fantozzi and Lambert (2007), for detectable leaks and bursts (reported and unreported), an assumption of N1 = 1.0 if pipe materials are not known. In the case of predominant splits in flexible pipes, the N1 is assumed to be between 1.0 and 1.5. For the case of predominant leaks from rigid pipes, or leaks from flexible pipes at the mains connection point, N1 is assumed to be between 0.5 and 1.0. Since the main focus is the leakage in flexible service connections, this gives the interval from 0.5 as a lower threshold for the N1.

Units: Dimensionless
Equation:

$$\mathrm{N1SC} = 0.5 \cdot 1(1 - \mathrm{RSC\%})$$

Equation 3.17: (Source: Personal Communication with Alan Lambert)

3.11.4 Number of Reported Burst and Leaks in Service Connections (NRBLSC)

The reported burst are defined as those events that are brought to the attention of the water utility by the general public or the water utility's own staff. A burst or a leak that, under urban conditions, manifests itself at the surface will normally be reported to the water utility (Liemberger, 2004).

Units: Number.
Equation: This value is an input for the model.

3.11.5 Volume per Event in Service Connections (VESC)

This volume is based on the Column 3 in Table 4 from Lambert et al (1999). According to the event duration it can have a value of 1.6 m^3/h for 8 days or 0.8 m^3/h for 16 days, or 0.4 m^3/h for 32 days. Table 3.5 shows those values.

Infrastructure Component	Unavoidable Background Leakage	Detectable Reported Leaks and Bursts	Detectable Unreported Leaks and Bursts
Mains	20 l/km/h	12.4 bursts/100 km/yr at 12 m^3/h for 3 days = 864 m^3/burst	0.6 bursts/100 km/yr at 6 m^3/h for 50 days = 7200 m^3/burst
Service connections, main to property line	1.25 l/conn/h	2.25 /1000 conn/yr at 1.6 m^3/h for 8 days = 307 m^3/burst	0.75 /1000 conn/yr at 1.6 m^3/h for 100 days = 3840 m^3/burst
Service connections, property line to meter, if customer meter is not located at the property line	0.50 l/conn/h*	1.5 /1000 conn/yr* at 1.6 m^3/h for 9 days = 346 m^3/burst	0.50 /1000 conn/yr* at 1.6 m^3/h for 101 days = 3878 m^3/burst
	* For 15 m average length		

Table 3.5: Parameters Values Used for Calculation of Unavoidable Annual Real Losses UARL for a pressure of 50 m
(Source: Lambert et al, 1999)

Units: m^3/h per event.
Equation: This value is an input for the model.

3.11.6 Repair Time in Service Connections (RTSC)

The analysis of repair logs will allow calculation of this value.

Units: Days.
Equation: This value is an input for the model.

3.11.7 Assumed Volume Lost per Reported Burst or Leak @ 50m Pressure in Service Connections (AVLSC@50m)

The AVLSC@50m is a volume per event. Considering the Volume per Event in Service Connections (VESC) and Repair Time in Service Connections (RTSC) that value can be obtained. A value of 307 m^3/event can be used as a guideline when the RTSC is unknown.

Units: m^3 per event
Equation:

$$\text{AVLSC@50m} = 24 \cdot VESC \cdot RTSC$$

Equation 3.18: (Source: The Author)

3.11.8 Reported Burst Volume on Service Connections (RBVSC)

Since the Assumed Volume Lost per Reported Burst or Leak @ 50m Pressure in Service Connections is calculated considering the volumes per event at 50 m (Table 3.5). That value has to be adapted to the current Average System Pressure. Using Equation 2.1 allows this. Then the Number of Reported Burst and Leaks in Service Connections is used to calculate a total value for RBVSC.

Units: m^{3}x10^3/yr
Equation:

$$\mathrm{RBVSC} = \frac{1}{1000} \cdot N\mathrm{RBLSC} \cdot \mathrm{AVLSC@50m} \cdot \left(\frac{\mathrm{ASP}}{50}\right)^{N1SC}$$

Equation 3.19: (Source: The Author)

3.11.9 Number of Reported Burst and Leaks in Distribution Mains (NRBLDM)

The reported burst are defined as those events that are brought to attention of the water utility by general public or water utility's own staff. A burst or a leak that, under urban conditions, manifests itself at the surface will normally be reported to the water utility (Liemberger, 2004).

Units: Number
Equation: This value is an input for the model.

3.11.10 Percentage of Rigid Distribution Mains (RDM%)

This information is available from water utility databases. Rigid pipe is classified as pipe that cannot deflect more than 2% without cracking (ASCE, 1998). Clay and concrete (reinforced and non-reinforced) are common examples (ibid).

Units: Percentage
Equation: This value is an input for the model.

3.11.11 FAVAD N1 for Distribution Mains (N1DM)

According to Fantozzi and Lambert (2007) for detectable leaks and bursts (reported and unreported), an assumption of N1 = 1.0 if pipe materials are not known. In the case of predominant splits in flexible pipes, the N1 is assumed to be between 1.0 and 1.5. For the case of predominant leaks from rigid pipes, or leaks from flexible pipes at mains connection point, N1 is assumed to be between 0.5 and 1.0. Since the main focus is the leakage in flexible distribution mains, this gives the interval from 0.5 as a lower threshold for the N1.

Units: Dimensionless
Equation:

$$\mathrm{N1DM} = 0.5 \cdot 1(1 - \mathrm{RDM\%})$$

Equation 3.20: (Source: Personal Communication with Alan Lambert)

3.11.12 Volume per Event in Distribution Mains (VEDM)

This volume is based on the Column 3 in Table 3.5 from (Lambert et al, 1999), 12 m^3/hr for 3 days, or equivalent, e.g. 36 m^3/hr for 1 day, or 18 m^3/hr for 2 days, or 6 m^3/hr for 6 days, or 3 m^3/hr for 12 days, etc. See Table 3.3.

Equation: This value is an input for the model.

Units: m^3/h.

3.11.13 Repair Time in Distribution Mains (RTDM)

The analysis of the repair logs will allow the calculation of this value.

Units: Days.
Equation: This value is an input for the model.

3.11.14 Assumed Volume Lost per Reported Burst or Leak @ 50m Pressure in Distribution Mains (AVLDM@50m)

The AVLDM@50m is a volume per event. Considering the Volume per Event in Distribution Mains (VEDM) and Repair Time in Distribution Mains (RTDM) that value can be obtained,

Units: m^3 per event
Equation:

$$\mathrm{AVLDM@50m} = 24 \cdot VEDM \cdot RTDM$$

Equation 3.21: (Source: The Author)

3.11.15 Reported Burst Volumes on Distribution Mains (RBVDM)

Since the Assumed Volume Lost per Reported Burst or Leak @ 50m Pressure on Distribution Mains is calculated considering the volumes per event at 50 m (Table 3.5), that value has to be adapted to the current Average System Pressure. Using Equation 2.1 allows this. Then the Number of Reported Burst and Leaks on Distribution Mains is used to calculate a total value for RBVDM.

Units: $m^3 x 10^3$/yr
Equation:

$$\mathrm{RBVDM} = \frac{1}{1000} \cdot N\mathrm{RBLDM} \cdot \mathrm{AVLDM@50m} \cdot \left(\frac{\mathrm{ASP}}{50}\right)^{N1DM}$$

Equation 3.22: (Source: The Author)

3.11.16 Reported Burst Volume in Distribution Mains and Service Connections (RBVDMSC)

This value is the sum of Reported Burst Volumes in Service Connections and Reported Burst Volumes on Distribution Mains

Units: $m^3 x 10^3$/yr
Equation:

$$\mathrm{R}BVDMSC = \mathrm{RBVSC} + \mathrm{RBVDM}$$

Equation 3.23: (Source: The Author)

3.12 Estimated Background Leakage

The Unavoidable Background Leakage is estimated from data on water distribution system infrastructure and pressure, using empirical relationships presented by Lambert et al (1999). This represents the minimum level of background leakage that could be achieved at this pressure for an *average* condition of the pipes (ICF = 1.0) and is used here in the ELL estimate. However, in practice Unavoidable Background Leakage depends on the water loss strategies in use (ibid). Table 3.6 lists variables and outputs in this section of the model.

Variables	Outputs Level 1	Outputs Level 2
Average Length of Service Connections From Property Boundary to Meter		
Distribution and Transmission Pipe Length		
Trunk Mains		
Unavoidable Annual Real Losses per Metre of Pressure for Distribution Mains		
Unavoidable Annual Real Losses per Metre of Pressure for Service Connections		
Number of Service Connections		
Number of Days		
Predicted Background Leakage		
FAVAD N1		
Background Leakage @ 50m Pressure and ICF = 1.0 for Service Connections		
Background Leakage @ 50m Pressure and ICF = 1.0 for Mains		
	Connection Density	
	Unavoidable Background Leakage for ICF=1.0	
	Unavoidable Background Leakage per day for ICF=1.0	
	Estimated Background Leakage, for ICF= Predicted Background Leakage	
	Additional Background Leakage if ICF = Predicted Background Leakage	
	Unavoidable Annual Real Losses (UARL)	
	UARL - Unavoidable Annual Real Losses	
		Infrastructure Leakage Index (ILI)

Table 3.6: List of the variables and outputs used in the Estimated background leakage section of the model.
(Source: The Author)

The Level 1, Level 2 outputs and the variables (Inside boxes) are showed in the Figure 3.7:

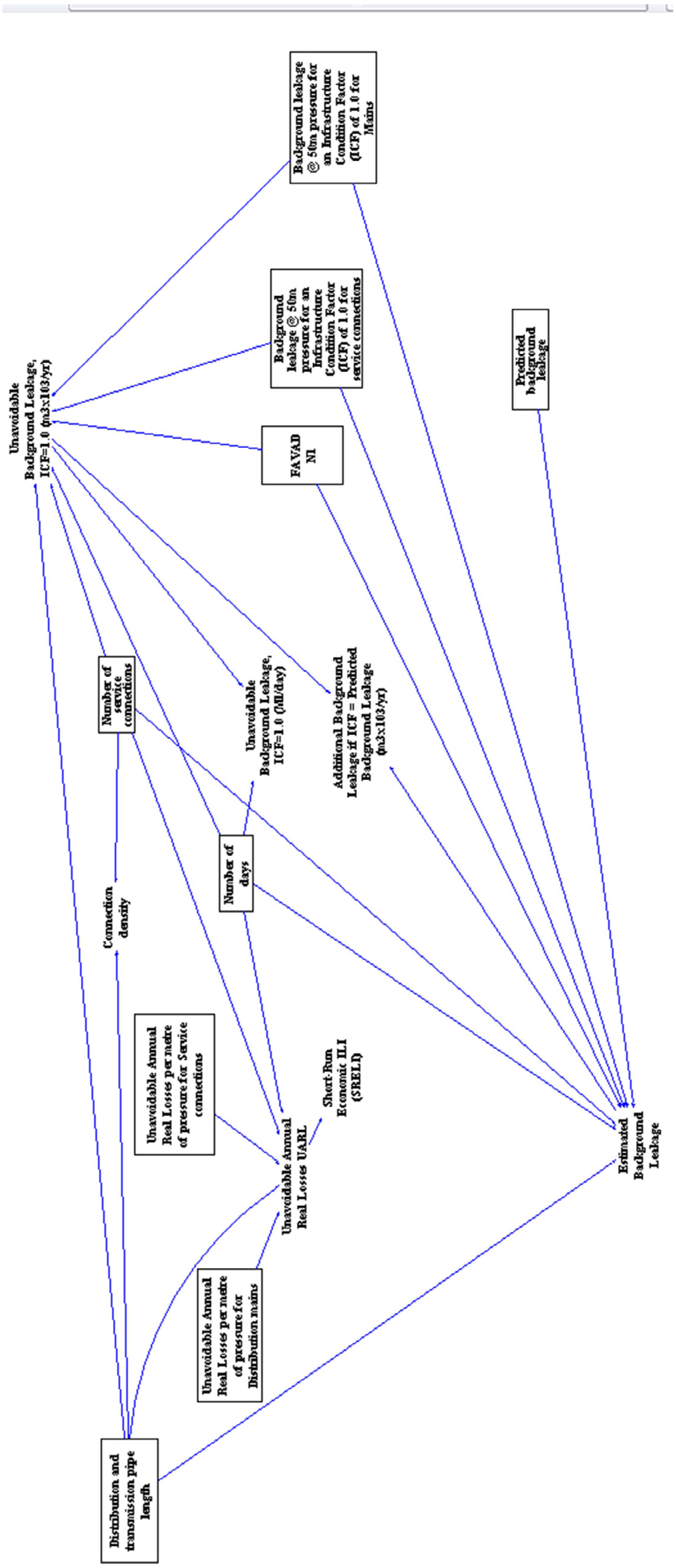


Figure 3.7: Estimated background leakage section of the model.
(Source: The Author)

3.12.1 Average Length of Service Connections from Property Boundary to Meter (Lp)

This information is available from the water utility databases.

Units: m.
Equation: This value is an input for the model.

3.12.2 Distribution and Transmission Pipe Length (Lm)

This information is available from the water utility databases.

Units: km.
Equation: This value is an input for the model.

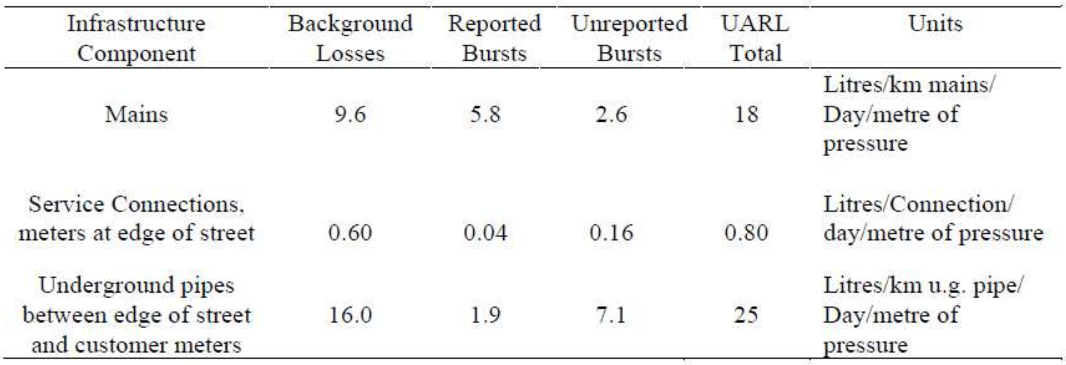
3.12.3 Trunk mains

This information can be obtained from the water utility database

Units: km
Equation: This value is an input for the model.

3.12.4 Unavoidable Annual Real Losses per Metre of Pressure for Distribution Mains (UARLDM)

This volume is based on the Column 5 in Table 4 in Lambert et al (1999),



Infrastructure Component	Background Losses	Reported Bursts	Unreported Bursts	UARL Total	Units
Mains	9.6	5.8	2.6	18	Litres/km mains/ Day/metre of pressure
Service Connections, meters at edge of street	0.60	0.04	0.16	0.80	Litres/Connection/ day/metre of pressure
Underground pipes between edge of street and customer meters	16.0	1.9	7.1	25	Litres/km u.g. pipe/ Day/metre of pressure

Table 3.7: Calculated Components of Unavoidable Annual Real Losses UARL (Source: Lambert et al, 1999)

Units: l/km mains/Day/m
Equation: This value is an input for the model.

3.12.5 Unavoidable Annual Real Losses per Metre of Pressure for Service Connections (UARLSC)

This volume is based on the Column 5 in Table 3.7.

Units: l/connection/Day/m
Equation: This value is an input for the model.

3.12.6 Number of Service Connections (Nc)

Alegre et al (2000) states that: "Where several registered customers or individually occupied premises share a physical connection or tapping off the main, e.g. apartment buildings, this will still be regarded as one connection for the purposes of the applicable PI, irrespective of the configuration and number of customers or premises"

But a common question is "Why use the 'Number of Service Connections' rather than 'Number of Properties'?" According to Lambert and McKenzie (2002) in many countries, a single service connection serves a much larger number of properties. But even in the case of individually metered flats, the water balance calculation is usually based on the leakage up to a single master meter on the service connection.

In the case of connections to mains for fire-fighting purposes, it is recommended counting these as service connections to "registered customers for public or institutional use" (ibid).

Units: Number
Equation: This value is an input for the model.

3.12.7 Connection Density (DC)

The Number of Service Connections and the Distribution and Transmission Pipe Length are used to calculate this value.

Units: conn/km
Equation:

$$\mathrm{DC} = \frac{Nc}{Lm}$$

Equation 3.24: (Source: The Author)

3.12.8 Number of Days

Since the water balance analysis is usually done for one year, this value tends to be 365 days.

Units: Number
Equation: This value is an input for the model.

3.12.9 Predicted Background Leakage (PBL)

In this case the value is 1 since is for an average condition of the pipes (ICF = 1) (Fantozzi and Lambert, 2007).

Units: Number
Equation: This value is an input for the model.

3.12.10 FAVAD N1

In this case the value is 0.5 since is for an average condition of the pipes (ICF = 1) (Fantozzi and Lambert, 2007).

Units: Number
Equation: This value is an input for the model.

3.12.11 Background Leakage @ 50m Pressure and ICF = 1.0 for Service Connections (BL@50mSC)

Equation: This value is an input for the model.
Units: l/connection/h

This volume is based on the Column 1 in Table 4.7 from Lambert et al (1999).

3.12.12 Background Leakage @ 50m pressure and ICF = 1.0 for Mains (BL@50mM)

This volume is based on the Column 1 in Table 4 from Lambert et al (1999).

Units: l/km/h
Equation: This value is an input for the model.

3.12.13 Unavoidable Background Leakage for ICF=1.0 (UBLICF)

Since the Background Leakage for Mains and the Background Leakage for Service Connections used consider the volume of leak at 50 m of pressure, those values have to be adapted to the current Average System Pressure. Using Equation 2.1 allows this.

Units: $m^3 x 10^3/yr$
Equation:

$$UBLICF = \frac{24 \cdot \text{Number of Days} \cdot (\text{Lm} \cdot \text{BL@50mM} + \text{Nc} \cdot \text{BL@50mSC})}{10^6} \cdot \left(\frac{ASP}{50}\right)^{FAVADN1}$$

Equation 3.25: (Source: Adaptation of Equation 3.19)

3.12.14 Unavoidable Background Leakage per Day for ICF=1.0 (UBLperDay)

Equation 3.25 calculates a yearly value. The Water Utilities might be interested in a daily value.

Units: $m^3 x 10^3/day$
Equation:

$$UBLperDay = \frac{UBLICF}{\text{Number of Days}}$$

Equation 3.26: (Source: The Author)

3.12.15 Estimated Background Leakage for ICF= Predicted Background Leakage (EBLPBL)

This calculation considers the ICF (Section 3.7.2) is equal to the Predicted Background Leakage.

Units: $m^3 x 10^3/yr$
Equation:

$$\text{EBLPBL} = PBL \cdot \frac{24 \cdot \text{Number of Days} \cdot (\text{Lm} \cdot \text{BL@50mM} + \text{Nc} \cdot \text{BL@50mSC}) \cdot}{10^6} \cdot \left(\frac{ASP}{50}\right)^{FAVADN1}$$

Equation 3.27: (Source: Adaptation of Equation 3.25)

3.12.16 Additional Background Leakage if ICF = Predicted Background Leakage (ABLPBL)

In the case of an Estimated Background Leakage for ICF= Predicted Background Leakage, there will be an additional Background Leakage. This is calculated as the difference between the Estimated Background Leakage for ICF= Predicted Background Leakage and the Unavoidable Background Leakage for ICF = 1.0

Units: m^3x10^3/yr
Equation:

$$\mathrm{ABLPBL} = \mathrm{EBLPBL} - \mathrm{UUBLICF}$$

Equation 3.28: (Source: The Author)

3.12.17 Unavoidable Annual Real Losses (UARL)

This value is calculated using the Unavoidable Annual Real Losses per Metre of Pressure for Distribution Mains and the Unavoidable Annual Real Losses per Metre of Pressure for Service Connections (UARLSC). Since the Unavoidable Annual Real Losses depend on the Distribution and Transmission Pipe Length and the Number of Connections, these variables are also considered.

Units: m^3x10^3/yr
Equation:

$$UARL = \frac{\mathrm{ASP} \cdot \mathrm{Number\ of\ Days} \cdot (\mathrm{UARLDM} \cdot (\mathrm{Lm} + \mathrm{Trunk\ Mains}) + \mathrm{UARLSC} \cdot \mathrm{Nc})}{10^6}$$

Equation 3.29: (Source: Lambert, 2009)

It is a more specific version of the equation presented in Equation 3.30:

$$\mathrm{UARL} = \frac{365 \cdot \mathrm{ASP} \cdot (18 \cdot \mathrm{Lm} + 0.8 \cdot \mathrm{N}c + 25 \cdot \mathrm{L}p)}{1000}$$

Equation 3.30: (Source: Lambert, 1999)

Lambert and McKenzie (2002) describes how this equation was derived:

The Annual Real Losses in any system are the aggregation of real losses volumes from individual leaks, bursts and overflows, and volume lost from each event is the product of duration and average flow rate.

The IWA approach is based on a relatively simple component analysis of Real Losses, assuming well-maintained infrastructure in good condition.

Assumptions for new leak frequency on mains (13/100 km/year) and service connections (5/1000 service connections/year) in good condition were based on published studies of repair statistics. But not every leak has the same average flow rate and the same average duration. Accordingly:

- Assumed frequencies for detectable leaks were split into groups of "reported" events (usually short duration) and "unreported" events (average duration depends upon frequency of active leakage control)

- Burst frequencies on service connections were split into "main to property line", and "property line to meter" (for service connections where meters are located after the property line).

- Typical flow rates for leaks on mains, and leaks on service connections, were collated from several countries (notably Germany, the UK, and Brazil), and were standardised to flow rates at 50m pressure.

- An average target duration (in days) considered appropriate for "best practice" intensive leakage management for each group of events was then specified, and the typical volume lost for each class of reported and unreported leak at 50m pressure was calculated.

- The typical volume lost per leak was then multiplied by appropriate assumed new leak frequencies to obtain the annual Real Losses from each class of leak.

In addition to the real losses volume generated by reported and unreported detectable leaks, there is also 'background' leakage from small non-visible leaks (usually individually less than several hundred litres/hour).

Background leaks occur mainly at joints and fittings, they run continuously, but do not generate sufficient noise to be detected by existing equipment. Estimates of lowest achievable background leakage (at 50m pressure) are based on analyses of "best achieved" night flows in small sectors with reliable low-flow metering, immediately after leak detection and repair (after deducting allowances for customer night use).

Finally, the UARL components were converted to a more "user friendly" pressure-dependent format for practical use. This equation was already presented as Equation 3.7.

$$\text{UARL (litres/day)} = \text{ASP} \cdot (18 \cdot \text{Lm} + 0.8 \cdot \text{Nc} + 25 \cdot \text{Lp})$$

Equation 3.31: (Source: Lambert and McKenzie, 2002)

This equation can be manipulated for calculation in different units. For example:

$$\text{UARL (litres/km mains/day/m pressure)} = (18 + 0.8 \cdot \text{DC}) + 25 \cdot \left(\frac{Lp}{Lm}\right)$$

Equation 3.32: (Source: Lambert and McKenzie, 2002)

If different measurement units are required (e.g. US Gallons, miles), the three coefficients in the Equation 3.33 (18, 0.8, 25) can easily be recalculated from first principles to suit the alternative units.

3.12.18 Infrastructure Leakage Index (ILI)

Units: ILI is a ratio, it has no units.
Equation:

$$\text{ILI} = \cdot \frac{CARL}{UARL}$$

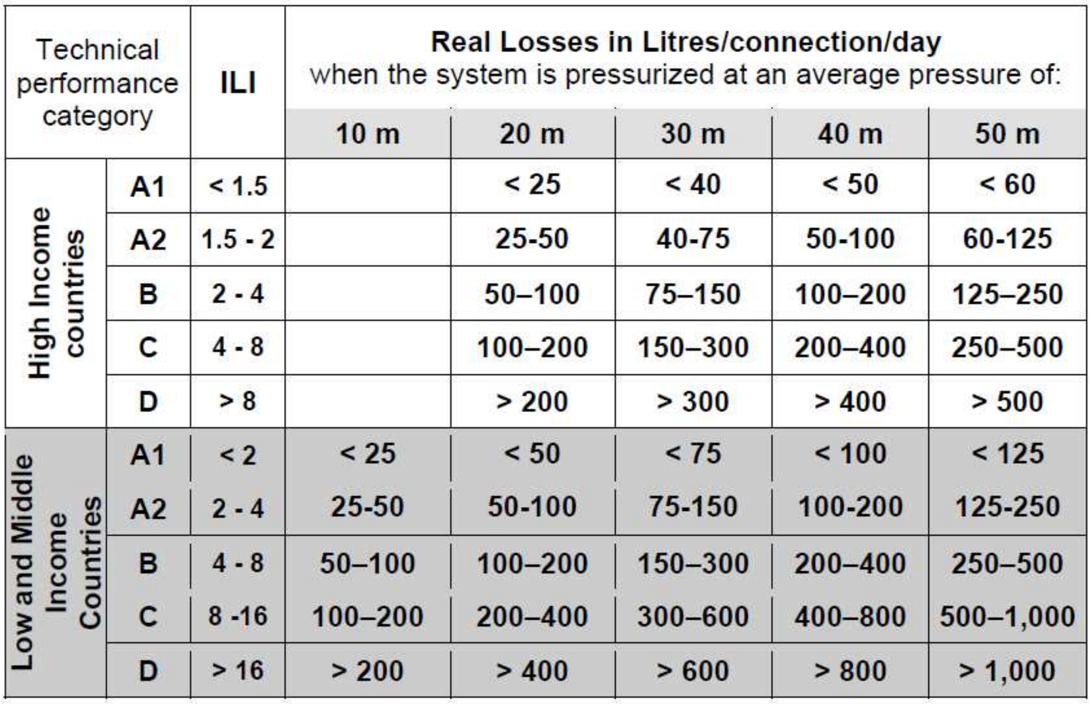
Equation 3.33: (Source: Lambert, 1999)

Accuracy of the ILI depends less on accuracy of the (empirical) UARL formula (Formula 3.7) but on the accuracy of annual volume of real losses, average pressure and distribution network data (Liemberger and McKenzie, 2005), and this specially critical in the case of developing countries. In the case of the lack of reliable information on the true network length, the maps often show only a fraction of the existing network. This will result in an underestimation of the UARL and an overestimated ILI.

If the number of service connections is unknown, number of customers tends to be used instead. Since the number of customers will in most cases be higher than the number of connections, this will result in overestimation of the UARL and an underestimated ILI.

A common problem of developing countries is the lack of pressure data or pressure loggers available. An estimated average pressure usually too high or "optimistic view" will result in overestimation of the UARL and an underestimated ILI. Also a high level of apparent losses (difficult to estimate) generates an unreliable and inaccurate volume of real losses.

Many utility managers and consultants, however, remain reluctant to switch from the "prehistoric" % UfW or % NRW to the ILI (both in the developed and developing world). To help address this issue, a simple look-up table, presented in Table 3.8 based on the ILI was suggested by Liemberger and McKenzie (2005) and then updated in 2010 (Liemberger, 2010). This allows a first simple assessment using litres per connection per day in combination with the approximate average pressure.



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

Table 3.8: Physical Loss Assessment Matrix
(Source: Liemberger, 2010)

This approach can be used to classify the leakage levels for utilities in developed and developing countries into four categories (ibid):

- Category A: Further loss reduction may be uneconomic unless there are shortages; careful analysis needed to identify cost-effective improvement.

- Category A1: World class leakage management performance; the potential for further physical loss reductions is small unless there is still potential for pressure reductions.

- Category A2: Further loss reduction may be uneconomic unless there are shortages; careful analysis needed to identify cost-effective improvement.

- Category B: Potential for marked improvements; consider pressure management; better active leakage control practices, and better network maintenance

- Category C: Poor leakage record; tolerable only if water is plentiful and cheap; even then, analyse level and nature of leakage and intensify leakage reduction efforts

- Category D: Highly inefficient; leakage reduction programs imperative and high-priority

3.13 Trunk Mains and Service Reservoir Leakage

Leakage from trunk mains and service reservoirs is estimated from data on the water distribution system infrastructure, taking account of the age of the pipes using empirical figures from Lambert (2009). Table 3.9 lists the variables and the outputs.

Variables	Outputs Level 1	Outputs Level 2
Age of Trunk Mains		
	Allowances for Real Losses from Trunk Mains	
Trunk Mains		
	Trunk Mains Leakage	
Volume of Service Reservoirs		
Allowances for Real Losses from Service Reservoirs		
	Service Reservoir Leakage at Margin of Error for ICF	
		Trunk Mains and Service Reservoir Leakage

Table 3.9: List of the variables and outputs used in the Trunk mains and service reservoir leakage section of the model.
(Source: The Author)

The Level 1 and Level 2 outputs are showed in the Figure 3.8.

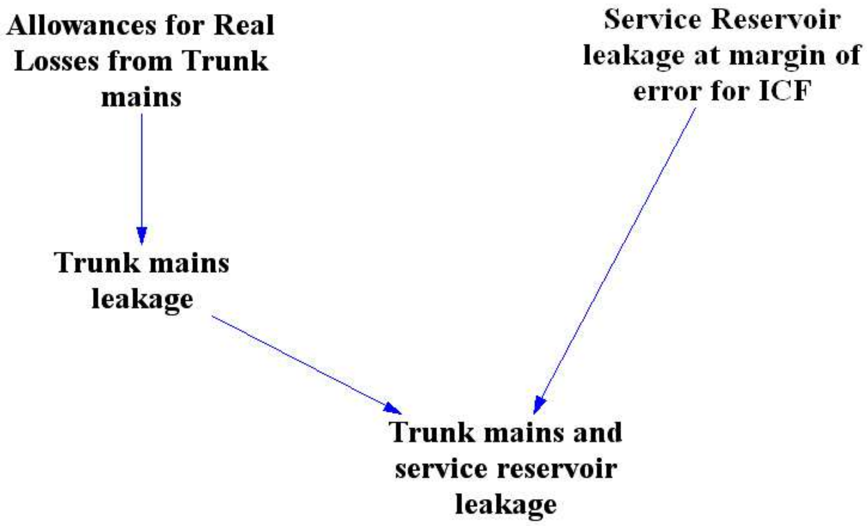


Figure 3.8: Simplification of the Trunk mains and service reservoir leakage section of the model.
(Source: The Author)

3.13.1 Age of Trunk Mains

This information can be obtained from the water utility database.

Units: Years
Equation: This value is an input for the model.

3.13.2 Allowances for Real Losses from Trunk Mains (ARLTM)

This value is for the 1.0 litre/sec detection threshold since leaks with an smaller volume couldn't be detected.

Units: m^3/km/Day
Equation:

$$ARLTM = 0.86 + 0.08 \cdot \text{Age of Trunk Mains}$$

Equation 3.34: (Source: Personal Communication con Alan Lambert)

3.13.3 Trunk Mains Leakage

The Allowances for Real Losses from Trunk Mains are converted in a yearly value.

Units: $m^3 x 10^3$/yr
Equation:

$$\text{Trunk Mains Leakage} = \frac{365 \cdot ARLTM \cdot \text{Trunk Mains}}{1000}$$

Equation 3.35: (Source: The Author)

3.13.4 Volume of Service Reservoirs

This information can be obtained from the water utility database.

Units: m^3
Equation: This value is an input for the model.

3.13.5 Allowances for Real Losses from Service Reservoirs (ARLSR)

Since the UARL formula has no allowance for leakage and overflow in service reservoirs, a value has to be included. (Lambert and McKenzie, 2002) explains the lack of leakage allowance on the IWA Water Losses Task Force perspective that service reservoirs should be constructed and maintained so as to be watertight, or made watertight if significant leakage is detected. The use of level control, telemetry, altitude valves, and other means can help in the elimination of service reservoir overflows. This value has to be estimated by the water utility using level drop tests in tanks.

Units: Percentage per day
Equation: This value is an input for the model.

3.13.6 Service Reservoir Leakage at Margin of Error for ICF (SRLME)

The Allowances for Real Losses from Service Reservoirs are converted in a yearly value.

Units: m^3x10^3/yr
Equation:

$$\text{SRLME} = 365 \cdot \text{ARLSR} \cdot \text{Volume of Service Reservoirs}$$

Equation 3.36: (Source: The Author)

3.13.7 Trunk Mains and Service Reservoir Leakage

This value is the sum of the Service Reservoir Leakage at Margin of Error for ICF and the Trunk Mains Leakage.

Units: m^3x10^3/yr
Equation:

$$\text{Trunk Mains and Service Reservoir Leakage} = \text{SRLME} + \text{Trunk Mains Leakage}$$

Equation 3.37: (Source: The Author)

3.14 Economic Unreported Real Losses and ELL

Introduction of active leakage control methods will reduce the volume of unreported real losses from mains and service connections. The economic limit (where cost of intervention exceeds cost of saved water) is estimated using the method and equations presented by Lambert and Lalonde (2005) and described in Section 3.7 (Some Basic Concepts), together with estimates of the cost of intervention and rate of rise in Zaragoza as will be described in Chapter 5. This gives the Economic Unreported Real Losses (EURL). Table 3.9 lists the variables and the outputs.

Variables	**Outputs Level 1**	**Outputs Level 2**	**Outputs Level 3**
Method of Active Leakage Control			
	Cost of One '”Whole System” Intervention, Excluding Cost of Repairs		
Average Rate of Rise of Unreported Leakage			
Assumed Variable Cost of Water			
	Economic Intervention Frequency EIF		
	Economic % EP of System to be Checked		
		Annual Budget for Interventions ABI	
		Economic Unreported Real Losses	
	Lost Water Volume in Each Economic Intervention		
		Economic Unreported Real Losses	
		Lost Water Volume Value	
			Short-Run Economic Level of Leakage
			Short-Run Economic ILI

Figure 3.9: List of the variables and outputs used in the Economic Unreported Real Losses section of the model.
(Source: The Author).

The Level 1, Level 2 and Level 3 outputs are showed in the Figure 3.10.

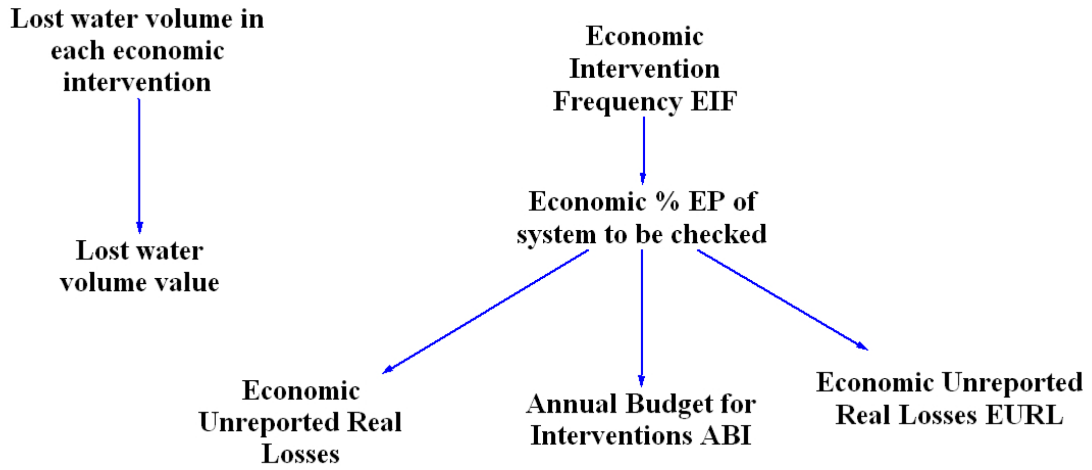


Figure 3.10: Simplification of the Economic Unreported Real Losses section of the model. (Source: The Author).

3.14.1 Method of Active Leakage Control

This is obtained from the repair and detection logs using the costs of workforce and materials and doesn't include the cost of repairing the unreported leaks found since there is no active leak detection. There can be different values for different strategies.

Units: Cost/km
Equation: This value is an input for the model.

3.14.2 Cost of One "Whole System" Intervention, Excluding Cost of Repairs (CI)

This value is calculated considering the Method of Active Leakage Control and the length of Trunk Mains. It is not usual to include the cost of repairs in the ELL calculation, as the cost of repairs is normally assumed to be independent of the frequency of intervention (as all leaks have to be repaired to achieve ELL).

Units: Cost
Equation:

$$CI = \text{Trunk Mains} \cdot \text{Method of Active Leakage Control}$$

Equation 3.38: (Source: Lambert and Lalonde, 2005)

3.14.3 Average Rate of Rise of Unreported Leakage (RR)

Units: m^3/day/yr
Equation: This value is an input for the model.

Lambert (2005) gives the following methods for calculating the Unreported Leakage Rate of Rise that were briefly discussed in Section 3.7.8 (Rate of Rise of unreported leakage (RR))

The first option is to compare Real Losses from Water Balances several years apart. This method can be used for systems without night flow measurements, where there has been no active leakage control in the period between the Annual Water Balances.

The first step is to calculate the annual volume of Real Losses in year 1 (= RL1) and 'N' years previously (=RLN). In the event of changes in the number of service connections or average pressure, the Real Losses in year 'N' must be adjusted to the number of connections and pressure in Year 1 (=RLN'). The Rate of Rise RR will be (RL1 - RLN')/N.

The second method can be used in the case of a system with a single intervention for all or part of it, that data can be used when there are no night flow measurements. The detected leaks are classified by typical average flow rate (e.g. Class A, Class B, Class C) and by which part of the infrastructure they occurred on (Mains, Hydrants, service connections Utility side, service connection customer side). The aggregate flow of all of the leaks found and the number of years over which they may have accumulated is estimated and then the flow is divided by the years to obtain the Rate of Rise RR. So annual rate of rise is expressed 'per service connection' or 'per km mains' for the surveyed part of the system, and assume this applies to the whole system

A variation of previous method is the case where the system lacks night flow measurements but where there have been two or more interventions with a known time interval in between. The detected leaks are classified by typical average flow rate (e.g. Class A, Class B, Class C), the aggregate flow calculated and then divided by the time period between interventions to get Rate of Rise.

The final method uses Measured Night Flows. This can be used for small and medium sized systems within a single pressure zone. The night flow measurement facilities don't need to be continuous or permanent. The flow is measured over several nights at times of year when exceptional night uses (irrigation, industrial) are minimal or absent, or can be identified. The measured flow rates are adjusted for any changes in pressure, or other influences and then the Rate of Rise is calculated in m3/hour/year from the difference in adjusted night flows, divided by the time period. Multiply by a suitable Night-Day Factor NDF (to allow for diurnal variation of leak rate with pressure (use NDF = 24 hrs/day as default).

3.14.4 Assumed Variable Cost of Water (CV)

The CV can be (and now usually is) more widely defined than simply costs of production and distribution - it could include bulk supply charges, or deferred capital investment or even be as high as sale price of water (where water saved from leakage could be sold to other customers) (Personal communication with Alan Lambert, 2010). In the case of this analysis, this value is obtained from the water utility costs database.

Units: $\$/m^3$
Equation: This value is an input for the model.

3.14.5 Economic Intervention Frequency (EIF)

This value depends on the Cost of Intervention, Assumed Variable Cost of Water and the Rate of Rise

Units: Years
Equation:

$$\mathrm{E}IF = \sqrt{\frac{CI}{365 \cdot 0.5 \cdot VC \cdot RR}}$$

Equation 3.39: (Source: Lambert, 1999)

3.14.6 Economic Percentage of System to be Checked (EP)

This value is obtained from the Economic Intervention Frequency.

Units: Percentage
Equation:

$$EP = \frac{1}{EIF}$$

Equation 3.40: (Source: Lambert, 1999)

3.14.7 Annual Budget for Interventions (ABI)

The product of the Cost of Intervention and the Economic Percentage of System to be checked.

Units: Cost
Equation:

$$\mathrm{ABI} = CI \cdot EP$$

Equation 3.41: (Source: Lambert, 1999)

3.14.8 Lost Water Volume in Each Economic Intervention (LWVEEI)

Units: $m^3 x10^3/yr$
Equation:

$$LWVEEI = \frac{CI}{1000 \cdot VC}$$

Equation 3.42: (Source: Lambert, 1999)

3.14.9 Economic Unreported Real Losses (EURL)

This value depends on the Cost of Intervention, Distribution and Transmission Pipe Length, Economic Percentage of System to be Checked and the Cost of Water.

Units: m^3x10^3/yr
Equation:

$$\mathrm{EURL} = \frac{\mathrm{CI} \cdot \mathrm{Lm} \cdot \mathrm{EP}}{VC \cdot 1000}$$

Equation 3.43: (Source: Lambert, 1999)

3.14.10 Lost Water Volume Value (LWVV)

Units: Cost
Equation:

$$\mathrm{LWVV} = 1000 \cdot VC \cdot \mathrm{LWVEEI}$$

Equation 3.44: (Source: Lambert, 1999)

3.14.11 Short-Run Economic Level of Leakage (SRELL)

Units: m^3x10^3/yr
Equation:

SRELL = Trunk Mains and Service Reservoir Leakage + Estimated Background Leakage, ICF= Predicted Background Leakage + Reported Burst Volume in Distribution mains and Service Connections + Economic Unreported Real Losses

Equation 3.45: (Source: Lambert, 1999)

3.14.12 Short-Run Economic ILI (SRELI)

Units: ILI is a ratio, it has no units.
Equation:

$$\mathrm{SRELI} = \frac{SRELL}{UARL}$$

Equation 3.46: (Source: Lambert, 1999)

3.15 Calculation of Externalities

So far the model has calculated the ELL for the system. This research extends that calculation to include the value of the energy externalities used in the leakage control activities. This value must be added to the Cost of One "Whole System" Intervention, Excluding Cost of Repairs (CI) variable (See Section 3.14.2) in the case the calculation wants to include it.

Variables	Outputs Level 1	Outputs Level 2	Outputs Level 3
Emissions due to Labour, Commuting and Welfare (ELCW)			
Distance Driven for Leakage Control			
Coefficient for Emission from Driving for Leakage Control			
	Emissions due to Driving for Leakage Control (EDLC)		
Number of Repair Events			
Pipe Length			
Coefficient for Emission from pipe lying (CEPL)			
	Emission from pipe lying (EPL)		
Volume of fuel in Generator Use (VGU)			
Coefficient for Emissions from Generator Use			
	Emissions from Generator Use (EGU)		
Volume of fuel in Compressor Use (VCU)			
Coefficient for Emissions from Compressor Use			
	Emissions from Compressor Use (ECU)		
		Emissions from Repair Events (ERE)	
			Estimated Emissions from Leakage Control Activities (ELCA)
Non-Traded Price of Carbon (NTPC)			Cost of Estimated Emissions from Leakage Control Activities (CELCA)

Figure 3.11: List of the variables and outputs used in the Energy Externalities section of the model.
(Source: The Author).

The Level 1, Level 2 and Level 3 outputs are showed in the Figure 3.12.

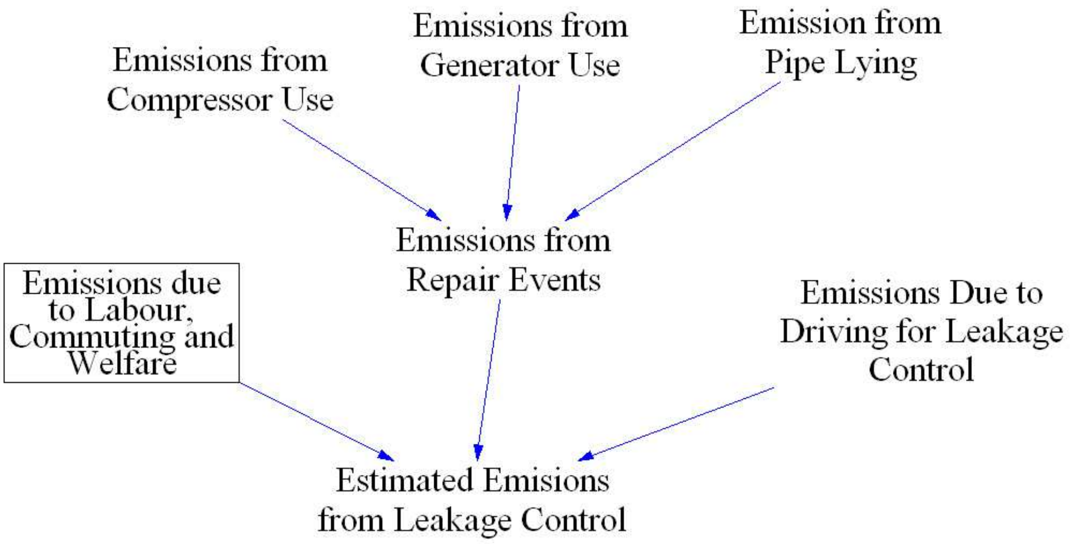
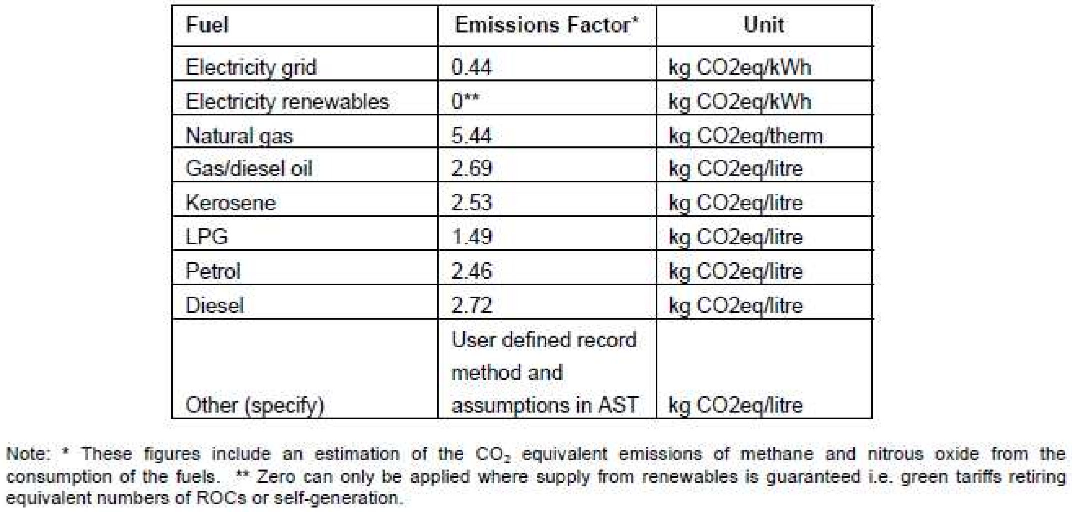


Figure 3.12: Simplification of the Externalities section of the model.
(Source: The Author).



Fuel	Emissions Factor*	Unit
Electricity grid	0.44	kg CO2eq/kWh
Electricity renewables	0**	kg CO2eq/kWh
Natural gas	5.44	kg CO2eq/therm
Gas/diesel oil	2.69	kg CO2eq/litre
Kerosene	2.53	kg CO2eq/litre
LPG	1.49	kg CO2eq/litre
Petrol	2.46	kg CO2eq/litre
Diesel	2.72	kg CO2eq/litre
Other (specify)	User defined record method and assumptions in AST	kg CO2eq/litre

Note: * These figures include an estimation of the CO_2 equivalent emissions of methane and nitrous oxide from the consumption of the fuels. ** Zero can only be applied where supply from renewables is guaranteed i.e. green tariffs retiring equivalent numbers of ROCs or self-generation.

Table 3.10: Emissions factors for converting fuel/energy consumption into CO_2
(Source: OFWAT, 2008)

3.15.1 Emissions due to Labour, Commuting and Welfare (ELCW)

The usual setup for leak control work involves one van and 4 persons. The emissions from the use of labour are estimated to be approximately 1 kg CO2e/person/hour (UKWIR, 2008). If there's a different distribution this value shall be corrected.

This is based on the assumptions: i) that site workers travel an average distance of 25 km each day from their lodgings to site and then back again by car or van (2 persons to a vehicle); and ii) that each labourer makes use of site welfare facilities (large heated portacabins). So the emissions for the leak control crew will be 32 kg CO2e per day or 6944 kg CO2e per year + the emission related to the Distance Driven for Leakage Control.

Units: kg CO2e per year
Equation: This value is an input for the model.

3.15.2 Distance Driven for Leakage Control

This information is obtained from the water utility databases. If the vehicles are also used for tasks different to leakage control this must be corrected.

Units: km per year
Equation: This value is an input for the model.

3.15.3 Coefficient for Emission from Driving for Leakage Control (CFEFDLK)

Consider a value of 0.210 kg CO2/km for emissions associated to diesel use (UKWIR 2008).

Units: kg CO2e/km
Equation: This value is an input for the model.

3.15.4 Emissions due to Driving for Leakage Control (EDLC)

This value is calculated using the Coefficient for Emission from Driving for Leakage Control and the Distance Driven for Leakage Control.

Units: kg CO2e per year
Equation:

$$\text{EDLC} = \text{CFEFDLK} \cdot \text{Distance Driven for Leakage Control}$$

Equation 3.47: (Source: The Author)

3.15.5 Number of Repair Events

This information is obtained from the water utility database.

Units: Number
Equation: This value is an input for the model.

3.15.6 Pipe Length

This is the *average* pipe length replaced per repair event. This should be classified per diameter. This information is obtained from the water utility database.

Units: m
Equation: This value is an input for the model.

3.15.7 Coefficient for Emission from pipe lying (CEPL)

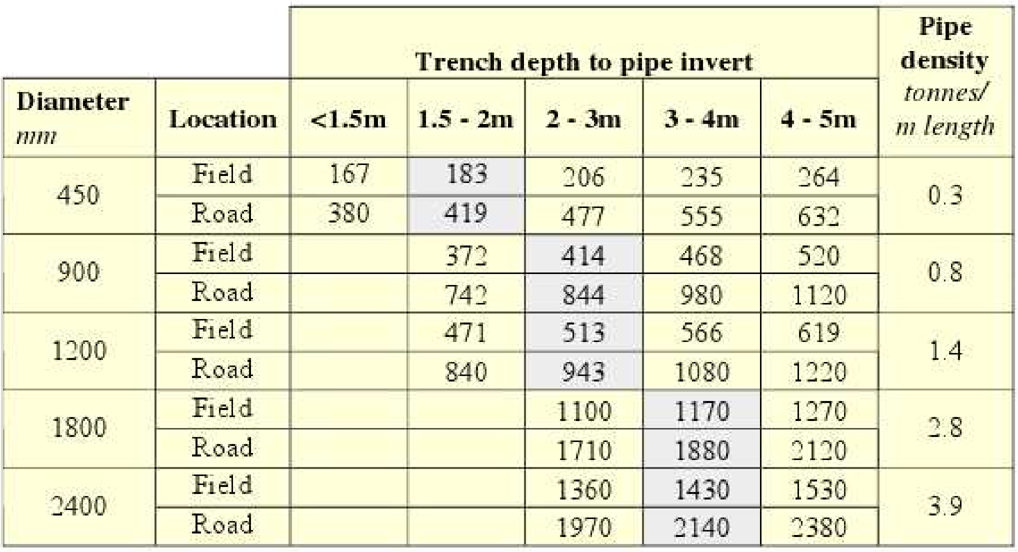
This information is obtained from the water utility database.

The pipe diameter will allow the calculation of the emissions for laying the pipe using the values in (UKWIR, 2008) showed in Table 3.11 and 3.12 according to the type.

Diameter (mm)	Location	Trench depth to pipe invert (m)					Pipe density (tonnes/m)
		<1.5	1.5 – 2	2 – 3	3 – 4	4 – 5	
125	Field	106	122	145	174	203	0.003
	Road	319	358	416	494	571	
250	Field	112	128	150	180	209	0.011
	Road	336	375	433	510	588	
450	Field	123	138	161	190	220	0.035
	Road	385	424	482	559	636	

Table 3.11: Emissions for laying polyethylene pipelines in fields and roads (kgCO2e/m length of pipe)
(Source: UKWIR, 2008)

The reference also gives data for precast concrete pipelines:



Diameter *mm*	Location	Trench depth to pipe invert					Pipe density *tonnes/ m length*
		<1.5m	1.5 - 2m	2 - 3m	3 - 4m	4 - 5m	
450	Field	167	183	206	235	264	0.3
	Road	380	419	477	555	632	
900	Field		372	414	468	520	0.8
	Road		742	844	980	1120	
1200	Field		471	513	566	619	1.4
	Road		840	943	1080	1220	
1800	Field			1100	1170	1270	2.8
	Road			1710	1880	2120	
2400	Field			1360	1430	1530	3.9
	Road			1970	2140	2380	

Table 3.12: Emissions for laying precast concrete pipelines in fields and roads (kgCO2e/m length of pipe)
(Source: UKWIR, 2008)

Units: kgCO2e/m length of pipe
Equation: This value is an input for the model.

3.15.8 Emission from Pipe Laying (EPL)

This variable requires the Coefficient for Emission from pipe laying, the Pipe Length and the Number of Repair Events.

Units: kg CO2e per year
Equation:

$$\mathrm{EPL} = \mathrm{C}EPL \cdot \mathrm{P}ipeLength \cdot \text{Number of repair events}$$

Equation 3.48: (Source: The Author)

3.15.9 Volume of Fuel in Generator Use (VGU)

This value is the total volume of fuel used in generator use for leakage control and repairs during the analysis period. This information is obtained from the water utility database.

Equation: This value is an input for the model.
Units: l per year

3.15.10 Coefficient for Emissions from Generator Use

In the case of diesel, a value of 2.72 (OFWAT, 2008) is used. In the case of a different fuel, Table 3.10 illustrates different values.

Units: kgCO2e/l
Equation: This value is an input for the model.

3.15.11 Emissions from Generator Use (EGU)

This value requires the Coefficient for Emissions from Generator Use and the Volume of Fuel in Generator Use.

Units: kg CO2 per year
Equation:

$$\mathrm{EGU} = \mathrm{Coefficient\ for\ Emissions\ from\ Generator\ Use} \cdot \mathrm{V}GU$$

Equation 3.49: (Source: The Author)

3.15.12 Volume of fuel in Compressor Use (VCU)

This value is the total volume of fuel used in compressor use for leakage control and repairs during the analysis period. This information is obtained from the water utility database.

Units: l per year
Equation: This value is an input for the model.

3.15.13 Coefficient for Emissions from Compressor Use

In the case of diesel, a value of 2.72 (OFWAT, 2008) is used. In the case of a different fuel, Table 3.10 illustrates different values.

Units: kgCO2e/l
Equation: This value is an input for the model.

3.15.14 Emissions from Compressor Use (ECU)

This value requires the Coefficient for Emissions from Compressor Use and the Volume of Fuel in Compressor Use.

Units: kg CO2e per year
Equation:

$$\mathrm{ECU} = \mathrm{Coefficient\ for\ Emissions\ from\ Compressor\ Use} \cdot \mathrm{V}CU$$

Equation 3.50: (Source: The Author)

3.15.15 Emissions from Repair Events (ERE)

The Repair Events include the Emissions from Pipe Lying, Emissions from Generator Use and Emissions from Compressor Use.

Units: kg CO2e per year
Equation:

$$\mathrm{ERE=EPL+EGU+ECU}$$

Equation 3.51: (Source: The Author)

3.15.16 Estimated Emissions from Leakage Control Activities (ELCA)

The sum of the Emissions due to Labour, Commuting and Welfare, Emissions due to Driving for Leakage Control and Emissions from Repair Events.

Units: kg CO2e per year
Equation:

$$\mathrm{ELCA=ELCW}+EDLC+\mathrm{ERE}$$

Equation 3.52: (Source: The Author)

3.15.17 Non-Traded Price of Carbon (NTPC)

Units: Cost per kg CO2e
Equation: This value is an input for the model

As it was discussed in Section 2.9.1 (Economic Inclusion of the Emissions), However, in July 2009, as a part of the UK Low Carbon Transition Plan the Department of Energy and Climate Change (DECC) announced that the shadow price of carbon has been replaced with the Non-Traded Price of Carbon (NTPC).

DECC (2010) clarifies that changes in emissions which occur in the traded sector are valued at the Traded Price of Carbon (TPC), whereas changes in emissions in the non-traded sector are valued at the Non-Traded Price of Carbon (NTPC). This means that the water utility sector is included in the Non-Trade sector and for that reason a NTPC should be in the economic calculations. Tables 3.13 and 3.14 gives the recommended values for the NTPC but this values will have to be updated on a yearly basis by the DECC.

	Non-traded Carbon Prices, £/t 2009		
Year	**Low**	**Central**	**High**
2008	25	50	75
2009	25	51	76
2010	26	52	78
2011	26	52	79
2012	27	53	80
2013	27	54	81
2014	27	55	82
2015	28	56	84
2016	28	57	85
2017	29	57	86
2018	29	58	87
2019	30	59	89
2020	30	60	90
2021	31	61	92
2022	31	62	93
2023	32	63	95
2024	32	64	96
2025	33	65	98
2026	33	66	99
2027	34	67	101
2028	34	68	102
2029	35	69	104
2030	35	70	105

Table 3.13: Non-Traded Price of Carbon (NTPC) 2008-2030
(Source: DECC, 2009)

	Non-traded Carbon Prices, £/t 2009		
Year	**Low**	**Central**	**High**
2031	38	77	115
2032	42	83	125
2033	45	90	134
2034	48	96	144
2035	51	103	154
2036	55	109	164
2037	58	116	173
2038	61	122	183
2039	64	129	193
2040	68	135	203
2041	71	142	212
2042	74	148	222
2043	77	155	232
2044	81	161	242
2045	84	168	251
2046	87	174	261
2047	90	181	271
2048	94	187	281
2049	97	194	290
2050	100	200	300

Table 3.14: Non-Traded Price of Carbon (NTPC) 2031-2050
(Source: DECC, 2009)

3.15.18 Cost of Estimated Emissions from Leakage Control Activities (CELCA)

This value will have to be added to the Method of Active Leakage.

Units: Cost per km
Equation:

$$\mathrm{CELCA} = \frac{NTPC \cdot \mathrm{ELCA}}{\text{Distribution and transmission pipe length}}$$

Equation 3.53: (Source: The Author)

3.16 Outputs

The following tables summarize the model outputs.

Output	Units
FAVAD N1 for Service Connections	-
Assumed Volume Lost per Reported Burst or Leak @ 50m Pressure in Service Connections	m^3 per event
Reported Bursts Volumes on Service Connections	m^3x10^3/yr
FAVAD N1 for Distribution Mains	-
Assumed Volume Lost per Reported Burst or Leak @ 50m Pressure in Distribution Mains	m^3 per event
Reported Bursts Volumes on Distribution Mains	m^3x10^3/yr
Reported Burst Volume in Distribution Mains and Service Connections	m^3x10^3/yr

Table 3.15: List of Outputs in the Reported burst volume in Distribution mains and Service connection section of the model.
(Source: The Author)

Output	Units
UARL - Unavoidable Annual Real Losses	$m^3/year$
Infrastructure Leakage Index (ILI)	-
Connection Density	conn/km
Unavoidable Background Leakage for ICF=1.0	m^3x10^3/yr
Unavoidable Background Leakage per day for ICF=1.0	m^3x10^3/day
Estimated Background Leakage, for ICF= Predicted Background Leakage	m^3x10^3/day
Additional Background Leakage if ICF = Predicted Background Leakage	m^3x10^3/day
Unavoidable Annual Real Losses (UARL)	m^3x10^3/day

Table 3.16: List of Outputs in the Estimated Background Leakage section of the model.
(Source: The Author)

Output	Units
Allowances for Real Losses from Trunk Mains	$m^3/km/day$
Trunk Mains Leakage	m^3x10^3/yr
Service Reservoir Leakage at Margin of Error for ICF	m^3x10^3/yr
Trunk Mains and Service Reservoir Leakage	m^3x10^3/yr

Table 3.17: List of Outputs in the Trunk mains and service reservoir leakage section of the model.
(Source: The Author)

Outputs	Units
Cost of One '"Whole System" Intervention, Excluding Cost of Repairs	Cost
Economic Intervention Frequency EIF	Years
Economic % EP of System to be Checked	Percentage
Annual Budget for Interventions ABI	Cost
Economic Unreported Real Losses	m^3x10^3/yr
Lost Water Volume in Each Economic Intervention	m^3x10^3/yr
Economic Unreported Real Losses	m^3x10^3/yr
Lost Water Volume Value	Cost
Short-Run Economic Level of Leakage	m^3x10^3/yr
Short-Run Economic ILI	-

Table 3.18: List of Outputs in the Economic Unreported Real Losses section of the model. (Source: The Author).

Output	Units
Emissions due to Driving for Leakage Control (EDLC)	kg CO_2e/yr
Emission from pipe lying (EPL)	kg CO2e/yr
Emissions from Generator Use (EGU)	kg CO2e/yr
Emissions from Compressor Use (ECU)	kg CO2e/yr
Emissions from Repair Events (ERE)	kg CO2e/yr
Estimated Emissions from Leakage Control Activities (ELCA)	kg CO2e/yr
Cost of Estimated Emissions from Leakage Control Activities (CELCA)	Cost

Table 3.19: List of Outputs in the Energy Externalities section of the model. (Source: The Author).

3.17 Chapter Conclusions

This chapter presented the components of the Dynamic Model that was applied to calculate the ELL, using the BABE methodology, and the inclusion of energy externalities. The data needs, listed and described, can easily be collected by the Water Utility, with a low level of investment in workforce and equipment. The next chapter will present the verification of the model and then apply it to Zaragoza.

4 VERIFICATION AND APPLICATION OF MODEL

In the previous chapter, the model was described and analysed. This chapter will present the validation of that model and the application for the calculation of the current conditions of Passive Leakage Control in Zaragoza to later compare the results of the inclusion of externalities in the case of Passive and Active Leakage Control with different options for detection and repair crews.

The second part of this chapter uses the concept of Scenario Planning to analyse three future possibilities for Zaragoza in 2030. This chapter will end with the sensitivity analysis of the model and the application of the concept of Statistical Screening (Ford and Flynn, 2005) to identifying high-leverage model parameters.

4.1 Verification

The model was tested using data from Wide Bay Water included in Lambert and Lalonde (2005), where the same methodology was applied. The idea was to verify if the model was working properly or not. But is important to stress that the verification in this case, involved only one case, since that was the data from a previous implementation of this model. This calls for the creation of a database of local or worldwide information about Water Utility performances. Not only at this first approach level, but at "ELL implemented" level that could help the process.

Table 4.1 presents the information used for the Reported Burst volume in Distribution mains and Service connections.

Variable	**Units**	**Initial Value**
Average system pressure	m	65
Number of Reported Burst and Leaks in Distribution Mains	Number	82
Number of reported burst and leaks in service connections	Number	333
Percentage of rigid distribution mains	Percentage	1
Percentage of rigid service connections	Percentage	1
Repair time in distribution mains	Days	5
Repair time in service connections	Days	15
Volume per event in distribution mains	m^3/h	12
Volume per event in service connections	m^3/h	0.8

Table 4.1: Initial values used in the Reported burst volume in Distribution mains and Service connection verification.
(Source:Lambert and Lalonde, 2005)

Table 4.2 presents the results from the calculation of the Estimated background leakage using the variables listed in the Table 4.1.

Variable	Units	Initial Value
Background leakage @ 50m pressure and ICF = 1.0 for Mains	l/km/h	20
Background leakage @ 50m pressure and ICF = 1.0 for service connections	l/connection/h	1.25
Distribution and transmission pipe length	Km	603
FAVAD N1	Number	1.5
Number of days	Number	365
Number of service connections	Number	16000
Predicted background leakage	Number	1
Unavoidable Annual Real Losses per metre of pressure for Distribution mains	l/km mains/Day/m	18
Unavoidable Annual Real Losses per metre of pressure for Service connections	l/connection/Day/m	0.8

Table 4.2: Initial values used in the Estimated background leakage verification (Source:Lambert and Lalonde, 2005)

In the case of the Trunk Mains and Service Reservoir Leakage, the paper assumes a value of 10% of the Estimated Background Leakage, showed in Table 4.3.

Variable	Units	Initial Value
Assumed Variable Cost of Water VC	Cost	0.12
Rate of Rise RR	m^3/day/year	320
Method of active leakage control	Cost/km	132.67

Table 4.3: Initial values used in the Economic Unreported Real Losses verification (Source:Lambert and Lalonde, 2005)

Table 4.4 presents the results of the leakage components calculated by the model.

Variable	Units	Initial Value
Economic Unreported Real Losses	m^3x10^3/yr	197.32
Trunk Mains and Service Reservoir Leakage	m^3x10^3/yr	41.62
Estimated Background Leakage for ICF= Predicted Background Leakage	m^3x10^3/yr	416.28
Reported burst volume in Distribution mains and Service connections	m^3x10^3/yr	225.00
Short-Run Economic Level of Leakage	m^3x10^3/yr	880.22

Table 4.4: Initial leakage values for the Wide Bay Water Values. (Source:Lambert and Lalonde, 2005)

Table 4.5 presents the summary of calculations in Lambert and Lalonde (2005).

System	Wide Bay Water, Australia			Average pressure (m.) =		65
Unavoidable background leakage multiplier UBLM =				1.1		
Infrastructure Component	Length or number	Real Losses from Reported	Background leakage		Economic Unreported	Short -run Economic
			Unavoidable	Additional		
		m^3/year	m^3/year	m^3/year	m^3/year	m^3/year
Mains (km)	*603*	*92,100*	*157,000*	**15,700**	*197,300*	**881,000**
Services	*16000*	*132,900*	*260,000*	**26,000**		
Total		**225,000**	**417,000**	**41,700**	**197,300**	**881000**
SRELL =	**150.9**	litres/service connection /day		**4.00**	m^3/km mains/day	

Table 4.5: Summary of ELL calculations for Wide Bay Water, assuming regular survey (Source:Lambert and Lalonde, 2005)

Table 4.6 will present the information of Tables 4.4 and 4.5 in the same format used in the Model.

Variable	**Units**	**Value Calculated by the model**	**Lambert and Lalonde Calculated Value**
Economic Unreported Real Losses	m^{3}x10^3/yr	197.32	197.30
Trunk Mains and Service Reservoir Leakage	m^{3}x10^3/yr	41.62	41.70
Estimated Background Leakage for ICF= Predicted Background Leakage	m^{3}x10^3/yr	416.28	417.00
Reported burst volume in Distribution mains and Service connections	m^{3}x10^3/yr	225.00	225.00
Short-Run Economic Level of Leakage	m^{3}x10^3/yr	880.22	881.00

Table 4.6: *Comparison of values obtained by the model and by Lambert and Lalonde (Source: The Author)*

The differences (Less than 1%) are due to the rounding of results. This verifies the Vensim model developed and allows the calculation of the ELL in Zaragoza.

4.2 Economic Level of Leakage in Zaragoza

4.2.1 Fieldwork Background

Zaragoza, the capital of Aragón region in North-eastern Spain, is one of the partner cities for the SWITCH project, and is a demonstration city. The research zone has already been selected and defined, to determine the current level of leakage.

According to the BOLETÍN ECONÓMICO CIUDAD DE ZARAGOZA Nº 6 (2º Trimestre 2011) (Economic City Report, 2nd trimester of 2011), the current population of Zaragoza is 700.765 inhabitants to March 30th/11. The same document gives a city wide water consumption figure of 39.274.770 m^3 for 2008, 35.542.497 m^3 for 2009 and 38.170.946 m^3 for 2010. Until July 2010, the main water source for Zaragoza used to be the Ebro river. The current source is water from a reservoir (Yesa) in the Pyrenees that supplies 100% of the city. The Ebro river is currently an strategic reserve (Personal communication with Javier Celma, director of the city environmental agency).

The water services provider is the City Council. However the meter reading task is done by a third party who reports to the City Council. The leakage control activities are carried out by a team of "Guardallaves". The task of the Guardallaves is to close the water valves and to help in the detection and location of the reported leaks. In Zaragoza the leaks are reported using a direct line to the Guardallaves, who answer the calls and reports of leaks by the users. The installation of valves and pipe replacement is done by "Plomeros" (plumbers). Both teams work for the City Council under the Service of Exploitation of Systems and Cartography who is in charge of drawing up the strategic plan for the water distribution system as well as its management and monitoring. Both teams have a chief who answers to the head of the section who answers to the head of Service.

Table 4.7 presents the Activity-Responsibility Matrix for the groups involved in the Leakage Control in Zaragoza. The R stands for Responsible, A for Aware and I for Involved.

Function	**Service of Exploitation of Systems and Cartography**	**Plomeros**	**Guardallaves**	**Drivers**
Water Flow Records	R			
Leakage Report	A	I	R	
Leakage Detection	A	A	R	
Leakage Repair	A	R	I	
Budget	R			
Staff	R			
Trench Digging		A	I	R
Get Leakage Report from customers	A	A	R	

Table 4.7: Activity-Responsibility Matrix in Zaragoza for Leakage Control. (Source: Author, 2010)

The research zone, known locally as Actur zone, was built at the end of the 70's and early 1980's as a part of a project from the central government to provide residential housing and develop the north side of the city. Figure 4.1 locates the Actur area in the city of Zaragoza. There are no industries within the research zone and the most common material for water distribution pipes is ductile cast iron. The relatively new age and condition of the pipes, combined with the lack of pressure variations, made the leakage control in the Actur zone a secondary task. But now that those pipes have started to show signs of aging, Zaragoza's water utility is interested in controlling leakage.

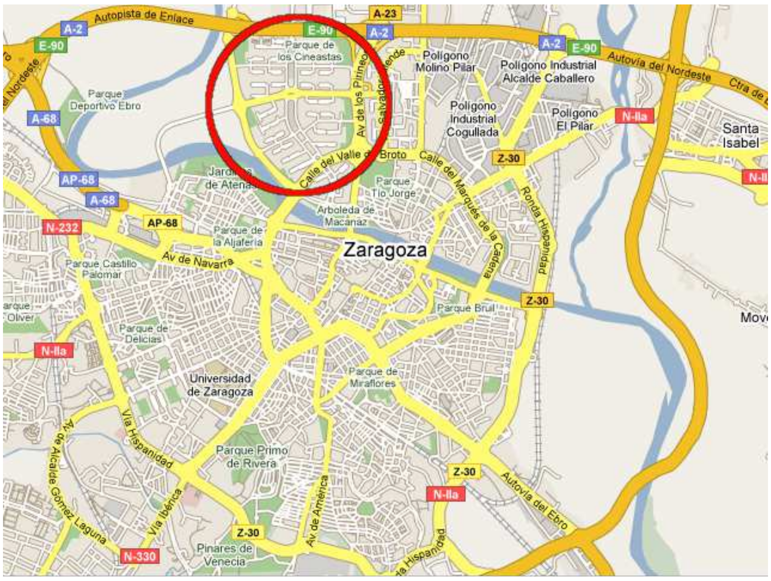


Figure 4.1: Zaragoza and the Actur area
(Source: The Author, 2008)

The leakage control in Zaragoza has been passive. This means that only when a leak was reported, the water utility mobilized a team for detection, location and repair of the leak. The budget of the water utility, which is a public utility, does not include the creation of an active leakage control work crew.

4.2.2 Test site

Figure 4.2 illustrates the location of the 4 DMAs test sites in the Actur area.

Figure 4.2: Research area in the Actur
(Source: The Author, 2008)

Table 4.8 resumes the characteristics of the meters for each of the sectors. The dataloggers are configured to store every 15 minutes the data related to the average consumption from the last 15 minutes as well as the average pressure, sending every 24 hours the data to the control center through SMS.

Sector	Location	Type	Ø
1	Cl/ Luis Legaz Lacambra	ABB MAGXE electromagnetic flowmeter Multilog GSM/SMS Datalogger	300
2	Cl/ Clara Campoamor	ABB MAGXE electromagnetic flowmeter Multilog GSM/SMS Datalogger	300
4	Cl/ Adolfo Aznar	ABB MAGMASTER electromagnetic flowmeter Pressure Reducing Valve Pegasus GSM datalogger	300
5	Cl/ Pablo Neruda	Siemens MAG 8000 electromagnetic flowmeter	300

Table 4.8: Meter characteristics of the DMAs in the Actur area, Zaragoza. (Source: Zaragoza Water Utility, 2010)

The pressure reducing valve in Sector 4 is an experimental installation that limits the night pressure (During low consumptions periods) to evaluate the effect of pressure in the leakages. The water utility has the project of analysing this data but so far they haven't got enough information.

The problems in the DMAs, besides valve problems are the lack of signal sent in some places, and sometimes, lack of mobile network coverage (SMS) (Personal communication with Alfonso Narvaiza, Head of the Service of Exploitation of Systems and Cartography).

Also the detection by the flow meters of low water flowing speed during long periods of time (coinciding with periods of low consumption), under the normal working limits of the flow meters, resulting in a measurement precision loss.

4.2.3 Number of connections

This information can be obtained from the water utility customer database, under the guidelines of Section 3.12.6 (Number of Service Connections (Nc))

In the case of Zaragoza, the values in Table 4.9 were obtained from the firm that does the meter reading for the Water Utility:

Test Sector	Number Of Connections
Sector 1	3016
Sector 2	5040
Total	**8056**

Table 4.9: Values of connections in test sectors in Zaragoza (Source: Zaragoza Water Utility, 2008)

4.2.4 Mains lengths

This information can be obtained from the water utility database.

In the case of Zaragoza, the values in Table 4.10 and 4.11 were obtained from the Water Utility GIS system, following the guidelines of Section 3.12.3 (Trunk Mains). That the pipes installed in the Actur sector were new and that the Water Utility GIS is keep up to date with the field data was an advantage.

Diameter	Length of Mains (m)
<100	479
100	5
150	6597
300	3056
Total	**10137**

Table 4.10: Values of Mains Length in Sector 1 in Zaragoza (Source: Zaragoza Water Utility, 2008)

Diameter	Length of Mains (m)
<100	86
150	7399
300	3068
Total	**10553**

Table 4.11: Values of Mains Length in Sector 2 in Zaragoza (Source: Zaragoza Water Utility, 2008)

4.2.5 Burst frequencies

This information can be obtained from the repair database in the water utility system. The required information includes average annual numbers of reported bursts on distribution mains, service pipes and supply pipes. Tables 4.12, 4.13 and 4.14 summarize the available information for Zaragoza.

Year	Sector 1	Sector 2
1995	14	16
1996	25	12
1997	24	9
1998	21	19
1999	36	15
2000	23	19
2001	19	17
2002	45	35
2003	6	26
2004	10	21
2005	16	18
2006	15	17
2007	15	16
Total	**269**	**240**

Table 4.12: Number of events reported since 1995 in Actur test sectors in Zaragoza (Source: Zaragoza Water Utility, 2008)

Code	Translation	95	96	97	98	99	00	01	02	03	04	05	06	07
1	Main burst	5	11	9	6	20	11	13	12	4	6	4	2	3
2	Service connection burst	3	3	4	3	2	5	1	1	1	3	2	3	2
3	Valve burst	3	4	5	11	3	4		9	1	1	1	1	1
4	Small leak	3	3	2	1	1		2	1			3	2	
7	No leak								1					1
9	Pipe change					9	2		19			5	5	4
20	Main burst by other causes		4	4			1	1	2			20		
30	Burst					1		2					1	
32	Burst marking													
38	Leak												1	3
39	Service connection repair													1
40	Burst in fountain													

Table 4.13: *Classification of events reported since 1995 in Actur test sector 1 in Zaragoza (Source: Zaragoza Water Utility, 2008)*

Code	Translation	95	96	97	98	99	00	01	02	03	04	05	06	07
1	Main burst	8	2	5	11	4	10	10	18	18	13	6	2	1
2	Service connection burst	4	4	3	2	2	4	2	2			1	2	5
3	Valve burst		2	1		1			4	3		1	1	
4	Small leak	4	1			1	3	3	1	1	1		1	1
7	No leak		1			1								1
9	Pipe change		1		2	2	1		10	3	7	10	6	2
20	Main burst by other causes		1		4	4				1				2
30	Burst						1	1					3	
32	Burst marking													
38	Leak												1	
39	Service connection repair													2
40	Burst in fountain												1	2

Table 4.14: Classification of events reported since 1995 in Actur test sector 2 in Zaragoza (Source: Zaragoza Water Utility, 2008)

This information allows the calculation of the repair costs in the Actur area. From the Repair Database, the information about the incidents of repair and replacement of pipe in the main network that included an incident of leak was extracted. In total there were 10 incidents that had information about duration of repairs.

From those incidents the total duration of the repair for all the incidents, from the verification of leak to the opening of the water service after the repair has finished, were 68 hours and 25 minutes. It is important to mention that the data that had no information about time is not present in this analysis.

A leak detection campaign from October 20/08 to December 23/08 was carried out. The resources used for this task were access to database, water lines plans, working crew of 3 to 4 persons, 25 Permalog noise loggers and a van. About the Permalog noise loggers they were left in the zone for at least 2 days. The water utility has a total of 30 of them, but they were not used in the totality, at least 6 were left in case of an emergency detection of a leak. Figure 4.3 shows the results of the leak detection campaign.

Figure 4.3: Results of the leak detection campaign (Source:The Author, 2008)

The total number of leaks in the Actur sector was 34.

Considering a crew of 4 persons with a salary of 200 Euros per day per person, an investment in transport and materials of 200 Euros per incident, the cost per incident will be

$$\left(\frac{25\ Euros\ per\ person\ per\ hour \cdot \left(68\ hours + \left(\frac{25\ \text{minutes}}{60\ \text{minutes}\ per\ hour}\right)\right) \cdot 4\,persons}{10\ incidents}\right) + 200\ Euros =$$

$$684.20\ Euros + 200\ Euros = 884.20\ Euros\ per\ incident$$

Equation 4.1: (Source: The Author)

So the total cost of repairing the leaks on Sectors 1 and 2 will be 30,062.80 Euros which is 884.20 Euros times 34 incidents. The repair program has not started in Zaragoza due to budget problems. This means that the detection and control cost curve has no points since the cost is known but the leakage control level it can achieve is not. This calls for the use of BABE model. This needs the value of N1 exponent, obtained from a pressure drop test.

4.2.6 Average Zonal Night Pressure (AZNP)

This information requires a SCADA system or the use of pressure sensors. It is necessary to consider the seasonal changes in the pressure, so year round data is preferable. Section 3.11.1 (Average System Pressure (ASP)) describes the conditions for this variable.

A field test was carried out from march 13th to march 20th in the Actur area. Even considering the problems with the budget for extra hours in the water utility, from this field test this research obtained information about the current N1 level and the AZNP in the sectors. The AZNP has a value of 40.2 MH2O, summarized in Table 4.15. That value is assumed for both test sectors. However this value has no indication of seasonal changes.

Test Sector	**AZNP (MH2O)**
Sector 1	40.2
Sector 2	40.2
Average	**40.2**

Table 4.15: Average Zonal Night Pressure in test sectors in Zaragoza (Source: Field test march 13th to march 20th,2009)

4.2.7 Data Not Available

The first step in the data collection process is to establish the boundaries of the collection. In this case only the current protocols in use by the water utility for detection, repair and pressure management will be considered. The consideration of alternatives for this protocol will be one of the uses of the ELL model that is going to be developed under this research and will use data and considerations from successful applications in other cases, which will be obtained from the technical literature.

The following data was collected using a format:

- Fuel used in active leak detection, leak repair and pressure management.
- Electricity used in active leak detection, leak repair, pressure management

This data refers to the data needed in Section 3.15 (Calculation of Externalities). For this reason, the data collected in the format was compared with the repair and fuel consumption information in the pipe replacement and repair and pressure management logbooks, to guarantee an appropriate level of confidence in the data. Also the logbooks provided information about the working crew used in the different leakage control approaches used. Tables 4.16 to 4.19 describe the available information that will be used in a city wide way. The water utility provided the data, using a format that was filled out every time a detection, repair, asset or pressure management action was carried out. The data include the different aspects that include energy consumption and emissions. The data collection time using the format was 6 months but it was replaced after 2 months. So the format was used to collect data for two months. The historical data available about leakage repair starts at 1995.

Item
SCADA records
Air compressors type,
Heating systems types
Heating systems fuel type
Lighting types
Lighting operating patterns
Pump performance curves
Pump log book
Pump and pumping system design data, including design duty information and pump performance curves
Actual pump flow rates
Actual pump operating pressures,
Actual pump power absorbed
Actual pump operating speeds

Table 4.16: Data currently available that will be asked only once to the water utility (Source: The Author, 2009)

Item
Generators ratings
Other electricity support services
Air compressors ratings
Air compressors controls
Air compressors operating set points
Air compressors operating profiles
Heating systems ratings
Heating systems controls
Heating systems set points
Heating systems operating patterns
Lighting ratings
Lighting controls

Table 4.17: Data currently not available that will be asked only once to the water utility (Source: The Author, 2009)

Item
Actual pump electricity consumption
Actual pump fuel consumption
Number of pumps run
Number hours run by the pumps
Lightning source of energy
Lighting purpose
Repair detected leaks
Leaks detected
Repair reported leaks
Renewal of main pipes
Renewal of service pipes
Repair time
Number of crew members
Repair crew van millage
Lightning source of energy

Table 4.18: Data currently available that will be collected with the weekly format (Source: The Author, 2009)

Item
Generators running hours
Air compressors running hours
Generators fuel consumption
Air compressors actual energy consumption
Heating systems running hours,
Heating systems actual energy consumption
Heating systems fuel consumption
Lighting annual operating hours
Detection time
Location time

Table 4.19: Data currently not available that will be collected with the weekly format (Source: The Author, 2009)

Fuel cost and Externalities in the water treatment process are not available and this data was obtained from available historical data. This involves talking about the price for a litre of fuel for the water utility. The externalities in water treatment will use values from UKWIR Reports 08/CL/01/5 (2008) and 08/CL/01/6 (2008). The fuel used in transport and equipment and the crew members hourly salary was not available information and was obtained from available historical data.

4.2.8 Problems with Data Collection

The lack of a centralized depository of information inside the water utility made the data collection process complicated for some data. Zaragoza's water utility has three types of working crews involved in the leakage detection and repair tasks. One is the Guardallaves team which is in charge of detection and repair verification. They have their own vehicles. The actual repair work is carried out by the plumbing crew (Plomeria). They also have their own vehicles. The third working crew are the drivers of lorries, cement mixers and heavy equipment that might be needed after the repair of the leak.

Each team has their own databases on fuel cost and consumption. These databases aren't standardized and they can't be accessed or shared between teams. Also teams are not aware of the information collected or considered by other teams inside the water utility. In the case of the generators and pumps fuel consumptions, the data is not stored in digital form. That made us think that such information didn't exist.

The use of the data collection format was discarded after realizing how different the teams where on the format filling process. However, those 2 months of data allowed the verification of the values, comparing with available historic data in databases and logbooks kept by technical staff.

Another consideration in the research is how the complete vehicle millage was on leak detection and control tasks. Although it can be true in some cases such as heavy equipment, some of the vehicles are used for quick tasks that might not be part of leak detection and control. This information is available also as fuel volumes or fuel volumes cost, but there is always the possibility of fraud with this information. This is a very delicate situation for the water utility since money is involved. That was one of the reasons it was decided to work with Distance and not volumes or costs.

Also Repair Time in Distribution Mains, needs a realistic assessment. Zaragoza's Water Utility had that information available in log books, but they kept the information of times for Guardallaves and for plumbers separated. This can generate a confusion between the detection time (done by the Guardallaves team) and the repair time (Done by the plumbers) since the tasks sometimes overlap. A proper discrimination and assessment will fix the confusion. The analysis of this data will allow not only calculating the costs of personal, but also allowing the calculation of time values for a second analysis.

4.2.9 Reliability

Reliability can be defined as the ability to produce consistent measurements each time (Kumar, 2010). In this case, the reliability was applied to the Dynamic Model verifying it against know values.

4.2.10 Reliability and Validity of Research Methods

This section will present the different issues and comments about the implementation and the Research Methods. It is important to stress again how the use of the BABE methodology, for the estimation of the background leakage, requires field data such as the number of bursts, the average zone night pressure, length of mains, trunk-main losses, and number of billed properties that might not be available but that can be obtained by the water utility with a reasonable level of investment. As it was mentioned in the Section 3.3, the Water Utility in Zaragoza had that data available but the need for information organization is key in the model implementation.

However is necessary to insist in the need for calibration of the data used to run the model. There is trust in the quality of the data given by Zaragoza's Water Utility but it might not be the case for data available in other locations. And if new data will be included in the model, for example from new pressure measurements, it is necessary to guarantee that the measurements are made with calibrated instruments. Also the model needs to maintain a consistency in the units. This is critical because the model uses coefficients that relate flow rates, times, volumes and lengths. These quantities can be presented in units that are different to the ones used in the model and that can affect the results.

The data obtained from the pressure drop test and the data collection format mentioned in Sections 4.2.6 and 4.2.7 are not considering seasonality. This data is only a snapshot of the winter conditions. The use of the log books allowed the analysis of year-wide information, and the verification of the information collected by the format. It's recommended to carry out at least 4 pressure drop tests, one for each season, to analyse the seasonality of the pressure readings.

Although the Actur zone might be considered a really recent area with a very different pipe and network condition from the city centre, with old cast iron pipes, it's important to stress that Zaragoza's growth and the condition of the new pipes and installation procedures allows the consideration of Actur as an average for a city wide consideration.

In the case of Zaragoza, the Apparent Losses (Section 2.2.1 and Section 3.10.28) were not an important part of the losses in the Actur area. However they tend to be an important part of losses in developing countries. To consider the effect and scope of Apparent Losses before implementing the calculation is an important issue.

In the case of this research, there were no values for the Allowances for Real Losses from Service Reservoirs (ARLSR) (Section 3.13.5) and no references for the FAVAD N1 (Section 3.11.3 and Section 3.11.11) so these values were assumed. For the research the research used an average condition of pipes, N1 = 0.5 for ICF = 1 according to Fantozzi (2007). The value of N1 is related to the ICF.

Also consider the case of the Pipe Length (Section 3.15.6) for the calculation of externalities. The use of a database, linked with the supply warehouse, will allow the use of a realistic value for this item. Also digging volume or work times can give a reference since they link the volume of the trench used in the repair process with the pipe length replaced. This can also be connected to the Coefficient for Emission from pipe lying (CEPL) (Section 3.15.7). For this variable, the research considered an average pipe diameter and average pipe length.

This model calculates the Allowances for Real Losses from Trunk Mains (Section 3.13.2) using the Age of Trunk Mains and considering a 1.0 litre/sec detection threshold, since leaks with an smaller volume couldn’t be detected. This is an argument to carry out more research and update that relation. Also the Water Utility needs to invest in the calculation of their own values for the Allowances for Real Losses from Service Reservoirs (Section 3.13.5).

This methodology requires only three system-specific parameters: Cost of Intervention (CI), Variable Cost of Lost Water (CV), and Rate of Rise of Unreported Leakage (RR) (Lambert & Lalonde, 2005).

Of these parameters, the most critical in the research was the RR due to the experimental nature. Lambert (2005) gives the following methods for calculating the Unreported Leakage Rate of Rise that will be briefly discussed in Section 3.7.8 (Rate of Rise of unreported leakage (RR)). It is important to mention that an approximate assessment of the Rate of Rise is acceptable to get started on Economic Intervention calculations. The results obtained can be refined in a later stage. The Rate of Rise is discussed in Section 3.14.3 (Average Rate of Rise of Unreported Leakage (RR)) and Section 4.2.11 presents the current value.

4.2.11 ELL Calculation

The data about the current condition and values was obtained following the procedures and recommendations mentioned in Chapters 2 and 3. The data will be classified according to the different component of leakage that will be calculated using it. It’s important to stress that this values correspond to the current state of the system where an scheme of passive leakage control is being applied Losses.

Table 4.20 presents the information used for the Reported Burst Volume in Distribution Mains and Service Connections. Section 3.11 describes with more detail the variables involved.

Variable	Units	Initial Value
Average system pressure	m	40.2
Number of Reported Burst and Leaks in Distribution Mains	Number	302
Number of Reported Bursts and leaks in Service Connections	Number	360
Percentage of rigid distribution mains	Percentage	1
Percentage of rigid service connections	Percentage	1
Repair time in distribution mains	Days	5
Repair time in service connections	Days	15
Volume per event in distribution mains	m^3/h	12
Volume per event in service connections	m^3/h	0.8

Table 4.20: Initial values used in the Reported burst volume in Distribution mains and Service connection section of the model for Zaragoza.
(Source: Zaragoza Water Utility)

Section 3.12 describes the calculation of the estimated background leakage using the variables listed in the Table 4.21.

Variable	Units	Initial Value
Background leakage @ 50m pressure and ICF = 1.0 for Mains	l/km/h	20
Background leakage @ 50m pressure and ICF = 1.0 for service connections	l/connection/h	1.25
Distribution and transmission pipe length	km	1235
FAVAD N1	Number	0.5
Number of days	Number	365
Number of service connections	Number	21530
Predicted background leakage	Number	1
Unavoidable Annual Real Losses per metre of pressure for Distribution mains	l/km mains/Day/m	18
Unavoidable Annual Real Losses per metre of pressure for Service connections	l/connection/Day/m	0.8

Table 4.21: Initial values used in the estimated background leakage section of the model for Zaragoza.
(Source: Zaragoza Water Utility)

Section 3.13 describes the calculation of the Trunk mains and service reservoirs leakage using the variables listed in the Table 4.22.

Variable	Units	Initial Value
Age of trunk mains	Years	30
Allowances for Real Losses from service reservoirs	m^3/km/Day	0.001
Trunk mains	km	238.61
Volume of service reservoirs	m^3	275510

Table 4.22: Initial values used in the Trunk Mains and Service Reservoir Leakage section of the model for Zaragoza
(Source: Zaragoza Water Utility)

The calculation of the current cost of intervention for the Method of active leakage control considers a crew of 4 persons with a payroll cost of 200 Euros per day per person, a investment in transport and materials of 200 Euros per incident. Using the figures of the case study in Actur Area where to carry on the active leak detection in Sector 1 for 10.137 km it took 5 days using noise loggers, the cost of intervention per km is 414.32 Euros, which can be approximated to 410 Euros/km since the value of materials is overestimated. The variable cost of water in 2009 (CV) is taken as €0.734 per m^3 after consultation with water supply managers in Zaragoza.

The Rate of Rise (RR) was estimated from two water balances for one DMA. This equated to 49 litres/connection/day/year or 1,057 m^3/day/yr for the city as a whole. This estimate was used in the absence of data from the rest of the city, though the pipe system in Actur is relatively new and in good condition compared with other parts of the city, so this rate of rise may be an underestimate.

Variable	Units	Initial Value
Assumed Variable Cost of Water VC	Cost	0.734
Method of active leakage control	Cost/km	410
Rate of Rise	m^3/day/yr	1,057

Table 4.23: Initial values used in the Economic Unreported Real Losses section of the model for Zaragoza
(Source: Zaragoza Water Utility)

If the model is run with the initial data included in Tables 4.20, 4.21, 4.22 and 4.23, the results for the different leakage components are presented in Table 4.24.

Variable	Units	Initial Value
Economic Unreported Real Losses	m^3x10^3/yr	364.80
Trunk Mains and Service Reservoir Leakage	m^3x10^3/yr	384.48
Estimated Background Leakage for ICF= Predicted Background Leakage	m^3x10^3/yr	405.41
Reported Burst Volume in Distribution Mains and Service Connections	m^3x10^3/yr	482.91
Short-Run Economic Level of Leakage	m^3x10^3/yr	1637.60

Table 4.24: Initial leakage values for the Zaragoza mode considering Active Leakage Control.
(Source: The Author)

From the above analysis, the Economic Level of Leakage for Zaragoza is estimated as 1,637.60 m^3x10^3/yr, as shown in Table 4.24. This is based on only one approach for active leakage detection (using noise loggers) and different approaches or combination of approaches will have different results for this ELL analysis. The volume of Non-Revenue Water in Zaragoza is estimated at approximately 21million m^3 per year (34%), as shown in Table 4.25. About half the estimated losses occur in the distribution network.

Item	Annual Volume m^3x10^6/yr
Treated Water delivered to distributions system	61.09
Metered delivery to customers	39.69
Non Metered Consumptions	1 to 2
Metering errors	4 to 5
Losses in treatment plant and tanks	0,5 to 1,5
Losses in private installations (e.g. inside the house or the network inside a university...)	3 to 4
Losses in distribution network	9 to 12

Table 4.25: Estimated Water Supply Volumes in Zaragoza, 2008
(Source: Zaragoza Municipality 2009)

Even having in mind that the volumes are not calculated as a IWA standard Water Balance (Section 2.2), this shows that considering losses of 9,000 m^3x10^3/yr, this value is almost 5.5 times bigger than the ELL. In the case of 12,000 m^3x10^3/yr, it goes to almost 7.3 times.

This means that the investment in Active Leakage Control would have a great opportunity to improve the performance of the water utility, reducing the losses in the distribution network. In fact, in Table 4.24 the values are very similar but Reported Burst Volume in Distribution Mains and Service Connections has the highest volume. This can be related to the awareness the Water Utility has on the losses in the distribution network.

But the first main result from this research is the figure of ELL for the city of Zaragoza, estimated at 1,637.60 m^3x10^3/yr, presented in Table 4.24. This ELL is based on only one approach for active leakage detection (using noise loggers). The volume of Non-Revenue Water in Zaragoza is estimated at approximately 21million m3 per year (34%), as shown in Table 4.25. About half the estimated losses occur in the distribution network. Even having in mind that the volumes are not calculated as a IWA standard Water Balance (Section 2.2), this shows that considering losses of 9,000 m^3x10^3/yr, this value is almost 5.5 times bigger than the ELL. In the case of 12,000 m^3x10^3/yr, this goes to almost 7.3 times.

This means that the investment in Active Leakage Control would have a great opportunity to improve the performance of the water utility, reducing the losses in the distribution network. In fact, in Table 4.24 the values are very similar but Reported Burst Volume in Distribution Mains and Service Connections has the highest volume. This can be related to the awareness the Water Utility has on the losses in the distribution network.

The Water Utility must then start to study what component of Real Losses should be tackled now. The calculation of ELL exercise allows the water utility to be aware of the current gaps in data, which should be considered and fixed as a part of the next step in the Leakage Control: The strategy implementation.

During this implementation process, the Water Utility will invest and once the investment has been made, there will be a new (lower) short-run economic level of leakage, which has to be re-calculated. This recalculation might involve a Long Term ELL analysis which can be part of a way forward for the Water Utility. But it is important to insist in the need of the detection and repair tasks to go hand to hand. It is pointless to detect leaks and not repair them, especially when one of the main points of the ELL calculation is that the recovered volume can cover those repair and detection costs.

4.3 Inclusion of Externalities

4.3.1 Passive Leakage Control

The following are the values used for the externality analysis obtained from Zaragoza's water utility using the procedures mentioned in Chapters 3 and 4.

Item	Units	Initial Value
Average Pipe Length Replaced Per Repair Event	M	2
Coefficient for Emission from Driving for Leakage Control	CO2/km	0.21
Coefficient for Emission from Pipe Lying	kgCO2e/m length of pipe	344
Coefficient for Emissions from Compressor Use	kg CO2/l	2.69
Coefficient for Emissions from Generator Use	kg CO2/l	2.72
Distance Driven for Leakage Control	Km	48879
Number of Repair Events	Number	501
Volume of Fuel in Compressor Use	L	7761
Volume of Fuel in Generator Use	L	1955
Emissions due to Labour, Commuting and Welfare	kg CO2/yr	6944

Table 4.26: Initial values for externality analysis in the Zaragoza model.
(Source: Zaragoza Water Utility)

The fuel consumption for compressors can be separated in the following items

Fuel consumption item	Units	Initial Value
Compressors	L	2406
Groups	L	520
Steamroll	L	115
Asphalt	L	195
Buy	L	4525

Table 4.27: Fuel consumptions in compressors used in leakage control for the Zaragoza model.
(Source: Zaragoza Water Utility)

Under this conditions, 388,091 kg CO2 will be emitted during the leak repair activities. This is equal to 388.091 tons per year. For a Non-Trade Carbon Price (NTCP) of 51 £/tCO2 (Recommend by DECC, 2009 and updated in 2010) the total cost of externalities will be 19,793£ per year. This value has to be added to the Intervention cost. The cost per km of distribution pipe will be 16.02 Euros/km.

When running again the model, the data included in the Tables 4.24, 4.26, 4.27 continues with the same values. The new value for the Cost of Intervention would be 410 + 16.02 = 426.02 Euros/km. Table 4.28 presents the results of the analysis and compares them with the initial leakage values from Table 4.24.

Variable	Units	Initial Value	Considering externalities
Economic Unreported Real Losses	m^3x10^3/yr	364.80	371.85
Trunk Mains and Service Reservoir Leakage	m^3x10^3/yr	384.48	384.48
Estimated Background Leakage for ICF= Predicted Background Leakage	m^3x10^3/yr	405.41	405.41
Reported Burst Volume in Distribution Mains and Service Connections	m^3x10^3/yr	482.91	482.91
Short-Run Economic Level of Leakage	m^3x10^3/yr	1637.60	1644.65

Table 4.28: Leakage values considering externalities for the Zaragoza model. (Source: Zaragoza Water Utility)

The higher volume in the Economic Unreported Real Losses (7.05 m^3x10^3, which is equal to an increase of 1.93%) is a product of the change in CI. Since the CV stays constant, there is an increase in the EURL. The relationship between CI and the other components of the ELL will be analysed with more detail in Section 4.11.6 (Cost of Intervention) and this will show why the change in CI has no effect in the other components.

Considering a CV of €0.734 will have a cost of €5,174.3. It might not seem like a big difference in cost but having the advantage to quantify the emissions will be useful in future scenarios when the legislation will make compulsory the calculation and report of them. After all the future trend in energy consumptions is not an increase but to save energy. Energy saving will mean less emissions and a lower volume of Economic Unreported Real Losses which results in a lower ELL. It would be interesting to see the effects of the other Leakage Management Approaches.

4.3.2 Active Leakage Control

The current conditions analysed in Section 4.3 and 4.3.1 only consider passive leakage control. The next step will include the scenario of active leakage management. As it was mentioned in Section 2.3.1 (Active Leakage Management), is simply described as detection of leakages before they appear on the surface, using various technical equipment. In this case a working crew only for detection will be added to the current situation.

So this condition has to consider not only the previous externalities but also the new externalities from this detection crew. From those externalities, the following items, collected in Table 4.29, will remind constant no matter the amount of crews used for leak detection and control:

Item	Units	Initial Value
Average Pipe Length Replaced Per Repair Event	m	2
Coefficient for Emission from Driving for Leakage Control	CO2/km	0.21
Coefficient for Emission from Pipe Lying	kgCO2e/m length of pipe	344
Coefficient for Emissions from Compressor Use	kg CO2/l	2.69
Coefficient for Emissions from Generator Use	kg CO2/l	2.72
Number of Repair Events	Number	501
Volume of Fuel in Compressor Use	l	1955
Volume of Fuel in Generator Use	l	9716

Table 4.29: List of externalities that remain constant during externality analysis in the Zaragoza model.
(Source: Zaragoza Water Utility)

So why the Distance Driven for Leakage control would change and the volume of fuel used in compressors and generators remain constant? It's related to the number of repair events. Since the number of repair events for the current condition remind constant, the fuel used in the repair of those events reminds constant too. The discrimination of the distances per vehicle is collected in Table 4.30.

Vehicle	Units	Initial Value
MERCEDES VITO	km	2413
OPEL CORSA-C	km	3537
MERCEDES VITO 109CDI	km	7022
MERCEDES VITO 109CDI	km	14729
MERCEDES VITO 109	km	21178

Table 4.30: Discrimination of distance driven for leakage control in the Zaragoza model.
(Source: Zaragoza Water Utility)

The Mercedes vans are used for carrying the materials and work crew. The Opel Corsa is used for fast responses to identify or diagnose leaks.

So an average intervention in Zaragoza would include using the Mercedes Van to located and fix the leak. In this case if an average distance driven by the van is used, it would be 14310 km per year. Then if the number of crews changes, the value of Distance Driven for leakage control will be the addition of the millage of all the cars used.

In the case of the Emissions due to Labour, Commuting and Welfare, the usual setup for leak control work involves one van and 4 persons as described in the section 3.15.1 (Emissions due to Labour, Commuting and Welfare) in the Model Description chapter. So if the number of crews changes, the value of 6944 kg CO2/yr shall be multiplied for the number of crews.

The calculation of the current cost of intervention considers a crew of 4 persons with a salary of 200 Euros per day per person, a investment in transport and materials of 200 Euros per incident. Using the figures of the case study in Actur Area where to carry on the active leak detection in Sector 1 for 10.137 km it took 5 days using noise loggers, the cost of intervention per km is 414.32 Euros, which can be approximated to 410 Euros/km since there is an overestimation of the value of materials.

Since this value depends on the amount of people in the work crew, it will be proportional to the number of working crews. So for 2 working crews it will be 820 Euros/km and for 3 crews 1230 Euros/km.

This analysis actually will allow us to answer a question: What are the advantages and disadvantages of a detection crew working at the same time as a repair crew? What are the effects of this in the leakage level?

4.3.3 One Detection Crew

If an extra detection crew is considered, Table 4.31 resumes the externalities considered for this analysis:

Item	Units	Initial Value
Average Pipe Length Replaced Per Repair Event	M	2
Coefficient for Emission from Driving for Leakage Control	CO2/km	0.21
Coefficient for Emission from Pipe Lying	kgCO2e/m length of pipe	344
Coefficient for Emissions from Compressor Use	kg CO2/l	2.69
Coefficient for Emissions from Generator Use	kg CO2/l	2.72
Distance Driven for Leakage Control	Km	48.879 + 14.310 = 63.189
Number of Repair Events	Number	501
Volume of Fuel in Compressor Use	l	7761
Volume of Fuel in Generator Use	l	1955
Emissions due to Labour, Commuting and Welfare	kg CO2/yr	6944+ 6944 = 13.888

Table 4.31: List of externalities for adding an extra detection crew in the Zaragoza model. (Source: The Author)

For the Cost of Intervention, the research considers that the analysis is for a detection crew. So it will not consider the cost of the materials per incident since they are already considered as a repair. This means that the Cost of Intervention will be the 410 Euros/km plus 400 Euros/km that will consider the cost of the 4 person crew working 5 days with a salary of 200 Euros per day per person. The Cost of Intervention will be 810 Euros/km. Table 4.32 presents the results of the externalities analysis and compares them with the initial values.

Variable	**Units**	**Initial Value**	**Considering Detection Crew**
Emissions Due to Driving for Leakage Control	kg CO2/yr	10,264.59	13,269.69
Emission from Pipe Lying	kg CO2/yr	344,688.00	344,688.00
Emissions from Compressor Use	kg CO2/yr	20,877.09	20,877.09
Emissions from Generator Use	kg CO2/yr	5,317.60	5,317.60
Emissions from Repair Events	kg CO2/yr	370,882.69	370,882.69
Emissions due to Labour, Commuting and Welfare	kg CO2/yr	6,944.00	13,888.00
Estimated Emisions from Leakage Control	**kg CO2/yr**	**388,091.28**	**398,040.38**
Cost of externalities	**Euros/km**	**16.026**	**16.437**

Table 4.32: Externalities costs considering an extra Detection Crew in the Zaragoza model. (Source: The Author)

The difference in externalities cost is 0.41 Euros per km. And this has to be considered in the Cost of Intervention. The data show that the fuel, energy and materials use at worksites is the major source of emissions, not energy use by labour and transport. Table 4.33 presents the results of the analysis and compares them with the initial leakage values from Table 4.28.

Variable	**Units**	**Initial Value**	**Considering externalities**	**Considering Detection Crew**
Economic Unreported Real Losses	m^3x10^3/yr	364.80	371.85	517.92
Short-Run Economic Level of Leakage	m^3x10^3/yr	1637.60	1644.65	1790.71

Table 4.33: Leakage values considering externalities and a Detection Crew for the Zaragoza model.
(Source: The Author)

The difference of 146.07 m^3x10^3 between the case of Considering Externalities and the case of Considering Detection Crew is again a product of the change in the CI. This difference is equal to a change in a 39.28% of the EURL. However, this extra detection crew would be only carrying out *detection* and not repair tasks. Considering the dimension of the difference, we better start considering effects of having a Detection Crew working at the same time as a Repair Crew.

4.3.4 One Detection crew working at the same time as a repair crew

This analysis will use the externalities listed in Table 4.29. This means that the results will be the same results listed in Table 4.30. The change in this analysis will be in the Cost of Intervention that, for this case, will consider the cost of the materials. The Cost of Intervention will be 820 Euros/km.

Table 4.34 presents the results of the analysis and compares them with the previous leakage values obtained.

Variable	Units	Initial Value	Considering externalities	Considering Detection Crew	Considering Crew doing Detection and Repair
Economic Unreported Real Losses	m^3x10^3/yr	364.80	371.85	517.92	521.04
Short-Run Economic Level of Leakage	m^3x10^3/yr	1637.60	1644.65	1790.71	1793.84

Table 4.34: Leakage values considering externalities and a Detection Crew doing Detection and Repair for the Zaragoza model.
(Source: The Author)

4.3.5 One Detection crew working at the same time as a repair crew and an only Detection crew

In this scenario, there will be a change in the externalities value due to the change in Distance Driven for Leakage Control and the Emissions due to Labour, Commuting and Welfare. Table 4.35 shows the changes.

Item	Units	Initial Value
Distance Driven for Leakage Control	Km	48879 + 14310 + 14310 = 77.490
Emissions due to Labour, Commuting and Welfare	kg CO2/yr	6944+ 6944 + 6944 = 20.832

Table 4.35: List of externalities for adding an extra detection and repair crew and a detection crew in the Zaragoza model.
(Source: The Author)

Table 4.36 compares the results obtained.

Variable	Units	Initial Value	Considering Detection Crew	Considering Crew for Detection and Repair and Crew for Detection
Emissions Due to Driving for Leakage Control	Kg CO2/yr	10,264.59	13,269.69	16,272.90
Emissions from Repair Events	Kg CO2/yr	370,882.69	370,882.69	370,882.69
Emissions due to Labour, Commuting and Welfare	Kg CO2/yr	6,944.00	13,888.00	20,832.00
Estimated Emisions from Leakage Control	**Kg CO2/yr**	**388,091.28**	**398,040.38**	**407987.59**
Cost of externalities	**Euros/km**	**16.026**	**16.437**	**16.848**

Table 4.36: Externalities costs considering an extra detection and repair crew and a detection crew in the Zaragoza model.
(Source: The Author)

Table 4.37 reports the leakage values. The Cost of Intervention will be 820 Euros/km for detection/repair crew plus 400 Euros/km for the detection crew.

Variable	Units	Initial Value	Considering externalities	Considering Detection Crew	Considering Crew doing Detection and Repair	Considering Crew for Detection and Repair and Crew for Detection
Economic Unreported Real Losses	m^3x10^3/yr	364.80	371.85	517.92	521.04	633.60
Short-Run Economic Level of Leakage	m^3x10^3/yr	1637.60	1644.65	1790.71	1793.84	1906.40

Table 4.37: Leakage values considering externalities, Detection and Repair Crew and Detection Crew for the Zaragoza model.
(Source: The Author)

In this case the difference between a Detection Crew and a Crew doing Detection and Repair is only 3.12 m^3x10^3 (0.60%). This would justify the investment of a crew that does Detection and Repair instead of having two different crews, one for each task.

To summarize, it was found out that having a dedicated workforce for Active Leak Detection makes sense. According to the analysis showed in Table 4.37, Section 4.4.5, considering the externalities in Zaragoza, the difference in ELL between a Detection Crew and a Crew that does Detection and Repair is only 3.12 m^3x10^3 (0.60%). This would justify the investment of a crew that does Detection and Repair instead of having two different crews, one for each task.

This section has analysed the current conditions of Zaragoza. But one of the advantages of having a model is to be able to consider future conditions to understand the possible system behaviour. In the next section, the concept of Scenario Planning, a tool that allowed the use of the model for three different future conditions in the city, will be introduced.

4.4 What is Scenario Planning?

Traditional planning is frequently based upon the belief that the application of professional expertise to achieve well-defined goals will ensure efficient and effective management (Peterson et al, 2003). However sometime the planning process fails in not consider the variety of local conditions or the propensity for novel situations to create extraordinary surprises. Scenario planning is a distinctly different planning tool than to predict the future and work toward it approach. Scenario planning does not focus on accurately predicting the future but rather is a process that produces a number of possible futures that are credible and yet uncertain (Keough and Shanahan, 2008).

Scenarios were initially developed by Herbert Kahn in response to the difficulty of creating accurate forecasts. Kahn worked at the RAND Corporation, an independent research institute with close ties to the U.S. military. He produced forecasts based on several constructed scenarios of the future that differed in a few key assumptions. Later, in the seventies, this tool was used by Shell Oil to develop scenarios concentrated on economic growth, oil supply, and oil price options that focused on the key variables of direct impact for the businesses. In a world characterized up until then by continuing and sustained expansion, the scenarios foresaw a disruption in oil supply and the subsequent rise in prices. (Cornelius et al, 2005). With the later Arab Oil Embargo in 1974 crystallizing these issues, Scenario Planning became a useful tool (ibid).

According to Davies (2002) "Scenarios are not projections, predictions or preferences. Rather they are coherent and credible stories, describing different paths that lead to alternative futures". Davis (2002) also states that the process of producing and using scenarios is as important as the scenario stories themselves. Building and using scenarios is about asking questions and not just providing answers. Keough and Shanahan (2008) present the different Scenario Building process. According to Schwartz, the steps are:

1. Identify focal issue or decision
2. Identify key factors in the local environment which influence the decision
3. Identify driving forces that influence key factors in the local environment
4. Rank by importance and uncertainty
5. Select scenario logics
6. Flesh out scenarios
7. Consider implications
8. Selection of leading indicators and signposts

Shoemaker (1995) gives the following steps:

- Define the Scope
- Identify the major stakeholders
- Identify basic trends
- Identify key uncertainties
- Construct Initial scenario themes
- Check for consistency and plausibility

- Develop Learning Scenarios
- Identify Research Needs
- Develop Quantitative models
- Evolve toward decision scenarios

Avin states a 12-Step Scenario Building Model, presented in Figure 4.4.

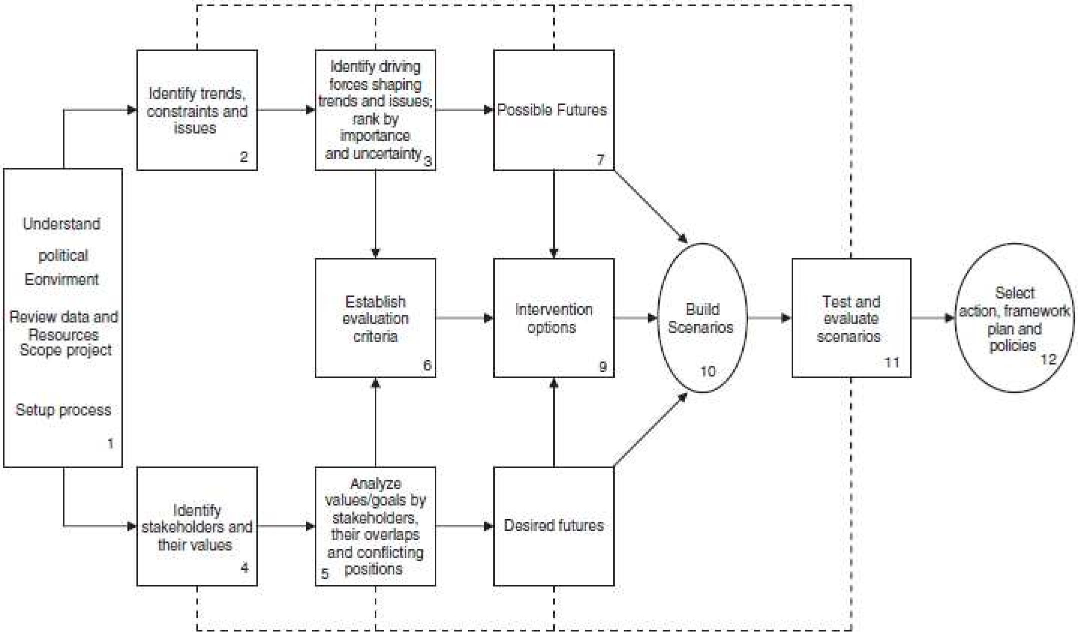


Figure 4.4: Avin's 12 steps to Scenario Building
(Source: Keough and Shanahan, 2008)

This research will use the Scenario Planning tool to consider three scenarios for Zaragoza in 2030. Scenario One (Section 4.5 Zaragoza Cares About Energy Emissions) will be a "Best Case Scenario", Scenario Two (Section 4.7 Low Growth Rate in Zaragoza) a critical Scenario and Scenario Three (Section 4.9) a "Business as Usual".

Each Scenario will be presented, explained and analysed in the following sections and use the "Atlas de Zaragoza 2009" ("City Atlas 2009") as source for the city statistics.

4.5 Scenario One: Zaragoza Cares About Energy Emissions

4.5.1 Narrative

In 2030, EU is now paying increased attention to emissions. Due to problems in China-India block, where food scarcity was linked with water scarcity and turned into an economic crisis, and to avoid depending on oil, the EU switch to a active "environment first" policy.

Spain has an advantage and in the case of Zaragoza, the advantage of being between Madrid and Barcelona and close to French border, easy access to solar and wind power, has resulted in a population growth with immigration of qualified workforce from other EU countries.

This population growth required new water sources. The city considered projects such as the Yesa 2 dam. However this had a big environmental impact that wasn't into the EU lines. The option the city found was to use water from wells. This has raised the price of water since is an energy intensive process, even considering the easy access to clean energy. The use of pressure management was a very efficient tool at the beginning but now the water utility is considering other options. The users are aware of the cost of water and are REALLY into water saving. The position of the water utility to share information and data in a simple, transparent and available way allows the users to keeping an eye on the water utility. In this case, the water utility is considering the use of biodiesel for their vehicles.

EVOLUCIÓN POBLACIÓN 2000–2008 PRINCIPALES CIUDADES ESPAÑOLAS / POPULATION EVOLUTION 2000–2008 IN THE MAIN SPANISH CITIES

CIUDAD CITY	POBLACIÓN POPULATION 2000	POBLACIÓN POPULATION 2003	POBLACIÓN POPULATION 2007	POBLACIÓN POPULATION 1-1- 2008	VARIACIÓN TOTAL VARIATION 2000–08	VARIACIÓN TOTAL VARIATION 2003–08	VARIACIÓN PROPORCIONAL PROPORTIONAL VARIATION 2000–08	VARIACIÓN PROPORCIONAL PROPORTIONAL VARIATION 2003–08
Madrid	2.882.860	3.092.759	3.132.463	3.240.000	357.140	147.241	12,38%	4,76%
Barcelona	1.496.266	1.582.738	1.595.110	1.623.220	126.954	40.482	8,48%	2,55%
Valencia	739.014	780.653	797.654	810.064	71.050	29.411	9,61%	3,76%
Sevilla	700.716	709.975	699.145	705.682	4.966	-4.293	0,71%	-0,61%
Zaragoza	604.631	626.081	654.390	682.283	77.652	56.202	12,84%	8,98%
Málaga	531.565	547.105	561.250	574.353	42.788	27.248	8,04%	4,98%

Fuente: INE (datos 2000–2007); Padrones municipales (para los datos 1-1-2008, de carácter provisional, pendientes de aprobación definitiva por parte del INE).
Source: (INE) (data 2000–2007); Municipal Register (for data 1-1-2008, provisional, still to be approved by the INE).

Table 4.38: Population Growth 2000-2008 in main Spanish cities (Source: Atlas Zaragoza, 2009).

In the case of 2009, the census showed a population of 693.086 and in 2010 the population was 696.656.This values were obtained from the City Statistics website (http://www.zaragoza.es/ciudad/estadistica/obtenerEvolucionPoblacion_Cifras). The growth of Zaragoza in the interval 2000 to 2010 was 92.025 persons which is a proportional variation of 15.22%. The population growth considered for this scenario is 16% until 2015. Then between 2015 and 2025 a smaller growth of 12% and between 2025 and 2030 a higher rate of 17%. At 2030, Zaragoza will be a million persons city. If those values are translated into an annual growth value, the value will be close to 1.41%.

Table 4.39 shows the calculated population projections.

Year	Projected Population
2015	808.121
2025	905.095
2030	1.058.962

Table 4.39: Population projections for the "Zaragoza Cares About Energy Emissions" scenario.
(Source: The Author)

The following are the values considered for the analysis

Variable	Units	Initial Value
Average system pressure	m	35
Number of Reported Burst and Leaks in Distribution Mains	Number	610
Number of Reported Bursts and leaks in Service Connections	Number	650
Percentage of rigid distribution mains	Percentage	0
Percentage of rigid service connections	Percentage	0
Repair time in distribution mains	Days	2
Repair time in service connections	Days	7
Volume per event in distribution mains	m^3/h	12
Volume per event in service connections	m^3/h	0.8

Table 4.40: Initial values used in the Reported burst volume in Distribution mains and Service connection section of the model for the "Zaragoza Cares About Energy Emissions" scenario.
(Source: The Author)

4.5.2 Average system pressure

The pressure management scheme has allowed a control of the pressure. There is a city wide system for pressure measurement and control. The removal of underground pressure break tanks in buildings has also helped in improving the system performance. A value of 35m will be used since it will be higher than the altitude difference of 31 m between Casablanca deposits (241 m above sea level) and the city average altitude (210 m above sea level).

4.5.3 Number of Reported Burst and Leaks in Distribution Mains

Considering a proportional relationship between population and number of leaks, for a population of 1.058.962 persons, the expected number of reported leaks is 460. However, the use of pressure measurements, higher sensibility in sensors, faster and cheaper computer power and the use of technology such as inverse transient and in-pipe leak detection have allowed a better performance in this field. A value of 610 (Considering an extra third of leaks being reported) will be used.

4.5.4 Number of Reported Bursts and leaks in Service Connections

The current average condition of service connections is 32.36 persons per service connection. A value of 30 persons per service connection in 2030 will be used since the city growth will be in apartment buildings. The total number of connection in 2030 will be 35.300. For a current number of 21530 service connections there is a value of 360 reported bursts and leaks in service connections. Using a linear relationship between connections and reported bursts, in 2030 there will be 590 reported bursts. A value of 650 will be used, since the use of better technology will improve the reporting of leaks.

4.5.5 Percentage of rigid distribution mains

The development of better materials and the pipe change policies will reduce the percentage of rigid service connections from 1.0% in 2010 to 0.0% in 2030.

4.5.6 Percentage of rigid service connections

The development of better materials and the pipe change policies will reduce the percentage of rigid service connections from 1.0% in 2010 to 0.0% in 2030.

4.5.7 Repair time in distribution mains

The repair time in distribution mains is down from 5 days in 2010 to 2 days in 2030 due to the increase in leak awareness and the reduction of detection and location time.

4.5.8 Repair time in service connections

The repair time in service connections is down from 15 days in 2010 to 7 days in 2030 due to the increase in leak awareness and the reduction of detection and location time

4.5.9 Volume per event in distribution mains

The current value of 12 m^3/h will be used.

4.5.10 Volume per event in service connections

The current value of 0.8 m^3/h will be used.

Variable	Units	Initial Value
Background leakage @ 50m pressure and ICF = 1.0 for Mains	l/km/h	20
Background leakage @ 50m pressure and ICF = 1.0 for service connections	l/connection/h	1.25
Distribution and transmission pipe length	Km	2025
FAVAD N1	Number	0.5
Number of days	Number	365
Number of service connections	Number	35.300
Predicted background leakage	Number	1
Unavoidable Annual Real Losses per metre of pressure for Distribution mains	l/km mains/Day/m	18
Unavoidable Annual Real Losses per metre of pressure for Service connections	l/connection/Day/m	0.8

Table 4.41: Initial values used in the Estimated background leakage section of the model for the "Zaragoza Cares About Energy Emissions" scenario
(Source: The Author)

4.5.11 Background leakage @ 50m pressure and ICF = 1.0 for Mains

The current value of 20 l/km/h will be used.

4.5.12 Background leakage @ 50m pressure and ICF = 1.0 for service connections

The current value of 1.25 l/conn/h will be used.

4.5.13 Distribution and transmission pipe length

For a current condition of 21.530 service connections, the value of distribution and transmission pipe would be 1.235 km. For 35.300 service connections, the pipe length will be 2025 km.

4.5.14 FAVAD N1

In this case the value is 0.5 since is for an average condition of the pipes (ICF = 1) (Fantozzi and Lambert, 2007).

4.5.15 Number of service connections

Calculated as 35.300 in the Number of Reported Bursts and leaks in Service Connections (Section 4.5.4).

4.5.16 Predicted background leakage Unavoidable Annual Real Losses per metre of pressure for Distribution mains

The current value of 18 l/km mains/Day/mca will be used.

4.5.17 Unavoidable Annual Real Losses per metre of pressure for Service connections

The current value of 0.8 l/connection/Day/mca will be used.

Variable	Units	Initial Value
Age of trunk mains	Years	15
Allowances for Real Losses from service reservoirs	m^3/km/Day	0
Trunk mains	km	391
Volume of service reservoirs	m^3	-

Table 4.42: Initial values used in the Trunk Mains and Service Reservoir Leakage section of the model for the "Zaragoza Cares About Energy Emissions" scenario.
(Source: The Author)

4.5.18 Age of trunk mains

Considering an on-going infrastructure investment since 2020, increasing specially from 2025, the average age of trunk mains is close to 15 years.

4.5.19 Allowances for Real Losses from service reservoirs

In this case, the water utility has established a policy value of no leakage in service reservoirs (0%) as the threshold. Again, the investment in control systems allows the fulfilment of this condition.

4.5.20 Trunk mains

For 1.235 km of distribution and transmission pipe, there would be 238.61 km of trunk mains. For 2025 km the pipe length will be 391 km.

4.5.21 Volume of service reservoirs

There are new service reservoirs in service. But considering that the leakage in the reservoirs is zero, this value is not obtained.

Variable	Units	Initial Value
Assumed Variable Cost of Water VC	Cost	1.3
Method of active leakage control	Cost/km	380

Table 4.43: Initial values used in the Economic Unreported Real Losses section of the model for the "Zaragoza Cares About Energy Emissions" scenario.
(Source: The Author)

4.5.22 Assumed Variable Cost of Water VC

The increase in the cost of water has not being only due to using water from wells but also to consider the use downstream of the Ebro River since not only Zaragoza uses it as a water source. The current value will be 1.3 Euros per cubic metre and the price change has been a gradual process in the course of the 20 years.

4.5.23 Rate of Rise RR

The Rate of Rise can be compared with the Rate of Rise for the Actur Area since the age of pipes is quite similar. However the replacement and investment in leakage control has improved it from 1057 m^3/day/yr to 750 m^3/day/yr.

4.5.24 Method of active leakage control

The calculation of the current cost of intervention for the Method of active leakage control considers a crew of 4 persons with a payroll cost of 200 Euros per day per person, an investment in transport and materials of 200 Euros per incident. Using the figures of the case study in Actur Area where to carry on the active leak detection in Sector 1 for 10.137 km it took 5 days using noise loggers, the cost of intervention per km is 414.32 Euros, which can be approximated to 410 Euros/km since there is an overestimation of the value of materials.

For this scenario, the crew of 4 persons is still considered, the cost per day is 450 Euros per day and the investment in transport and material is 300 Euros per incident. The active leak detection time for 10.137 km is 2 days so the Cost of intervention per km is 384.73 Euros, which can be approximated to 380 Euros per km.

Item	Units	Initial Value
Average Pipe Length Replaced Per Repair Event	m	2
Coefficient for Emission from Driving for Leakage Control	CO2/km	0.003
Coefficient for Emission from Pipe Lying	kgCO2e/m length of pipe	344
Coefficient for Emissions from Compressor Use	kg CO2/l	0.003
Coefficient for Emissions from Generator Use	kg CO2/l	0.003
Number of Repair Events	Number	1260
Volume of Fuel in Compressor Use	l	19517.40
Volume of Fuel in Generator Use	l	3946.70

Table 4.44: Initial values used in the Externalities section of the model for the "Zaragoza Cares about Energy Emissions" scenario.
(Source: The Author)

4.5.25 Emissions due to Labour, Commuting and Welfare

The current value of 6944 kg CO_2e per year will be used.

4.5.26 Distance Driven for Leakage Control

If the current Distance Driven for Leakage Control (48.879 km) is related to the current Number of Repair events (501), the average Distance Driven for Leakage Control will be 97.56 km per event.

Considering that all the Reported Bursts and Leaks in Distribution Mains and Service Connections are repaired, the number of repair events is 1260. This is the sum of the Number of Reported Burst and Leaks in Distribution Mains (610) and the Number of Reported Bursts and leaks in Service Connections (650). Then the Distance Driven for Leakage Control is 1260 events times 97.56 km per event which equals 122 925.6 km per year.

4.5.27 Coefficient for Emissions due to Driving for Leakage Control

The emissions in a diesel engine using diesel compared to the emissions of an engine using biodiesel will not be that different. What changes is the life cycle analysis since the crop used for the biodiesel crop soaked up carbon dioxide during growth the net emissions to the atmosphere are lower but it depends on which crop you have used and which production method used. The emissions savings can vary quite significantly depending on what crop is used.

The advantages of biodiesel are (Beer et al, 2001):

- It is a renewable bio-based fuel and, as such, has lower life cycle CO_2 emissions than diesel derived from mineral oils.
- Neat biodiesel contains almost no sulphur and no aromatics. In a properly tuned engine this is expected to lead to lower particle exhaust emissions.
- The material is bio-degradable and non-toxic.
- As an oxygenated compound, it reduces the non-soluble fraction of the particles.
- The PAH content of exhaust particles is reduced.
- In a mixture with low-sulphur diesel, biodiesel can act as a lubrication improver.
- The absence of sulphur makes oxidation catalysts more efficient.
- Existing diesel infrastructure could be converted to use biodiesel.
- Biodiesel can be used in existing diesel engines.

The value of emissions will depend on the type of biodiesel considered in the analysis. In this case Spain has a resource of rapeseed, with a production of 1100 lt of biodiesel per Ha compared with 420 lt of biodiesel per Ha by soy or 890 lt of biodiesel per Ha by sunflower (Campo, 2005). This makes rape seed a viable option as a source for biodiesel. Beer et al (2001) gives a value of 0.441 kg CO_2/km. This is a ″full fuel-cycle″ or the ‛‛well-to-wheel′′ emissions (even though the raw materials for biofuels do not come from wells) and considers the chain of feedstock production, feedstock transportation, fuel production, fuel distribution, and finally, vehicle use (ibid).

This contrasts with tailpipe emissions, which can be estimated fairly accurately from the carbon content of a particular fuel and the amount of fuel used per kilometre. In the case of this analysis, only the tailpipe emissions, like it was stressed in Section 3.15 (Calculation of Externalities), are considered. Beer et al (2001) describe the values of externalities before tailpipe emissions as 0.438 kg CO_2/km. This gives a value for tailpipe emissions of 0.003 kg CO_2/km.

4.5.28 Number of Repair Events

The number of repair events is 1260. This is the sum of the Number of Reported Burst and Leaks in Distribution Mains (610 in Section 4.5.3) and the Number of Reported Bursts and leaks in Service Connections (650 in Section 4.5.4).

4.5.29 Average Pipe Length Replaced Per Repair Event

The current value of 2 m will be used.

4.5.30 Coefficient for Emission from pipe lying

The current value of 344 kgCO_2e/m of pipe will be used.

4.5.31 Volume of fuel in Generator Use

If the current Volume of fuel in Generator Use (1955 l) is related to the current Number of Distribution Mains Repair (302), the average Volume of fuel in Generator Use will be 6.47 l per event.

Considering that only the Reported Bursts and Leaks in Distribution Mains require the use of generator in the repair, the Volume of fuel in Generator Use will be 6.47 l per event times 610 events which equals 3946.70 l.

4.5.32 Coefficient for Emissions from Generator Use

Biodiesel will be used for generator and compressors. A value of 0.003 kg CO_2/l will be considered for this item.

4.5.33 Volume of fuel in Compressor Use

If the current Volume of fuel in Compressor Use (7761 l) is related to the current Number of repair Events (501), the average Volume of fuel in Compressor Use will be 15.49 l per event.

Considering that all the Reported Bursts and Leaks in Distribution Mains and Service Connections require the use of compressor, the Volume of fuel in Compressor Use will be 15.49 l per event times 1260 events which equals 19517.40 l.

4.5.34 Coefficient for Emissions from Compressor Use

As mentioned in the coefficient for Emissions from Generator use, biodiesel will be used and the value of 0.003 kg CO_2/l will be considered for this item.

4.6 Results for Scenario One

If model is run with the initial data included in Tables 4.40 to 4.44, the results for the different leakage components are presented in Table 4.45:

Variable	Units	Initial Value
Economic Unreported Real Losses	m^3x10^3/yr	284.64
Trunk Mains and Service Reservoir Leakage	m^3x10^3/yr	293.99
Estimated Background Leakage for ICF= Predicted Background Leakage	m^3x10^3/yr	620.23
Reported Burst Volume in Distribution Mains and Service Connections	m^3x10^3/yr	256.94
Short-Run Economic Level of Leakage	m^3x10^3/yr	1455.80

Table 4.45: Initial leakage values for "Zaragoza Cares about Energy Emissions" scenario. (Source: The Author)

Table 4.46 resumes the externalities results in the model

Variable	Units	Initial Value
Emissions Due to Driving for Leakage Control	*kg CO_2/yr*	*368.78*
Emission from Pipe Lying	kg CO_2/yr	866,880
Emissions from Compressor Use	kg CO_2/yr	58.55
Emissions from Generator Use	kg CO_2/yr	11.84
Emissions from Repair Events	*kg CO_2/yr*	*866,950*
Emissions due to Labour, Commuting and Welfare	*kg CO_2/yr*	*6,944.00*
Estimated Emissions from Leakage Control	**kg CO_2/yr**	**874,263**
Cost of externalities	**Euros/km**	**45.33**

Table 4.46: Externalities values for "Zaragoza Cares About Energy Emissions" scenario. (Source: The Author)

Under this conditions, 874,263 kg CO2 will be emitted during the leak repair activities. This is equal to 874.263 tons per year. According to (DECC, 2009 and updated in 2010), the NTCP for 2030 will be 105 £/tCO2. This analysis considers the High NTCP to reflect the conditions of emission control. The total cost of externalities will be 91,797.62 £ per year. This value has to be added to the Intervention cost. The cost per km of distribution pipe will be 91,797.62/2025 = 45.33 Euros/km

Table 4.47 presents the results of the analysis and compares them with the initial leakage values from Table 4.45.

Variable	**Units**	**Initial Value**	**Considering externalities**
Economic Unreported Real Losses	m^3x10^3/yr	284.64	301.14
Trunk Mains and Service Reservoir Leakage	m^3x10^3/yr	293.99	293.99
Estimated Background Leakage for ICF= Predicted Background Leakage	m^3x10^3/yr	620.23	620.23
Reported Burst Volume in Distribution Mains and Service Connections	m^3x10^3/yr	256.94	256.94
Short-Run Economic Level of Leakage	m^3x10^3/yr	1455.80	1,472.30

Table 4.47: Leakage values considering externalities for "Zaragoza Cares about Energy Emissions" scenario.
(Source: The Author)

The volume difference in the ELL is 16.50 m^3x10^3/yr. This is equal to 1.12% of the initial value considered. In this case, the effect of the consideration of the externalities is really small. However the city will have the benefit of quantifying emissions in a really detailed way.

4.7 Scenario Two: Low Growth Rate in Zaragoza

4.7.1 Narrative

The current situation in 2030 made cities like Madrid and Barcelona the main employers since tourism is still the main industry in Spain.

Zaragoza is having problems with the water supply due to climate problems and currently works under an intermittent water supply condition. The melting of snow-caps in the Pyrenees altered the wind patterns which made the wind farming a non-viable option. The use of solar power was the next option with the problem of the space intensive use.

Leakage control is currently a priority for the city. Pressure management has been employed in the last 10 years but there is no money for pipe replacement. Water is expensive, energy is expensive and the growth in the city has been very slow.

The population growth considered for this scenario is a constant 0.75% per year. At 2030, Zaragoza will have a population of 808.946 habitants. The following are the values considered for the analysis.

Variable	Units	Initial Value
Average system pressure	M	35
Number of Reported Burst and Leaks in Distribution Mains	Number	351
Number of Reported Bursts and leaks in Service Connections	Number	450
Percentage of rigid distribution mains	Percentage	0.3
Percentage of rigid service connections	Percentage	0.3
Repair time in distribution mains	Days	5
Repair time in service connections	Days	15
Volume per event in distribution mains	m^3/h	12
Volume per event in service connections	m^3/h	0.8

Table 4.48: Initial values used in the Reported burst volume in Distribution mains and Service connection section of the model for the "Low Growth rate in Zaragoza" scenario.
(Source: The Author)

4.7.2 Average system pressure

The pressure management scheme has allowed a control of the pressure. A value of 35m will be used.

4.7.3 Number of Reported Burst and Leaks in Distribution Mains

Considering a proportional relationship between population and number of leaks, for a population of 808.946 persons, the expected number of reported leaks is 351.

4.7.4 Number of Reported Bursts and leaks in Service Connections

The current average condition of service connections is 32.36 persons per service connection. A value of 30 persons per service connection in 2030 will be used since the city growth will be in buildings. The total number of connections in 2030 will be 26.965. For a current number of 21.530 service connections the value of reported bursts and leaks in service connections is 360. In 2030 there will be 450.

4.7.5 Percentage of rigid distribution mains

0.3% of the system Distribution Mains is still rigid pipe.

4.7.6 Percentage of rigid service connections

0.3% of the system Service Connections is still rigid pipe.

4.7.7 Repair time in distribution mains

The repair time in distribution mains is still 5 days.

4.7.8 Repair time in service connections

The repair time in service connections is still 15 days.

4.7.9 Volume per event in distribution mains

The current value of 12 m^3/h will be used.

4.7.10 Volume per event in service connections

The current value of 0.8 m^3/h will be used.

Variable	Units	Initial Value
Background leakage @ 50m pressure and ICF = 1.0 for Mains	l/km/h	20
Background leakage @ 50m pressure and ICF = 1.0 for service connections	l/connection/h	1.25
Distribution and transmission pipe length	km	1.547
FAVAD N1	Number	0.5
Number of days	Number	365
Number of service connections	Number	26.965
Predicted background leakage	Number	1
Unavoidable Annual Real Losses per metre of pressure for Distribution mains	l/km mains/Day/m	18
Unavoidable Annual Real Losses per metre of pressure for Service connections	l/connection/Day/m	0.8

Table 4.49: Initial values used in the Estimated background leakage section of the model for the "Low Growth rate in Zaragoza" scenario
(Source: The Author)

4.7.11 Background leakage @ 50m pressure and ICF = 1.0 for Mains

The current value of 20 l/km/h will be used.

4.7.12 Background leakage @ 50m pressure and ICF = 1.0 for service connections

The current value of 1.25 l/conn/h will be used.

4.7.13 Distribution and transmission pipe length

For a current condition of 21.530 service connections, the value of distribution and transmission pipe would be 1.235 km. For 26.965 service connections the pipe length will be 1.547 km.

4.7.14 FAVAD N1

In this case the value is 0.5 since is for an average condition of the pipes (ICF = 1) (Fantozzi and Lambert, 2007).

4.7.15 Number of service connections

Calculated as 26.965 in the Number of Reported Bursts and leaks in Service Connections section.

4.7.16 Predicted background leakage Unavoidable Annual Real Losses per metre of pressure for Distribution mains

The current value of 18 l/km mains/Day/mca will be used.

4.7.17 Unavoidable Annual Real Losses per metre of pressure for Service connections

The current value of 0.8 l/connection/Day/mca will be used.

Variable	Units	Initial Value
Age of trunk mains	Years	25
Allowances for Real Losses from service reservoirs	m^3/km/Day	0
Trunk mains	km	300
Volume of service reservoirs	m^3	-

Table 4.50: Initial values used in the Trunk Mains and Service Reservoir Leakage section of the model for the "Low Growth rate in Zaragoza" scenario. (Source: The Author)

4.7.18 Age of trunk mains

Since infrastructure investment is not a priority, the average age of trunk mains is close to 25 years.

4.7.19 Allowances for Real Losses from service reservoirs

In this case, the water utility has established a policy value of no leakage in service reservoirs (0%) as the threshold.

4.7.20 Trunk mains

For 1.235 km of distribution and transmission pipe, there would be 238.61 km of trunk mains. For 1.547 km the pipe length will be 300 km.

4.7.21 Volume of service reservoirs

There are new service reservoirs in service. But considering that the leakage in the reservoirs is zero, this value is not obtained.

Variable	Units	Initial Value
Assumed Variable Cost of Water VC	Cost	1.5
Method of active leakage control	Cost/km	930

Table 4.51: Initial values used in the Economic Unreported Real Losses section of the model for the "Low Growth rate in Zaragoza" scenario.
(Source: The Author)

4.7.22 Assumed Variable Cost of Water VC

The increase in the cost of water has not being only due to using water from wells but also to consider the use downstream of the Ebro River since not only Zaragoza uses it as a water source. The current value will be 1.5 Euros per cubic metre and the price change has been a gradual process in the course of the 20 years.

4.7.23 Rate of Rise RR

The Rate of Rise can be compared with the Rate of Rise for the Actur Area since the age of pipes is quite similar. But the pipe condition hasn't improved and this is reflected in the RR with a value of 1057 m^3/day/yr in 2010 to 1250 m^3/day/yr.

4.7.24 Method of active leakage control

The calculation of the current cost of intervention for the Method of active leakage control considers a crew of 4 persons with a payroll cost of 200 Euros per day per person, a investment in transport and materials of 200 Euros per incident. Using the figures of the case study in Actur Area where to carry on the active leak detection in Sector 1 for 10.137 km it took 5 days using noise loggers, the cost of intervention per km is 414.32 Euros, which can be approximated to 410 Euros/km since there is an overestimation of the value of materials.

For this scenario, the crew of 4 persons is still considered, the cost per day is 450 Euros per day and the investment in transport and material is 450 Euros per incident. The active leak detection time for 10.137 km is 5 days so the Cost of intervention per km is 932.23 Euros, which can be approximated to 930 Euros per km.

Item	Units	Initial Value
Average Pipe Length Replaced Per Repair Event	M	2
Coefficient for Emission from Driving for Leakage Control	CO2/km	0.003
Coefficient for Emission from Pipe Lying	kgCO2e/m length of pipe	344
Coefficient for Emissions from Compressor Use	kg CO2/l	0.003
Coefficient for Emissions from Generator Use	kg CO2/l	0.003
Number of Repair Events	Number	801
Volume of Fuel in Compressor Use	l	12407.49
Volume of Fuel in Generator Use	l	2270.97

Table 4.52: List of externalities that remain constant during externality analysis in the "Low Growth rate in Zaragoza" model.
(Source: The Author)

4.7.25 Emissions due to Labour, Commuting and Welfare

The current value of 6944 kg CO_2e per year will be used.

4.7.26 Distance Driven for Leakage Control

If the current Distance Driven for Leakage Control (48.879 km) is related to the current Number of Repair events (501), the average Distance Driven for Leakage Control will be 97.56 km per event.

Considering that all the Reported Bursts and Leaks in Distribution Mains and Service Connections are repaired, the number of repair events is 801. This is the sum of the Number of Reported Burst and Leaks in Distribution Mains (351) and the Number of Reported Bursts and leaks in Service Connections (450).

Then the Distance Driven for Leakage Control is 801 events times 97.56 km per event which equals 78145.56 km per year.

4.7.27 Coefficient for Emissions due to Driving for Leakage Control

The value of 0.003 kg CO2/km will be used.

4.7.28 Number of Repair Events

The number of repair events is 801.

4.7.29 Average Pipe Length Replaced Per Repair Event

The current value of 2 m will be used.

4.7.30 Coefficient for Emission from pipe lying

The current value of 344 $kgCO_2e/m$ of pipe will be used.

4.7.31 Coefficient for Emissions from Generator Use

0.003 kg CO_2/l will be considered for this item since the generators use biofuel.

4.7.32 Volume of fuel in Compressor Use

If the current Volume of fuel in Compressor Use (7761 l) is related to the current Number of repair Events (501), the average Volume of fuel in Compressor Use will be 15.49 l per event.

Considering that all the Reported Bursts and Leaks in Distribution Mains and Service Connections require the use of compressor, the Volume of fuel in Compressor Use will be 15.49 l per event times 801 events which equals 12407.49 l.

4.7.33 Volume of fuel in Generator Use

If the current Volume of fuel in Generator Use (1955 l) is related to the current Number of Distribution Mains Repair (302), the average Volume of fuel in Generator Use will be 6.47 l per event.

Considering that only the Reported Bursts and Leaks in Distribution Mains require the use of generator in the repair, the Volume of fuel in Generator Use will be 6.47 l per event times 351 events which equals 2270.97 l.

4.7.34 Coefficient for Emissions from Compressor Use

As mentioned in the coefficient for Emissions from Generator use, biodiesel will be used and the value of 0.003 kg CO_2/l will be considered for this item

4.8 Results for Scenario Two

If model is run with the initial data included in Tables 4.48 to 4.52 the results for the different leakage components are presented in Table 4.53:

Variable	Units	Initial Value
Economic Unreported Real Losses	m^3x10^3/yr	467.76
Trunk Mains and Service Reservoir Leakage	m^3x10^3/yr	313.17
Estimated Background Leakage for ICF= Predicted Background Leakage	m^3x10^3/yr	473.8
Reported Burst Volume in Distribution Mains and Service Connections	m^3x10^3/yr	413.92
Short-Run Economic Level of Leakage	m^3x10^3/yr	1,668.65

Table 4.53: Initial leakage values for "Low Growth rate in Zaragoza" scenario. (Source: The Author)

Table 4.54 resumes the externalities results in the model

Variable	Units	Initial Value
Emissions Due to Driving for Leakage Control	*Kg CO_2/yr*	*234.44*
Emission from Pipe Lying	Kg CO_2/yr	551,088
Emissions from Compressor Use	Kg CO_2/yr	37.22
Emissions from Generator Use	Kg CO_2/yr	6.813
Emissions from Repair Events	*kg CO_2/yr*	*551,132*
Emissions due to Labour, Commuting and Welfare	*kg CO_2/yr*	*6,944.00*
Estimated Emissions from Leakage Control	**kg CO_2/yr**	**558,310.47**
Cost of externalities	**Euros/km**	**45.33**

Table 4.54: Externalities values for "Low Growth rate in Zaragoza" scenario. (Source: The Author)

Under this conditions, 558,310.47 kg CO_2 will be emitted during the leak repair activities. This is equal to 558.310 tons per year. According to (DECC, 2009 and updated in 2010), the NTCP for 2030 will be 105 £/tCO_2. The analysis considers the High NTCP to reflect the conditions of emission control. The total cost of externalities will be 58,622.60 £ per year. This value has to be added to the Intervention cost. The cost per km of distribution pipe will be 58,622.60/1547 = 37.89 Euros/km

Table 4.55 presents the results of the analysis and compares them with the initial leakage values from Table 4.53:

Variable	Units	Initial Value	Considering externalities
Economic Unreported Real Losses	m^3x10^3/yr	467.76	477.20
Trunk Mains and Service Reservoir Leakage	m^3x10^3/yr	313.17	313.17
Estimated Background Leakage for ICF= Predicted Background Leakage	m^3x10^3/yr	473.8	473.80
Reported Burst Volume in Distribution Mains and Service Connections	m^3x10^3/yr	413.92	413.92
Short-Run Economic Level of Leakage	m^3x10^3/yr	1,668.65	1,678.09

Table 4.55: Leakage values considering externalities for "Low Growth rate in Zaragoza" scenario.
(Source: The Author)

The volume difference in the ELL is 9.44 m^3x10^3/yr. This is equal to 0.56% of the initial value considered. In this case, the effect of the consideration of the externalities is really small.

4.9 Scenario Three: Business as Usual in Zaragoza

4.9.1 Narrative

The population growth considered for this scenario is a constant 1.2% per year, calculated from official city statistics. At 2030, Zaragoza will have a population of 884.359 habitants.

The following are the values considered for the analysis

Variable	Units	Initial Value
Average system pressure	m	40
Number of Reported Burst and Leaks in Distribution Mains	Number	510
Number of Reported Bursts and leaks in Service Connections	Number	520
Percentage of rigid distribution mains	Percentage	0
Percentage of rigid service connections	Percentage	0
Repair time in distribution mains	Days	4
Repair time in service connections	Days	11
Volume per event in distribution mains	m^3/h	12
Volume per event in service connections	m^3/h	0.8

Table 4.56: Initial values used in the Reported burst volume in Distribution mains and Service connection section of the model for the "Business as Usual in Zaragoza" scenario.
(Source: The Author)

4.9.2 Average system pressure

The pressure management scheme has allowed a control of the pressure. A value of 40m will be used.

4.9.3 Number of Reported Bursts and leaks in Distribution Mains

Considering a proportional relationship between population and number of leaks, for a population of 884.359 persons, the expected number of reported leaks is 383. However, the use of pressure measurements, higher sensibility in sensors, faster and cheaper computer power and the use of technology such as inverse transient and in-pipe leak detection have allowed a better performance in this field. A value of 510 (Considering an extra third of leaks being reported) will be used.

4.9.4 Number of Reported Bursts and leaks in Service Connections

The current average condition of service connections is 32.36 persons per service connection. A value of 30 persons per service connection in 2030 will be used since the city growth will be in apartment buildings. The total number of connection in 2030 will be 29.480. For a current number of 21530 service connections there is a value of 360 reported bursts and leaks in service connections. Using a linear relationship between connections and reported bursts, in 2030 there will be 493 reported bursts. A value of 520 will be used, since the use of better technology will improve the reporting of leaks.

4.9.5 Percentage of rigid distribution mains

The development of better materials and the pipe change policies will reduce the percentage of rigid service connections from 1.0% in 2010 to 0.0% in 2030.

4.9.6 Percentage of rigid service connections

The development of better materials and the pipe change policies will reduce the percentage of rigid service connections from 1.0% in 2010 to 0.0% in 2030.

4.9.7 Repair time in distribution mains

The repair time in distribution mains is down from 5 days in 2010 to 4 days in 2030 due to the increase in leak awareness and the reduction of detection and location time.

4.9.8 Repair time in service connections

The repair time in service connections is down from 15 days in 2010 to 11 days in 2030 due to the increase in leak awareness and the reduction of detection and location time.

4.9.9 Volume per event in distribution mains

The current value of 12 m^3/h will be used.

4.9.10 Volume per event in service connections

The current value of 0.8 m^3/h will be used.

Variable	Units	Initial Value
Background leakage @ 50m pressure and ICF = 1.0 for Mains	l/km/h	20
Background leakage @ 50m pressure and ICF = 1.0 for service connections	l/connection/h	1.25
Distribution and transmission pipe length	km	1,691
FAVAD N1	Number	0.5
Number of days	Number	365
Number of service connections	Number	29,480
Predicted background leakage	Number	1
Unavoidable Annual Real Losses per metre of pressure for Distribution mains	l/km mains/Day/m	18
Unavoidable Annual Real Losses per metre of pressure for Service connections	l/connection/Day/m	0.8

Table 4.57: Initial values used in the Estimated background leakage section of the model for the "Business as Usual in Zaragoza" scenario
(Source: The Author)

4.9.11 Background leakage @ 50m pressure and ICF = 1.0 for Mains

The current value of 20 l/km/h will be used.

4.9.12 Background leakage @ 50m pressure and ICF = 1.0 for service connections

The current value of 1.25 l/conn/h will be used.

4.9.13 Distribution and transmission pipe length

For a current condition of 21.530 service connections, the value of distribution and transmission pipe would be 1.235 km. For 29,480 service connections the pipe length will be 1,691 km.

4.9.14 FAVAD N1

In this case the value is 0.5 since is for an average condition of the pipes (ICF = 1) (Fantozzi and Lambert, 2007).

4.9.15 Number of service connections

Calculated as 29,480 in the Number of Reported Bursts and leaks in Service Connections section.

4.9.16 Predicted background leakage Unavoidable Annual Real Losses per metre of pressure for Distribution mains

The current value of 18 l/km mains/Day/mca will be used.

4.9.17 Unavoidable Annual Real Losses per metre of pressure for Service connections

The current value of 0.8 l/connection/Day/mca will be used.

Variable	Units	Initial Value
Age of trunk mains	Years	18
Allowances for Real Losses from service reservoirs	m^3/km/Day	0
Trunk mains	km	327
Volume of service reservoirs	m^3	-

Table 4.58: Initial values used in the Trunk Mains and Service Reservoir Leakage section of the model for the "Business as Usual in Zaragoza" scenario. (Source: The Author)

4.9.18 Age of trunk mains

The average age of trunk mains is close to 18 years.

4.9.19 Allowances for Real Losses from service reservoirs

In this case, the water utility has established a policy value of no leakage in service reservoirs (0%) as the threshold.

4.9.20 Trunk mains

For 1.235 km of distribution and transmission pipe, there would be 238.61 km of trunk mains. For 2025 km the pipe length will be 391 km.

4.9.21 Volume of service reservoirs

There are new service reservoirs in service. But considering that the leakage in the reservoirs is zero, this value is not obtained.

Variable	Units	Initial Value
Assumed Variable Cost of Water VC	Cost	1.05
Method of active leakage control	Cost/km	930

Table 4.59: Initial values used in the Economic Unreported Real Losses section of the model for the "Business as Usual in Zaragoza" scenario. (Source: The Author)

4.9.22 Assumed Variable Cost of Water VC

The increase in the cost of water has not being only due to using water from wells but also to consider the use downstream of the Ebro River since not only Zaragoza uses it as a water source. The current value will be 1.05 Euros per cubic metre and the price change has been a gradual process in the course of the 20 years.

4.9.23 Rate of Rise RR

The Rate of Rise has changed from 1057 m^3/day/yr in 2010 to 850 m^3/day/yr.

4.9.24 Method of active leakage control

The calculation of the current cost of intervention for the Method of active leakage control considers a crew of 4 persons with a payroll cost of 200 Euros per day per person, an investment in transport and materials of 200 Euros per incident. Using the figures of the case study in Actur Area where to carry on the active leak detection in Sector 1 for 10.137 km it took 5 days using noise loggers, the cost of intervention per km is 414.32 Euros, which can be approximated to 410 Euros/km since there is an overestimation of the value of materials.

For this scenario, the crew of 4 persons is still considered, the cost per day is 450 Euros per day and the investment in transport and material is 450 Euros per incident. The active leak detection time for 10.137 km is 5 days so the Cost of intervention per km is 932.23 Euros, which can be approximated to 930 Euros per km.

Item	Units	Initial Value
Average Pipe Length Replaced Per Repair Event	m	2
Coefficient for Emission from Driving for Leakage Control	CO2/km	0.003
Coefficient for Emission from Pipe Lying	kgCO2e/m length of pipe	344
Coefficient for Emissions from Compressor Use	kg CO2/l	0.003
Coefficient for Emissions from Generator Use	kg CO2/l	0.003
Number of Repair Events	Number	1030
Volume of Fuel in Compressor Use	l	15,954.70
Volume of Fuel in Generator Use	l	3299.70

Table 4.60: List of externalities that remain constant during externality analysis in the Zaragoza model.
(Source: The Author)

4.9.25 Emissions due to Labour, Commuting and Welfare

The current value of 6944 kg CO_2e per year will be used.

4.9.26 Distance Driven for Leakage Control

If the current Distance Driven for Leakage Control (48.879 km) is related to the current Number of Repair events (501), the average Distance Driven for Leakage Control will be 97.56 km per event.

Considering that all the Reported Bursts and Leaks in Distribution Mains and Service Connections are repaired, the number of repair events is 1030. This is the sum of the Number of Reported Burst and Leaks in Distribution Mains (510) and the Number of Reported Bursts and leaks in Service Connections (520).

Then the Distance Driven for Leakage Control is 1030 events times 97.56 km per event which equals 100486.8 km per year.

4.9.27 Coefficient for Emissions due to Driving for Leakage Control

The value of 0.003 kg CO_2/km will be used.

4.9.28 Number of Repair Events

The number of repair events is 1030.

4.9.29 Average Pipe Length Replaced Per Repair Event

The current value of 2 m will be used.

4.9.30 Coefficient for Emission from pipe lying

The current value of 344 kgCO_2e/m of pipe will be used.

4.9.31 Volume of fuel in Generator Use

If the current Volume of fuel in Generator Use (1955 l) is related to the current Number of Distribution Mains Repair (302), the average Volume of fuel in Generator Use will be 6.47 l per event.

Considering that only the Reported Bursts and Leaks in Distribution Mains require the use of generator in the repair, the Volume of fuel in Generator Use will be 6.47 l per event times 510 events which equals 2,299.70 l.

4.9.32 Coefficient for Emissions from Generator Use

0.003 kg CO_2/l will be considered for this item since the generators use biofuel.

4.9.33 Volume of fuel in Compressor Use

If the current Volume of fuel in Compressor Use (7761 l) is related to the current Number of repair Events (501), the average Volume of fuel in Compressor Use will be 15.49 l per event.

Considering that all the Reported Bursts and Leaks in Distribution Mains and Service Connections require the use of compressor, the Volume of fuel in Compressor Use will be 15.49 l per event times 1030 events which equals 15,954.70 l.

4.9.34 Coefficient for Emissions from Compressor Use

As mentioned in the coefficient for Emissions from Generator use, biodiesel will be used and the value of 0.003 kg CO_2/l will be considered for this item

4.10 Results for Scenario Three

If model is run with the initial data included in Tables 4.56 to 4.60, the results for the different leakage components are presented in Table 4.61:

Variable	Units	Initial Value
Economic Unreported Real Losses	m^3x10^3/yr	482.01
Trunk Mains and Service Reservoir Leakage	m^3x10^3/yr	274.52
Estimated Background Leakage for ICF= Predicted Background Leakage	m^3x10^3/yr	553.71
Reported Burst Volume in Distribution Mains and Service Connections	m^3x10^3/yr	498.98
Short-Run Economic Level of Leakage	m^3x10^3/yr	1,809.22

Table 4.61: Initial leakage values for “Business as Usual in Zaragoza” scenario. (Source: The Author)

Table 4.62 resumes the externalities results in the model

Variable	Units	Initial Value
Emissions Due to Driving for Leakage Control	*Kg CO2/yr*	*301.46*
Emission from Pipe Lying	Kg CO2/yr	708,640
Emissions from Compressor Use	Kg CO2/yr	47.86
Emissions from Generator Use	Kg CO2/yr	9.899
Emissions from Repair Events	*kg CO2/yr*	*708,698*
Emissions due to Labour, Commuting and Welfare	*kg CO2/yr*	*6,944.00*
Estimated Emissions from Leakage Control	**kg CO_2/yr**	**715,943.22**
Cost of externalities	**Euros/km**	**45.33**

Table 4.62: Externalities values for “Business as Usual Zaragoza” scenario. (Source: The Author)

Under this conditions, 715,943.22 kg CO_2 will be emitted during the leak repair activities. This is equal to 715.943 tons per year. According to (DECC, 2009 and updated in 2010), the NTCP for 2030 will be 105 £/tCO_2. The analysis considers the High NTCP to reflect the conditions of emission control. The total cost of externalities will be 75,174.04 £ per year. This value has to be added to the Intervention cost. The cost per km of distribution pipe will be 75,174.04/1,691 = 44.46 Euros/km

Table 4.63 presents the results of the analysis and compares them with the initial leakage values from Table 4.61.

Variable	Units	Initial Value	Considering externalities
Economic Unreported Real Losses	m^3x10^3/yr	482.01	493.40
Trunk Mains and Service Reservoir Leakage	m^3x10^3/yr	274.52	274.52
Estimated Background Leakage for ICF= Predicted Background Leakage	m^3x10^3/yr	553.71	553.71
Reported Burst Volume in Distribution Mains and Service Connections	m^3x10^3/yr	498.98	498.98
Short-Run Economic Level of Leakage	m^3x10^3/yr	1,809.22	1,820.61

Table 4.63: Leakage values considering externalities for "Business as Usual Zaragoza" scenario.
(Source: The Author)

The volume difference in the ELL is 11.39 m^3x10^3/yr. This is equal to 0.62% of the initial value considered. In this case, the effect of the consideration of the externalities is really small. The impact of considering externalities in the ELL is minimum.

4.11 Variables for Sensitivity Analysis

The change of specific variable values can change the performance of the model described in Chapter 3. However, this changes do not occur for all the variables. It is the structure of the system, and not the parameter values, that has most influence on the behaviour of the system (Breierova and Choudhari, 2001).

The idea with the Sensitivity Analysis is to determine how the system reacts to a change in a parameter value, so in that way it reduces the modeller's uncertainty in the behaviour. Also it allows a better understanding of the dynamic behaviour of the system. In the case of this model, the focus is on parameter sensitivity. Parameter sensitivity is usually performed as a series of tests in which the modeller sets different parameter values to see how a change in the parameter causes a change in the dynamic behaviour of the stocks. (ibid).

4.11.1 Initial considerations

Statistical screening uses multiple simulations generated by varying model input parameters to calculate linear correlation coefficients that measure the direction and strength of the relationship between input parameters and a user-defined system performance variable (Ford and Flynn, 2005). This correlation coefficient values vary between −1 and +1, with the polarity denoting the direction of impact in the same manner as causal link polarity.

A value of "1" in a correlation coefficient means a perfect correlation with the performance variable, a value of "0" indicates no correlation and a value of "-1" indicates a perfectly inverse correlation.

The six steps for improving model understanding using statistical screening are (ibid):

1. Select a specific set of exogenous model parameters and a performance variable for analysis. Select ranges of possible exogenous parameter values based on an understanding of the real system.

When considering the ELL model, certain initial variables are used in more equations than others. It is important to mention how the Graphic User Interface of Vensim makes easier to identify these variables. In order of number of equations used, the following variables are identified:

- Pipe Length: 9 Equations
- Pressure: 7 Equations
- Number of Service Connections: 5 Equations
- Cost Single Intervention: 5 Equations
- Water Cost: 5 Equations
- Number of Reported Burst and Leaks in Distribution Mains: 2 Equations
- Number of Reported Burst and Leaks in Service Connections: 2 Equations

Because we want to consider the effect of the interventions on the current condition of the system, Pipe Length and Number of Service Connections remain constant during the analysis.

Pressure is the most important variable to consider. Since Zaragoza lacks a proper way to read pressures, this also can be used as an argument for investing in pressure metering of the system.

The cost of Intervention per km depends on the cost of the survey crew, transport and materials and the pipe length. So a change in the cost of the repair crew can have an effect on the model. Also the change in the number of repair and replacement events can affect the results of the model since the reported leakage volume will change. The objective is to know the impact of this variable.

In the case of the Reported Burst and Leaks by themselves, these variables actually affect the Reported Burst Volume calculation. But the interest is in see how the volume changes in relation with the amount of reported leaks.

2. Perform statistical screening of the model to calculate correlation coefficients for the selected exogenous model parameters. Plot both the correlation coefficients and the behaviour of the performance variable over time.

The statistical screening of the model is the process of changing your assumptions about the value of Constants in the model and examining the resulting output for change in values (Vensim, 1999). Manual sensitivity testing involves changing the value of a Constant (or several Constants at once) and simulating, then changing the value of the Constant again and simulating again, and repeating this action many times to get a spread of output values.

The advantage of modelling in Vensim is to automatize this process using Monte Carlo simulation. Hundreds or even thousands of simulations can be performed, with Constants sampled over a range of values, and output stored for later analysis.

Maximum and minimum values are assigned to the variables to be analysed, along with a probability distribution over which to vary them to see their impact on the model behaviour. There are two options for the probability distribution:

The simplest distribution is the Random Uniform Distribution, in which any number between the minimum and maximum values is equally likely to occur. Another commonly-used distribution is the Normal Distribution in which values near the mean or more likely to occur than values far from the mean.

Since the Normal Distribution requires the specification of a standard deviation that is not available, the distribution to be used is the Random Uniform.

3. Select a time period for analysis by examining time series of the performance variable and the correlation coefficients.

Since the ELL model considers the current condition of the system, the performance will not vary during time. So the consideration of the time period in the step 3 will be only for the current condition or the time frame the different variables are considered.

4. Create a list of high-leverage parameters. High-leverage parameters are the parameters with the highest absolute correlation coefficient values during the selected time period.

5. Identify the high-leverage model structure(s) for each parameter identified in step 4 as those that are directly connected to the high-leverage parameter. If multiple parameters from step 4 are directly connected to the same model structure, add each parameter set to the list.

6. Use additional structure–behaviour analysis methods (e.g. verbal reasoning, scenario analysis, and behavioural analysis) to explain how each parameter or set of parameters and the structures they influence drive the behaviour of the system. In this case data collected in Zaragoza will be used to analyse this influence.

In the following sections, if the correlation between the variable under analysis and the different leakage components calculated is considered, it can be expressed as:

$$Leakage\ Component = F(\mathrm{variable})$$

$$d(Leakage\ Component) = d(\mathrm{variable})$$

Equation 4.2: (Source: The Author)

4.11.2 Rate of Rise

The current value for Rate of Rise is 1057 m3/day/yr. Considering an interval of 500 to 5000 m3/day/yr and 5000 simulations, the Table 4.64 shows the results for the sensitivity analysis, done using Excel.

Variables	Correlation coefficient
Economic Unreported Real Losses	0.991
Estimated Background Leakage for ICF= Predicted Background Leakage	0.000
Reported burst volume in Distribution mains and Service connections	0.000
Trunk Mains and Service Reservoir Leakage	0.000
Short-Run Economic Level of Leakage	0.991

Table 4.64: Correlation coefficients for Rate of Rise sensitivity analysis and the different leakage components
(Source: The Author)

There is a strong correlation between Rate of Rise and Economic Unreported Real Losses (correlation coefficient = 0.991743) and between Rate of Rise and SRELL (correlation coefficient = 0.991743).

Considering the equation for Economic Unreported Real Losses in section 3.14.9 where

$$EURL = \frac{CI \cdot Lm \cdot EP}{CV}$$

Equation 4.3: (Source: Lambert, 1999)

Where CI is the Cost of one 'whole system' intervention, excluding cost of repairs, EP is the Economic Percentage of system to be surveyed, Lm is the Distribution and Transmission Pipe Length and CV is the Assumed Variable Cost of Water.

The EP is obtained as described in section 3.14.6

$$\mathrm{EP} = \frac{1}{\mathrm{EIF}}$$

Equation 4.4: (Source: Lambert, 1999)

Where EIF is the Economic Intervention Frequency. EIF is obtained as described in section 3.14.5

$$\mathrm{EIF} = \sqrt{\frac{\mathrm{CI}}{0.5 \cdot \mathrm{CV} \cdot \mathrm{RR} \cdot 365}}$$

Equation 4.5: (Source: Lambert, 1999)

Then EP can be expressed as

$$\mathrm{EP}=\sqrt{\frac{\mathrm{CV}\cdot 0.5\cdot \mathrm{RR}\cdot 365}{\mathrm{CI}}}$$

Equation 4.6: (Source: The Author)

The EURL, expressed in function of the RR will be

$$EURL=\frac{CI\cdot Lm\cdot\sqrt{\frac{0.5\cdot CV\cdot RR\cdot 365}{CI}}}{CV}$$

$$\frac{\partial(EURL)}{\partial(RR)}=\frac{CI\cdot CV\cdot Lm\frac{\frac{182.5\cdot CI\cdot CV}{\sqrt{CI}}}{2\sqrt{\frac{182.5\cdot CV\cdot RR}{CI}}}}{\sqrt{CV}}$$

$$\frac{\partial(EURL)}{\partial(RR)}=\frac{CI\cdot CV\cdot Lm\cdot\frac{91.25\cdot CI\cdot CV}{\sqrt{182.5\cdot CV\cdot RR}}}{\sqrt{CV}}$$

$$\frac{\partial(EURL)}{\partial(RR)}=\frac{91.25\cdot CI\cdot CV\cdot Lm\cdot CI}{\sqrt{182.5\cdot RR}}$$

$$\frac{\partial(EURL)}{\partial(RR)}=\frac{91.25\cdot CI\cdot CV\cdot Lm\cdot CI}{\sqrt{182.5\cdot RR}}$$

$$\frac{\partial(EURL)}{\partial(RR)}=\frac{91.25\cdot CI\cdot CV\cdot Lm\cdot CI}{\sqrt{182.5\cdot RR}}\cdot\frac{\sqrt{182.5\cdot RR}}{\sqrt{182.5\cdot RR}}$$

$$\frac{\partial(EURL)}{\partial(RR)}=\frac{91.25\cdot CI\cdot CV\cdot Lm\cdot CI\cdot\sqrt{182.5\cdot RR}}{182.5\cdot RR}$$

$$\frac{\partial(EURL)}{\partial(RR)}=\frac{6.754628\cdot CI^{2}\cdot CV\cdot Lm\cdot\sqrt{RR}}{RR}$$

Equation 4.7: (Source: The Author)

In the case of the Estimated Background Leakage for ICF= Predicted Background Leakage, Reported Burst volume in Distribution Mains and Service Connections and the Trunk Mains and Service Reservoir Leakage, RR is not a variable. Then the derivative of this function will be 0. This means that the values will remind constant during this analysis. For example: The Trunk Mains and Service Reservoir Leakage will remind constant under the analysis because the trunk leakage considered in this component considers the age of trunks for the calculation of the allowances, it's not affected directly by the RR in the system.

The results of the simulations can be consolidated in tabular form in Table 4.65.

Average rate of rise of unreported leakage RR	**Economic Unreported Real Losses (m^3x10^3/yr)**	**Estimated Background Leakage for ICF= Predicted Background Leakage (m^3x10^3/yr))**	**Reported burst volume in Distribution mains and Service connections (m^3x10^3/yr)**	**Trunk Mains and Service Reservoir Leakage (m^3x10^3/yr)**	**Short-Run Economic Level of Leakage (m^3x10^3/yr)**
500	250.90	405.41	482.91	384.48	1523.69
950	345.84	405.41	482.91	384.48	1618.63
1400	419.83	405.41	482.91	384.48	1692.63
1850	482.61	405.41	482.91	384.48	1755.41
2300	538.12	405.41	482.91	384.48	1810.91
2750	588.41	405.41	482.91	384.48	1861.2
3200	634.73	405.41	482.91	384.48	1907.52
3650	677.89	405.41	482.91	384.48	1950.68
4100	718.46	405.41	482.91	384.48	1991.26
4550	756.86	405.41	482.91	384.48	2029.66
4999	793.33	405.41	482.91	384.48	2066.12

Table 4.65: Sample of sensitivity analysis data for Rate of Rise
(Source: The Author)

Figure 4.5 presents the information of Table 4.65.

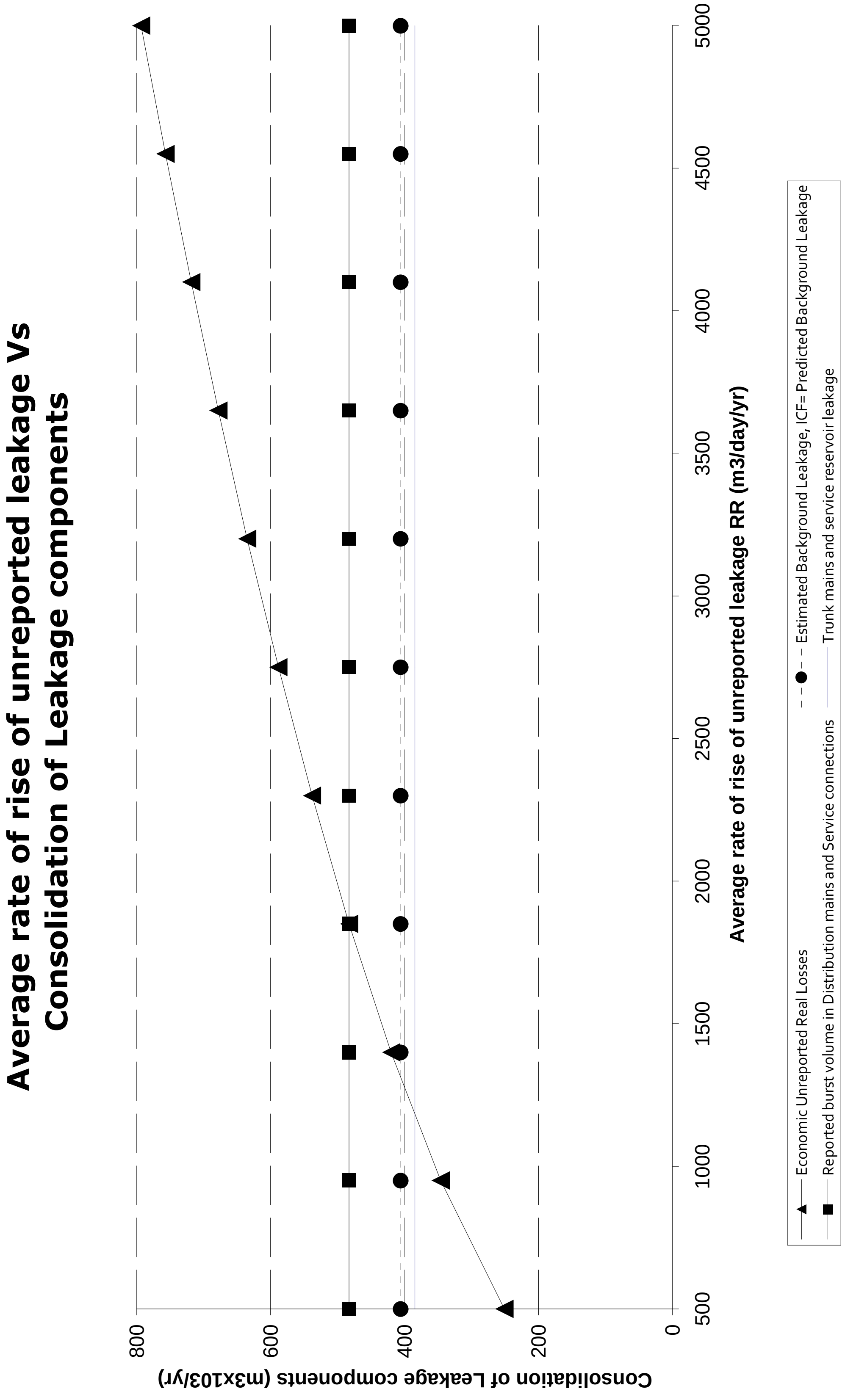


Figure 4.5: Consolidation of leakage components for Rate of Rise sensitivity analysis (Source: The Author)

Considering the Rate of Rise, there's a threshold value close to 1800 where the value of the Economic Unreported Real Losses starts to be the higher volume in the leakage components. This will correspond to a system with no maintenance and no leak control. So for Rate of Rise values smaller than this threshold value, it's better for the water utility to invest in the control of Estimated Background Leakage for ICF= Predicted Background Leakage, Reported burst volume in Distribution mains and Service connections and Trunk Mains and Service Reservoir Leakage. In the case of a Rate of Rise of 5000, the value of Economic Unreported Real Losses is almost the double of any other component.

Finally Figure 4.6 shows the SRELL results for this analysis.

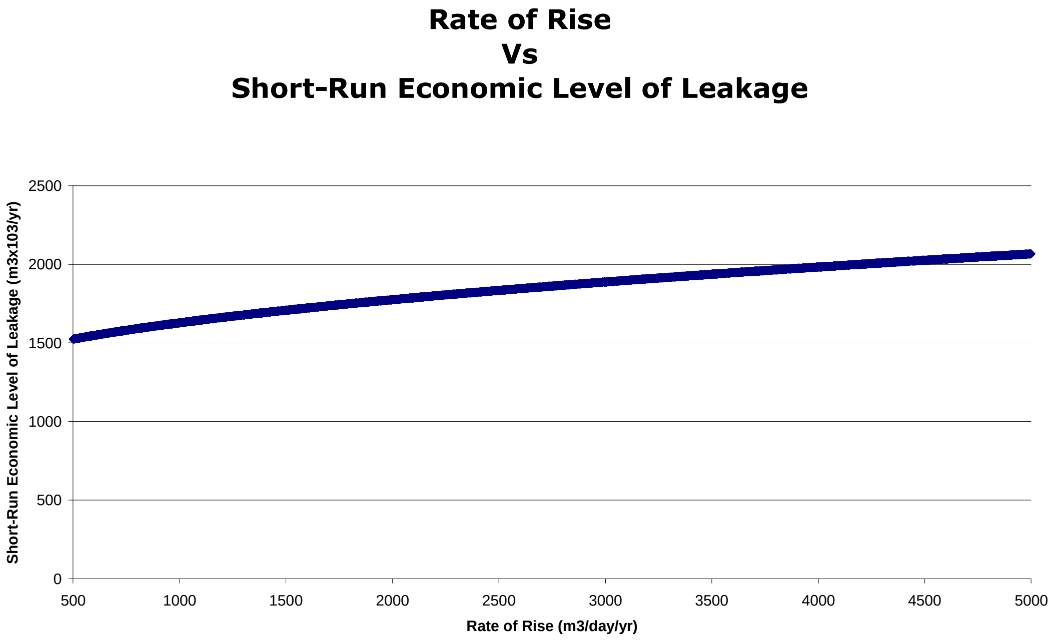


Figure 4.6: Rate of Rise vs. Short-Run Economic Level of Leakage. (Source: The Author).

These results show how to have a reliable value for the RR is an important requirement for this analysis. The need of field data on the subject is recommended.

4.11.3 Pressure

For pressure, the Spanish Law Real Decreto 314/2006, de 17 de marzo (Royal Decree 314/2006 from March 17th) aproves the Technical building code. In the appendix HS 4 (Water supply), Section 2.1.3 it states:

2 En los puntos de consumo la presión mínima debe ser:
a) 100 kPa para grifos comunes;
b) 150 kPa para fluxores y calentadores.

3 La presión en cualquier punto de consumo no debe superar 500 kPa.

(2 In consumption points, the minimum pressure must be
100 kPa for water faucets
150 kPa for WC flush valves and water heaters

3 The pressure in any consumption point can't be higher than 500 kPa)

100 kPa equals to 10.21 m of water column and 500 kPa equals 50.90 m of water column. However these values are for consumption points and the pressures in the water distribution system can be higher.

Zaragoza is a plain city and the main part of the city is a gravity fed system. From the Casablanca deposits (241 m above sea level) to the city average altitude (210 m above sea level) the altitude difference is 31 m. The highest tank in the system is the Academia (282 m above sea level) and is fed from the Los Leones tank (226.5 m above sea level). This is a difference of 55.5 m.

So an interval from 10.21 to 55.5 m of water column can be used as a guideline for the analysis. All the altitude information was obtained from the water utility.

The current value for Average System Pressure is 40.2 m. Considering an interval of 10.21 to 55.5 and 5000 simulations, the Table 4.66 shows the results for the sensitivity analysis, done using Excel.

Variables	Correlation coefficient
Economic Unreported Real Losses	0.000
Estimated Background Leakage for ICF= Predicted Background Leakage	0.994
Reported burst volume in Distribution mains and Service connections	0.994
Trunk Mains and Service Reservoir Leakage	0.000
Short-Run Economic Level of Leakage	0.994

Table 4.66: Correlation coefficients for Average System Pressure sensitivity analysis and the different leakage components
(Source: The Author)

There is a strong correlation between Average System Pressure and Estimated Background Leakage for ICF= Predicted Background Leakage, Reported burst volume in Distribution mains and Service connections and Short-Run Economic

Level of Leakage. This makes sense since this background leakage and reported burst leakage components use pressure as one of the variables in their calculation.

In the case of the Estimated Background Leakage for ICF = Predicted Background Leakage, Section 3.12.17 describes this leakage as the background leakage from transmission and distribution pipes plus the background leakage from service connections. Since this analysis considers a background leakage for a condition of 50m of pressure (Section 3.12), the values shall be adjusted for the current system pressure:

$$\text{Estimated Background Leakage }(\text{m}^3\text{x}10^3/\text{yr})=(\text{L}m\cdot\text{Background}$$
$$\text{Leakage for Mains}+\text{Number of service connections}\cdot\text{Background Leakage for Service Connections})\cdot$$
$$\text{Predicted Background Leakage}\cdot\frac{24\cdot(\frac{\text{ASP}}{50})^{FAVADN1}\cdot Numberofdays}{10^6}$$

Equation 4.8: (Source: Adapted from Equation 3.27)

In Equation 4.8, the Background Leakage for Mains is the Background leakage @ 50m pressure and ICF = 1.0 for Mains and the Background Leakage for Service Connections is the Background leakage @ 50m pressure and ICF = 1.0 for service connections. Differentiating the equation:

$$\frac{\partial\,(\text{F})}{\partial Pressure}=480\cdot Numberofdays\cdot(\text{L}m\cdot\text{Background Leakage for Mains}+\text{Nc}\cdot\text{Background Leakage for Service Connections})\cdot$$
$$PBL\cdot FAVADN1\cdot(\frac{\text{ASP}}{50})^{FAVADN1-1}\cdot$$

Equation 4.9: (Source: The Author)

Reported Burst volume in Distribution Mains and Service Connections is defined by the equation described in Section 3.11.16 as

$$\text{RBVDMSC}=\text{RBVSC}+\text{RBVDM}$$

Equation 4.10: (Source: The Author)

Where RBVSC is Reported Bursts Volumes on Service Connections and RBVDM is Reported Bursts Volumes on Distribution Mains.

This can be expressed as

$$\text{RBVDM}=\frac{1}{1000}\cdot N\text{RBLDM}\cdot\text{AVLDM@50m}\cdot\left(\frac{\text{ASP}}{50}\right)^{N1DM}$$

$$\text{RBVDMSC}=$$
$$\frac{1}{1000}\cdot(N\text{RBLDM}\cdot\text{AVLDM@50m}\cdot\left(\frac{\text{ASP}}{50}\right)^{N1DM}+N\text{RBLSC}\cdot\text{AVLSC@50m}\cdot\left(\frac{\text{ASP}}{50}\right)^{N1SC})$$

Equation 4.11: (Source: The Author)

Where NRBLDM is the Number of Reported Burst and Leaks in Distribution Mains, AVLDM is the Assumed Volume Lost per Reported Burst or Leak @ 50m Pressure in Distribution Mains, ASP is the Average system pressure, NRBLSC is the Number of Reported Burst and Leaks in Service Connections, AVLSC is the Assumed Volume Lost per Reported Burst or Leak @ 50m Pressure in Service Connections.

The differential of that equation in function of pressure will be

$$\frac{\partial\,(\mathrm{F})}{\partial ASP} =$$

$$\frac{1}{50.000}\cdot(N\mathrm{RBLDM}\cdot\mathrm{AVLDM@50m}\cdot \mathrm{N1}DM\cdot\left(\frac{\mathrm{ASP}}{50}\right)^{N1DM-1} +$$

$$N\mathrm{RBLSC}\cdot\mathrm{AVLSC@50m}\cdot N\mathrm{1SC}\cdot\left(\frac{\mathrm{ASP}}{50}\right)^{N1SC-1})$$

Equation 4.12: (Source: The Author)

The Economic Unreported Real Losses (227.198 m^3x10^3/yr) will remind constant for this analysis. The Trunk mains and reservoir leakage remains constant during this analysis since the derivative is zero.

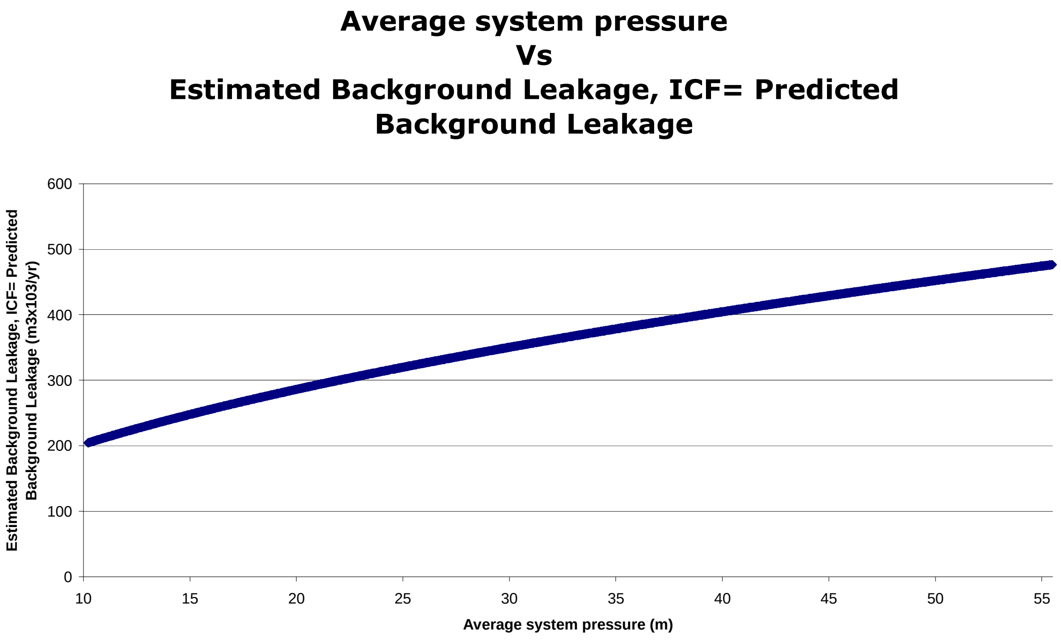


Figure 4.7: Average System Pressure vs. Estimated Background Leakage for ICF= Predicted Background Leakage (Source: The Author).

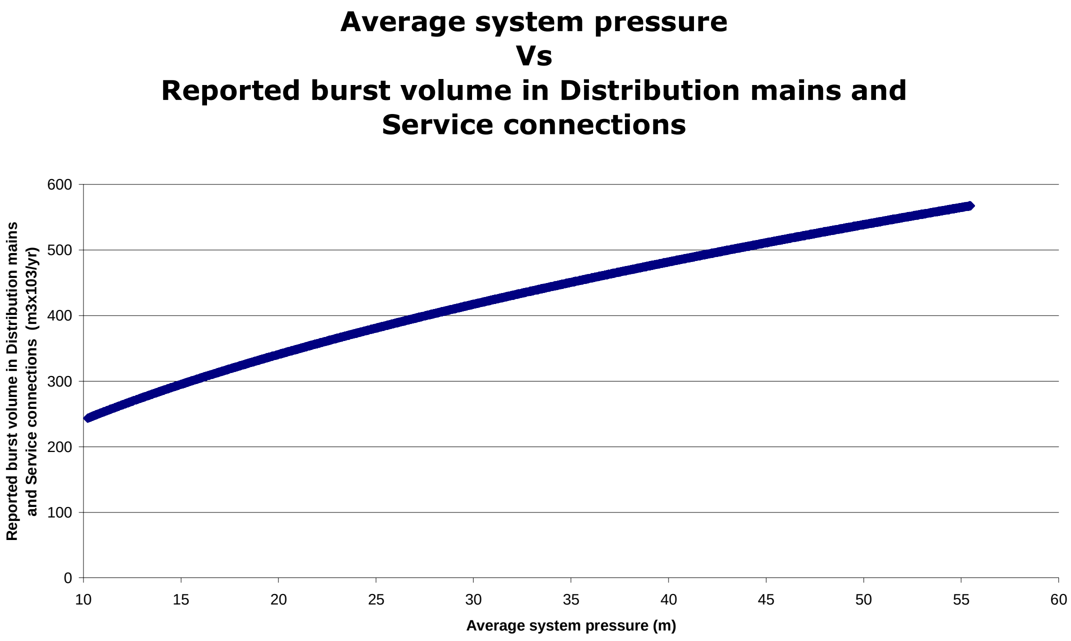


Figure 4.8: Average System Pressure vs. Reported burst volume in Distribution mains and Service connections
(Source: The Author)

The previous information can be consolidated in tabular form in Table 4.67.

Economic Unreported Real Losses (m^3x10^3/yr)	**Estimated Background Leakage for ICF= Predicted Background Leakage (m^3x10^3/yr))**	**Reported burst volume in Distribution mains and Service connections (m^3x10^3/yr)**	**Trunk Mains and Service Reservoir Leakage (m^3x10^3/yr)**	**Short-Run Economic Level of Leakage (m^3x10^3/yr)**	**Economic Unreported Real Losses (m^3x10^3/yr)**
10.2107	227.20	204.32	243.38	384.48	1059.37
14.7397	227.20	245.48	292.41	384.48	1149.57
19.6806	227.20	283.66	337.88	384.48	1233.22
23.791	227.20	311.88	371.50	384.48	1295.06
28.3213	227.20	340.28	405.33	384.48	1357.29
32.8013	227.20	366.20	436.21	384.48	1414.09
37.381	227.20	390.93	465.67	384.48	1468.28
41.9141	227.20	413.96	493.09	384.48	1518.73
46.4401	227.20	435.74	519.03	384.48	1566.45
50.97	227.20	456.49	543.76	384.48	1611.93
55.4984	227.20	476.34	567.40	384.48	1655.42

Table 4.67: Sample of sensitivity analysis data for Average System Pressure
(Source: The Author)

Figure 4.9 presents the information of Table 4.67.

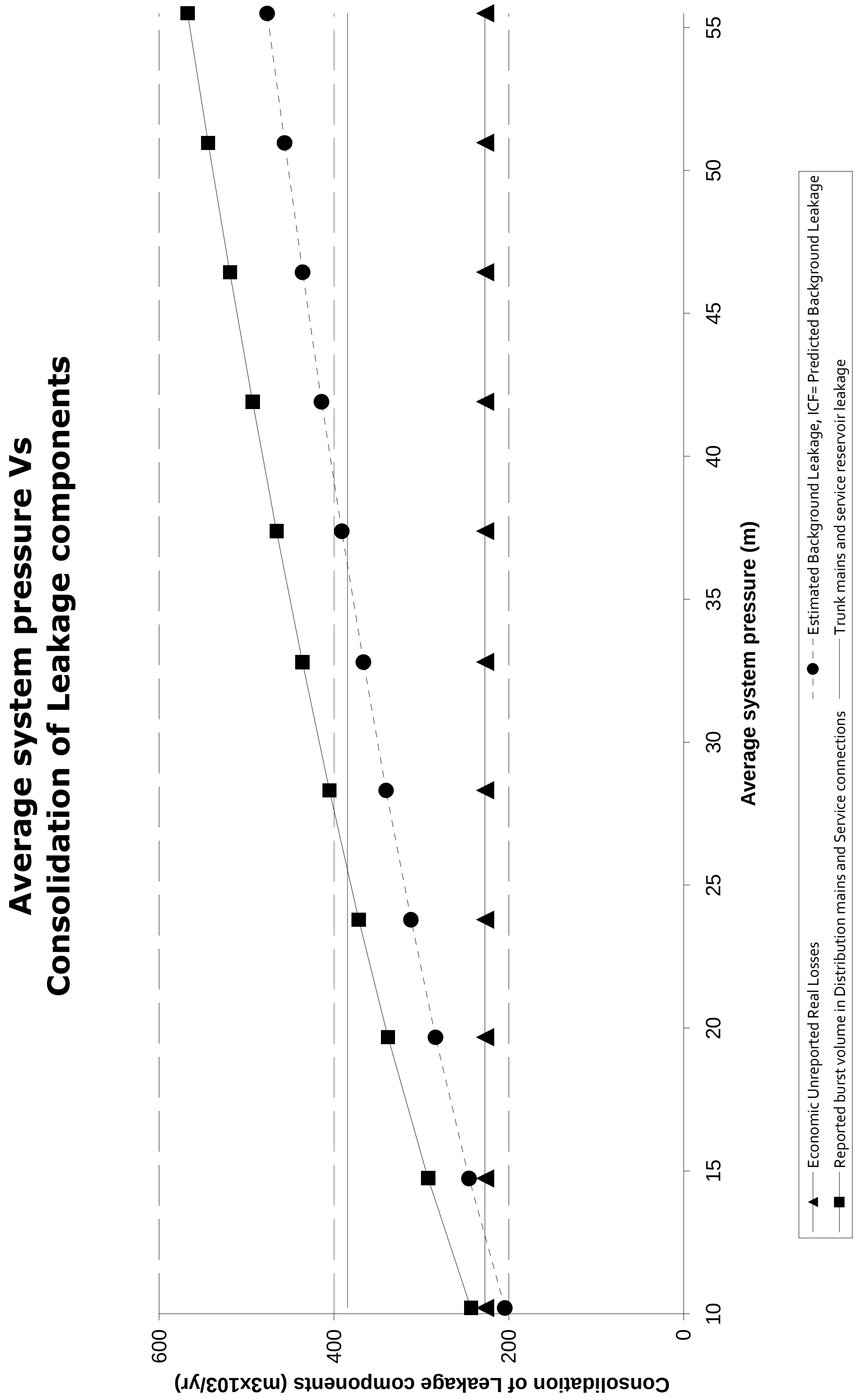


Figure 4.9: Consolidation of leakage components for Average System Pressure sensitivity analysis
(Source: The Author)

The behaviour of the Estimated Background Leakage for ICF= Predicted Background Leakage and the Reported Burst Volume in Distribution Mains and Service Connections is quite similar. However the Reported Burst Volume is higher. It's important to mention than for the Estimated Background Leakage, the analysis is considering an average condition of the pipes so this volume is not overestimated.

The leakage volumes for Estimated Background Leakage for ICF= Predicted Background Leakage and the Reported Burst Volume in Distribution Mains and Service Connections are higher than the Trunk Mains and Reservoir Leakage when the pressure is higher than 38 m, such as the current conditions in Zaragoza. For pressures under 24 m, the Trunk Mains and Reservoir Leakage becomes the leakage component with the highest volume.

Finally Figure 4.10 presents the SRELL results for this analysis.

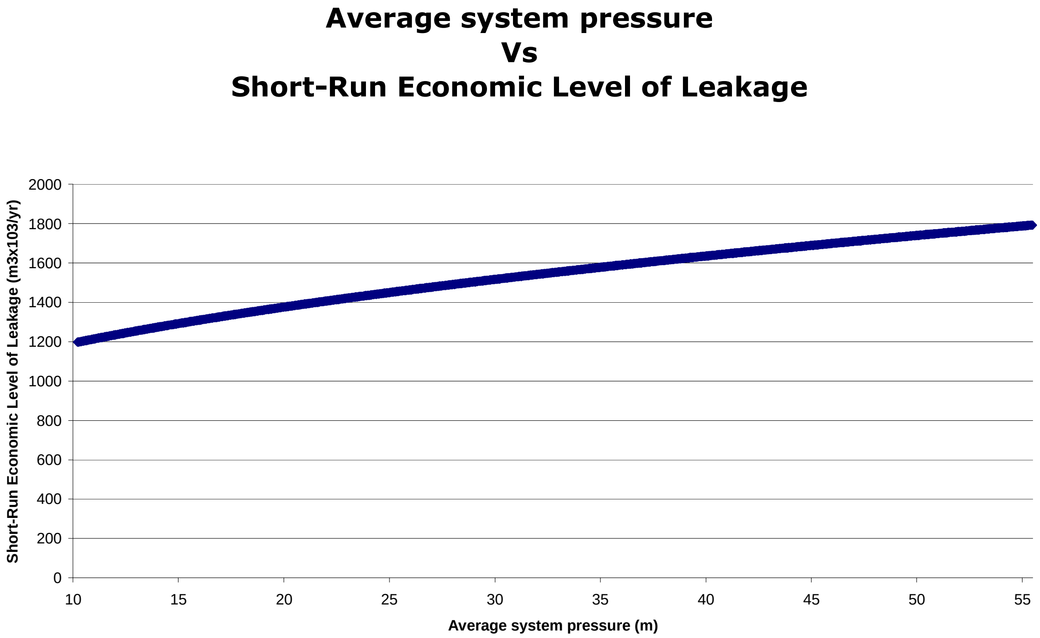


Figure 4.10: Average System Pressure vs. Short-Run Economic Level of Leakage. (Source: The Author)

4.11.4 Number of Reported Burst and Leaks in Distribution Mains

The current value for the Reported Bursts and Leaks in Distribution Mains is 302. Considering an interval of 302 to 906 and 5000 simulations, the Table 4.68 shows the results for the sensitivity analysis, done using Excel.

Variables	Correlation coefficient
Economic Unreported Real Losses	0.000
Estimated Background Leakage for ICF= Predicted Background Leakage	0.000
Reported burst volume in Distribution mains and Service connections	1.000
Trunk Mains and Service Reservoir Leakage	0.000
Short-Run Economic Level of Leakage	1.000

Table 4.68: Correlation coefficients for Number of Reported Burst and Leaks in Distribution Mains sensitivity analysis and the different leakage components (Source: The Author)

There is a perfect correlation between Number of Reported Burst and Leaks in Distribution Mains and Reported Burst Volume in Distribution Mains and Service Connections and Short-Run Economic Level of Leakage. Considering the Reported Burst Volume in Distribution Mains and Service Connections depends directly of the number of bursts, the analysis can define the Reported Burst Volume in Distribution Mains and Service Connections using the Equation described in section 3.11.16 as:

$$\mathrm{RBVDMSC} = \mathrm{RBVSC} + \mathrm{RBVDM}$$

Equation 4.13: (Source: The Author)

Where RBVSC is Reported Bursts Volumes on Service Connections and RBVDM is Reported Bursts Volumes on Distribution Mains.

This can be expressed as

$$\mathrm{RBVDM} = \frac{1}{1000} \cdot N\mathrm{RBLDM} \cdot \mathrm{AVLDM@50m} \cdot \left(\frac{\mathrm{ASP}}{50} \right)^{N1DM}$$

Equation 4.14: (Source: The Author)

Where NRBLDM is the Number of Reported Burst and Leaks in Distribution Mains, AVLDM is the Assumed Volume Lost per Reported Burst or Leak @ 50m Pressure in Distribution Mains, ASP is the Average system pressure, NRBLSC is the Number of Reported Burst and Leaks in Service Connections, AVLSC is the Assumed Volume Lost per Reported Burst or Leak @ 50m Pressure in Service Connections.

$$\mathrm{RBVDMSC} = \frac{1}{1000}\cdot(N\mathrm{RBLDM}\cdot\mathrm{AVLDM@50m}\cdot\left(\frac{\mathrm{ASP}}{50}\right)^{N1DM} + N\mathrm{RBLSC}\cdot\mathrm{AVLSC@50m}\cdot\left(\frac{\mathrm{ASP}}{50}\right)^{N1SC})$$

Equation 4.15: (Source: The Author)

The derivative of that equation in function of the Number of Reported Burst and Leaks in Distribution Mains will be:

$$\frac{\partial\,(\mathrm{F})}{\partial NRBLDM} = \frac{1}{1.000}\cdot(\mathrm{AVLDM@50m}\cdot\left(\frac{\mathrm{ASP}}{50}\right)^{N1DM})$$

Equation 4.16: (Source: The Author)

Since the number of reported bursts in mains is not related to the Economic Unreported Real Losses, the volume reminds constant during the analysis.

The value of zero for the Correlation Coefficient between Number of Reported Burst and Leaks in Distribution Mains and Estimated Background Leakage for ICF= Predicted Background Leakage is an indicator of how this volume will remind constant during the analysis.

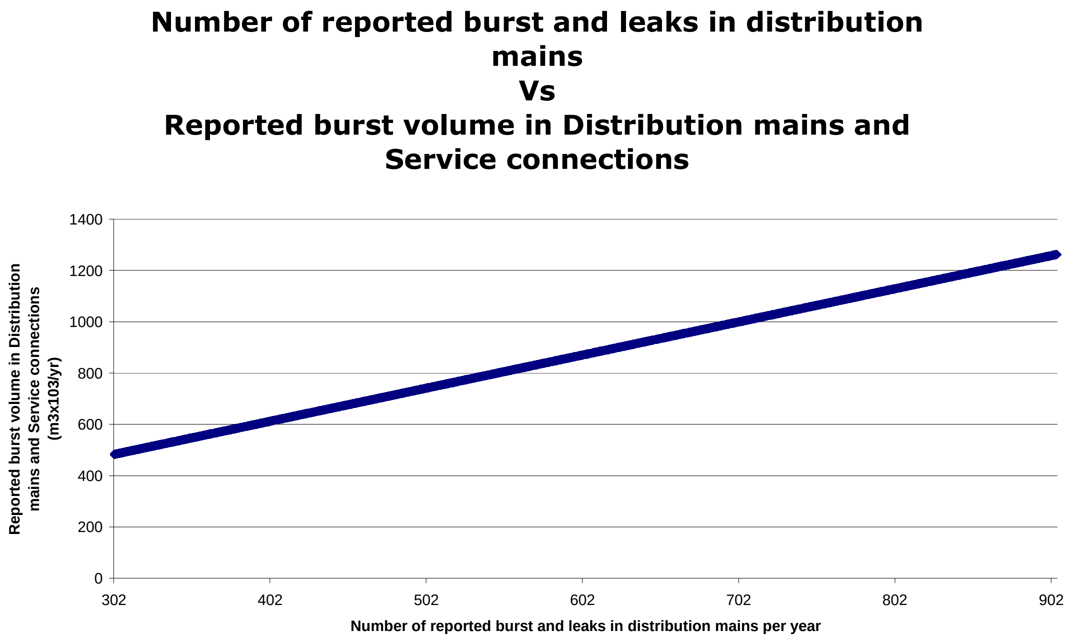


Figure 4.11: Number of Reported Burst and Leaks in Distribution Mains Vs Reported Burst Volume in Distribution Mains and Service Connections
(Source: The Author).

Since the Reported Burst volume depends on the number of reported bursts in mains, a higher number of reported bursts will result in a higher volume of leakage. A lineal relationship can be observed in the graph.

The previous information can be consolidated in tabular form in Table 4.69.

Number of Reported Burst and Leaks in Distribution Mains	**Economic Unreported Real Losses (m^3x10^3/yr)**	**Estimated Background Leakage for ICF= Predicted Background Leakage (m^3x10^3/yr)**	**Reported burst volume in Distribution mains and Service connections (m^3x10^3/yr)**	**Trunk Mains and Service Reservoir Leakage (m^3x10^3/yr)**	**Short-Run Economic Level of Leakage (m^3x10^3/yr)**
302	227.20	405.41	482.91	384.48	1499.99
362	227.20	405.41	560.38	384.48	1577.46
422	227.20	405.41	637.85	384.48	1654.94
483	227.20	405.41	716.61	384.48	1733.7
543	227.20	405.41	794.08	384.48	1811.17
604	227.20	405.41	872.85	384.48	1889.93
664	227.20	405.41	950.32	384.48	1967.4
724	227.20	405.41	1027.79	384.48	2044.88
785	227.20	405.41	1106.55	384.48	2123.64
905	227.20	405.41	1261.49	384.48	2278.58

Table 4.69: Sample of sensitivity analysis data for Number of Reported Burst and Leaks in Distribution Mains
(Source: The Author)

Figure 4.12 presents the information of Table 4.69.

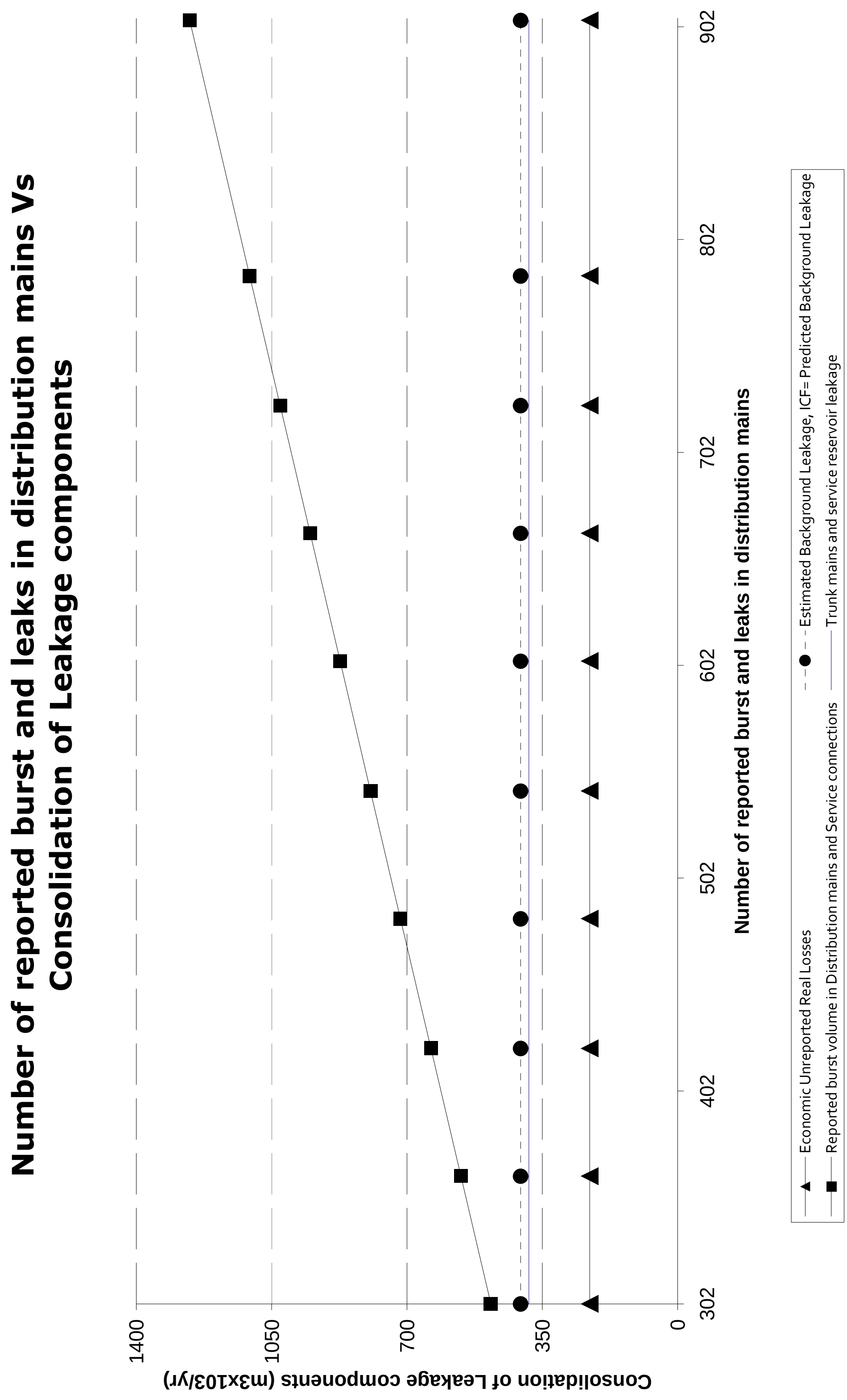


Figure 4.12: Consolidation of leakage components for Number of Reported Burst and Leaks in Distribution Mains sensitivity analysis
(Source: The Author)

In this case, the volume of Reported Burst Volume in Distribution Mains and Service Connections is higher than the other leakage components.

Finally Figure 4.13 shows the SRELL results for this analysis.

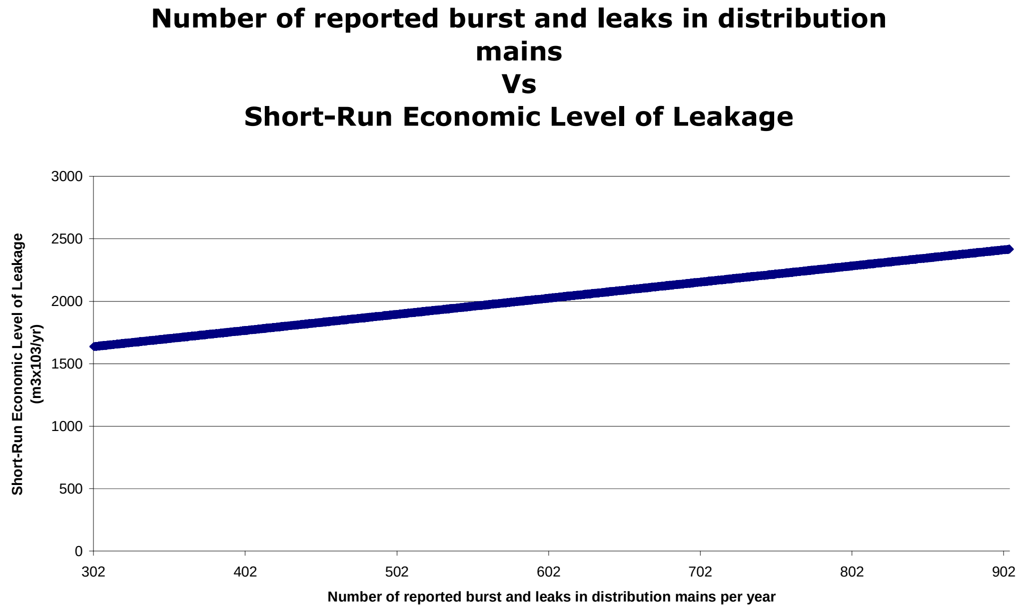


Figure 4.13: Number of Reported Burst and Leaks in Distribution Mains vs. Short-Run Economic Level of Leakage.
(Source: The Author).

The SRELL is definitely influenced by the number of Reported Bursts in Distribution Mains. This is a way to prove that reducing the number of bursts using Active Leakage Detection has an effect in reducing the ELL.

4.11.5 Number of Reported Bursts and Leaks in Service Connections

The current value for the Reported Bursts and Leaks in Service Connections is 360. Considering an interval of 360 to 1080 and 5000 simulations, the Table 4.70 shows the results for the sensitivity analysis, done using Excel.

Variables	Correlation coefficient
Economic Unreported Real Losses	0.000
Estimated Background Leakage for ICF= Predicted Background Leakage	0.000
Reported Burst Volume in Distribution Mains and Service Connections	1.000
Trunk Mains and Service Reservoir Leakage	0.000
Short-Run Economic Level of Leakage	1.000

Table 4.70: Correlation coefficients for Number of reported burst and leaks in service connections sensitivity analysis and the different leakage components (Source: The Author)

The results are similar to the ones found in Section 4.11.4: A perfect correlation between Number of Reported Bursts and Leaks in Service Connections and Reported Burst Volume in Distribution Mains and Service Connections and Short-Run Economic Level of Leakage. Again: This volume will remind constant for this analysis.

Using the equation:

$$\mathrm{RBVDMSC} = \mathrm{RBVSC} \div \mathrm{RBVDM}$$

Equation 4.17: (Source: The Author)

Where RBVSC is Reported Bursts Volumes on Service Connections and RBVDM is Reported Bursts Volumes on Distribution Mains.

This can be expressed as

$$\mathrm{RBVDMSC} = \frac{1}{1000}\cdot(N\mathrm{RBLDM}\cdot \mathrm{AVLDM@50m}\cdot\left(\frac{\mathrm{ASP}}{50}\right)^{N1DM} + N\mathrm{RBLSC}\cdot\mathrm{AVLSC@50m}\cdot\left(\frac{\mathrm{ASP}}{50}\right)^{N1SC})$$

Equation 4.18: (Source: The Author)

Where NRBLDM is the Number of Reported Burst and Leaks in Distribution Mains, AVLDM is the Assumed Volume Lost per Reported Burst or Leak @ 50m Pressure in Distribution Mains, ASP is the Average system pressure, NRBLSC is the Number of Reported Burst and Leaks in Service Connections, AVLSC is the Assumed Volume Lost per Reported Burst or Leak @ 50m Pressure in Service Connections.

The derivative of that equation in function of the Number of Reported Bursts and Leaks in Service Connections will be

$$\frac{\partial\,(\mathrm{F})}{\partial NRBLSC} = \frac{1}{1.000}\cdot(\mathrm{AVLSC@50m}\cdot\left(\frac{\mathrm{ASP}}{50}\right)^{N1SC})$$

Equation 4.19: (Source: The Author)

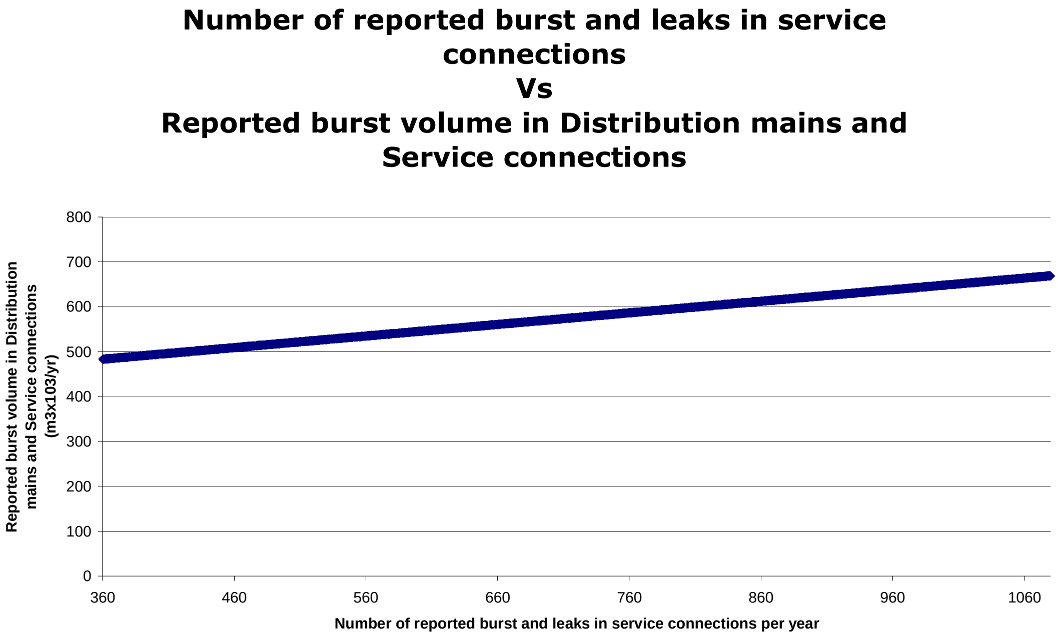


Figure 4.14: Number of Reported Bursts and leaks in Service Connections vs. Reported burst volume in Distribution mains and Service connections (Source: The Author).

A lineal relationship is found again for the Number of Reported Bursts and Leaks in Service Connections vs. Reported Burst Volume in Service Connections and Service Connections. However the volume is lower since the flow for the bursts in connections is smaller than the flow for bursts in mains.

Again the volume of leakage in Trunk mains and reservoirs do not change during the analysis. The previous information can be consolidated in tabular form in Table 4.71.

Number of Reported Bursts and leaks in Service Connections	Economic Unreported Real Losses (m^3x10^3/yr)	Estimated Background Leakage for ICF= Predicted Background Leakage (m^3x10^3/yr)	Reported burst volume in Distribution mains and Service connections (m^3x10^3/yr)	Trunk Mains and Service Reservoir Leakage (m^3x10^3/yr)	Short-Run Economic Level of Leakage (m^3x10^3/yr)
360	227.20	405.41	482.91	384.48	1499.99
432	227.20	405.41	501.50	384.48	1518.59
504	227.20	405.41	520.09	384.48	1537.18
576	227.20	405.41	538.69	384.48	1555.77
648	227.20	405.41	557.28	384.48	1574.37
720	227.20	405.41	575.87	384.48	1592.96
792	227.20	405.41	594.46	384.48	1611.55
864	227.20	405.41	613.06	384.48	1630.14
936	227.20	405.41	631.65	384.48	1648.74
1008	227.20	405.41	650.24	384.48	1667.33

Table 4.71: Sample of sensitivity analysis data for Number of Reported Bursts and leaks in Service Connections
(Source: The Author)

Figure 4.15 presents the information of Table 4.71.

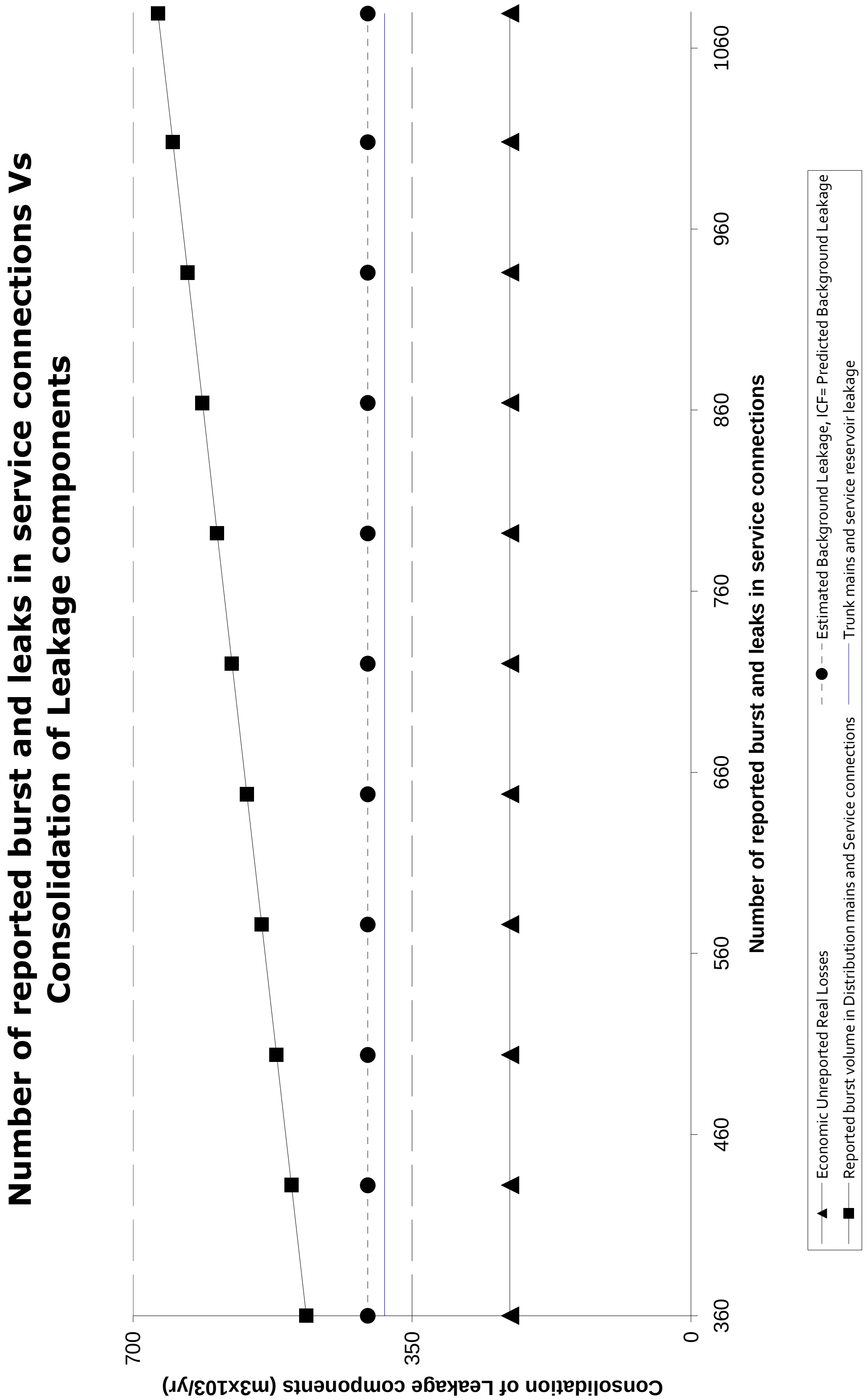


Figure 4.15: Consolidation of leakage components for Number of Reported Bursts and leaks in Service Connections sensitivity analysis
(Source: The Author)

The Reported Burst Volume in Distribution Mains and Service Connections will be higher than the other leakage components. However is lower than the volume considered for the change in burst in mains.

Finally Figure 4.16 presents the SRELL results for this analysis.

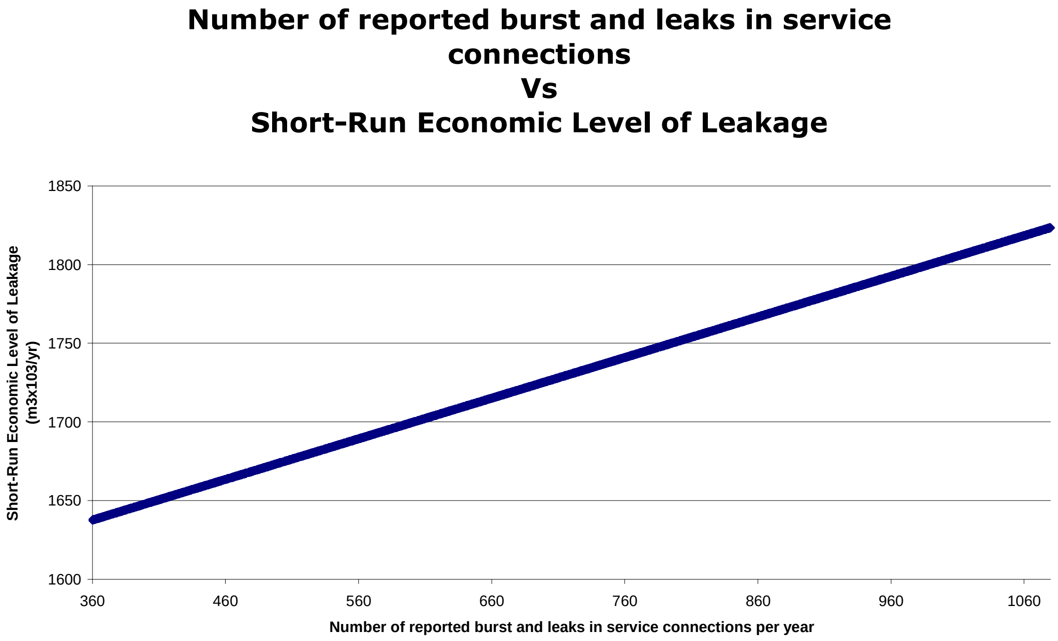


Figure 4.16: Number of Reported Bursts and leaks in Service Connections Vs Short-Run Economic Level of Leakage.
(Source: The Author).

If Figure 4.16 is compared with Figure 4.13, presented again in Figure 5.15, that illustrates the effects Number of Reported Burst and Leaks in Distribution Mains, it shows that an investment in the repair of burst in mains will have a higher result in the reduction of SRELL than an investment in repair of bursts in service connections. The analysis refers to repair since the repair conditions are not considered under the Unreported Leakage component but under the Reported Bursts component.

4.11.6 Cost of Intervention

The current value for the Cost of Intervention is 410 Euros/km. Considering an interval of 205 to 820 and 5000 simulations, the Table 4.72 shows the results for the sensitivity analysis, done using Excel.

Variables	Correlation coefficient
Economic Unreported Real Losses	0.996
Estimated Background Leakage for ICF= Predicted Background Leakage	0.000
Reported Burst Volume in Distribution Mains and Service Connections	0.000
Trunk Mains and Service Reservoir Leakage	0.000
Short-Run Economic Level of Leakage	0.996

Table 4.72: Correlation coefficients for Cost of Intervention sensitivity analysis and the different leakage components
(Source: The Author)

There is a strong correlation between Cost of Intervention and Economic Unreported Real Losses and between Cost of Intervention and Short-Run Economic Level of Leakage.

Considering the equation for Economic Unreported Real Losses in section 3.14.9 where

$$EURL = \frac{CI \cdot Lm \cdot EP}{CV}$$

Equation 4.20: (Source: The Author)

Where CI is the Cost of one 'whole system' intervention, excluding cost of repairs, Lm is the Distribution and Transmission Pipe Length, EP is the Economic Percentage of system to be surveyed and CV is the Assumed Variable Cost of Water. Derivating the equation:

$$\frac{\partial(EURL)}{\partial(CI)} = \frac{Lm \cdot EP}{CV}$$

Equation 4.21: (Source: The Author)

The strong Correlation Coefficient and the fact the derivative of the equation is a constant are indicators of a direct relationship between the Cost of Intervention and the Economic Unreported Real Losses.

The previous information can be consolidated in tabular form in Table 4.73.

Cost of Intervention	Economic Unreported Real Losses (m^3x10^3/yr)	Estimated Background Leakage for ICF= Predicted Background Leakage (m^3x10^3/yr)	Reported burst volume in Distribution mains and Service connections (m^3x10^3/yr)	Trunk Mains and Service Reservoir Leakage (m^3x10^3/yr)	Short-Run Economic Level of Leakage (m^3x10^3/yr)
205	160.65	405.41	482.91	384.48	1433.45
328	203.21	405.41	482.91	384.48	1476.01
389	221.30	405.41	482.91	384.48	1494.1
451	238.29	405.41	482.91	384.48	1511.08
512	253.89	405.41	482.91	384.48	1526.69
574	268.82	405.41	482.91	384.48	1541.62
635	282.75	405.41	482.91	384.48	1555.54
697	296.23	405.41	482.91	384.48	1569.02
758	308.92	405.41	482.91	384.48	1581.72
819	321.11	405.41	482.91	384.48	1593.91

Table 4.73: Sample of sensitivity analysis data for Cost of Intervention (Source: The Author)

Figure 4.17 presents the information of Table 4.73.

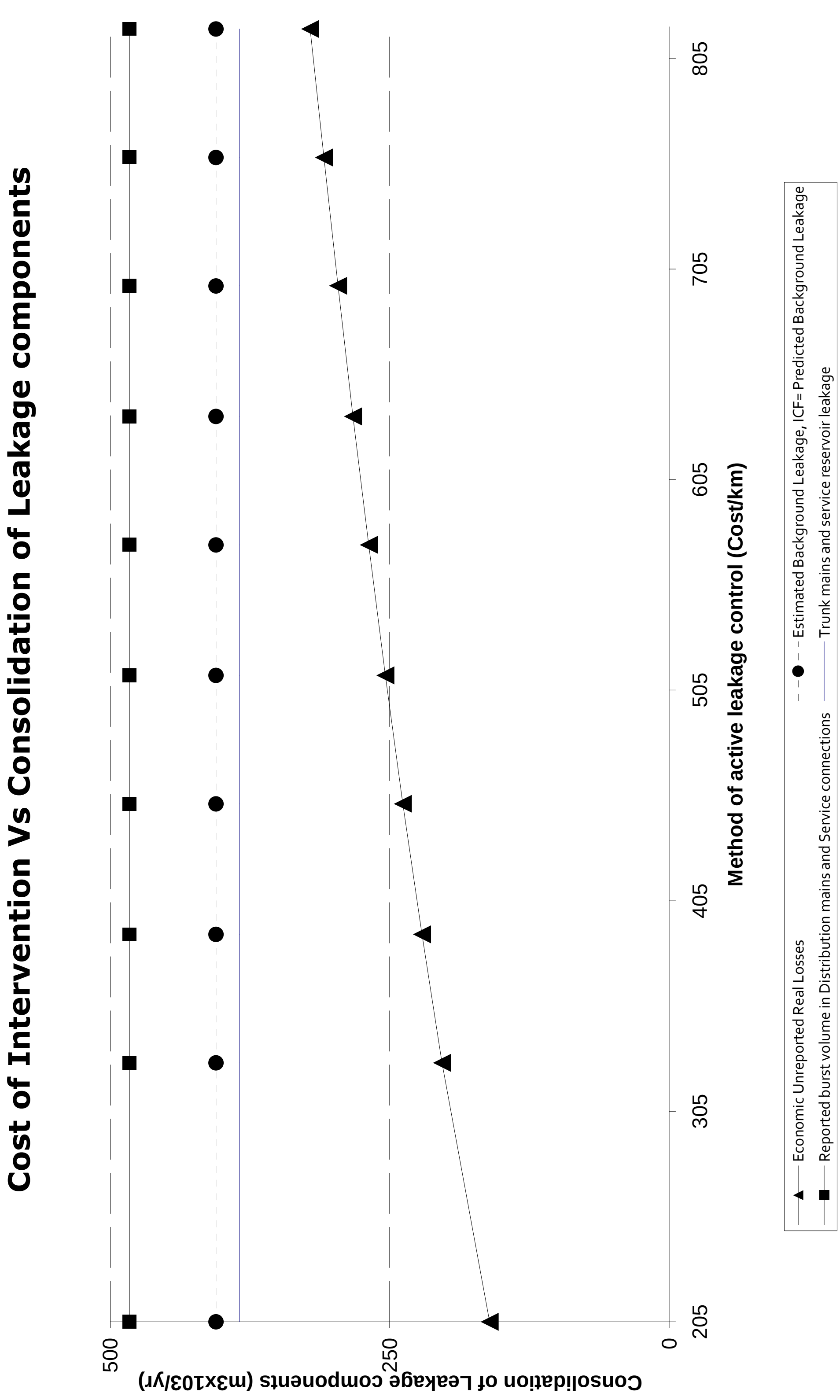


Figure 4.17: Consolidation of leakage components for Cost of Intervention sensitivity analysis
(Source: The Author)

The effect of the Cost of Intervention in the Economic Unreported Real Losses is definitely not as evident in the leakage volume. During this analysis, the highest leakage volume comes from Reported Burst Volume in Distribution Mains and Service Connections. Finally Figure 4.18 shows the SRELL results for this analysis.

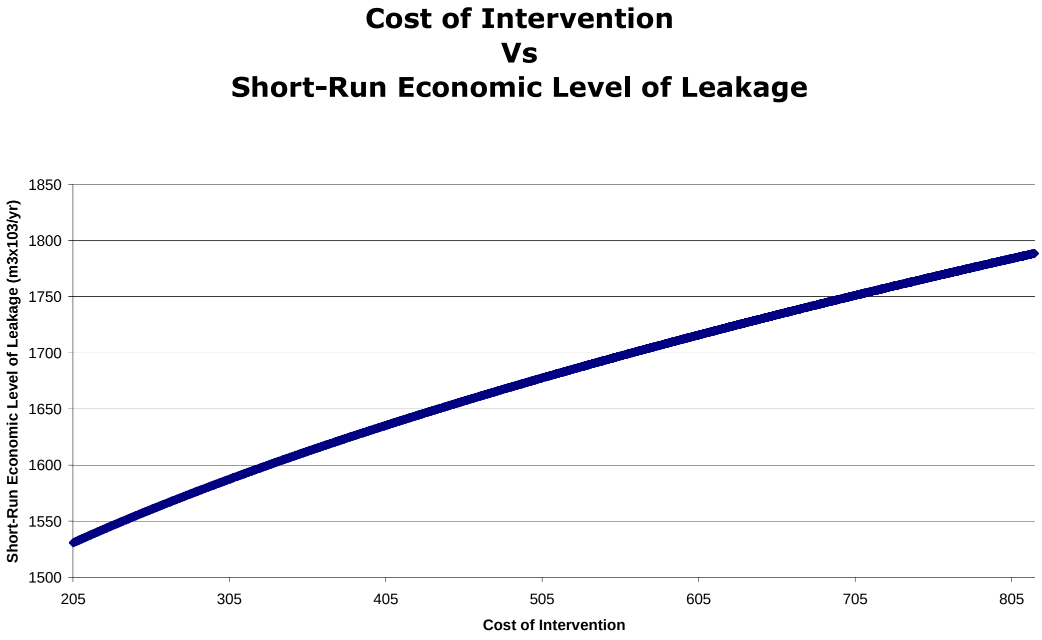


Figure 4.18: Cost of Intervention vs Short-Run Economic Level of Leakage. (Source: The Author).

4.11.7 Survey Frequency

The economic value for Survey Frequency is calculated from the Rate of Rise. However the water utility might want to consider the effect of a different survey frequency. In the case of this analysis, it considers the change in the frequency of intervention. The model has already calculated an Economic Intervention Frequency, in years, which is valid for the current Rate of Rise and conditions of the system.

Since the intervention frequency is the kind of active leakage detection that the water utility will be considering to implement, it's necessary to understand the behaviour of the leakage levels under different intervention frequencies. What happens when the intervention frequency is higher or lower than the Economic Intervention Frequency?

The Intervention Frequency is used to calculate the % of system to be surveyed annually EP. A higher value of Intervention Frequency will result in a lower percentage of the system to be surveyed. This can be understand this as a need to intervene less in the system. But what happens when there is no Intervention Frequency? How can it be interpreted?

A condition of passive leakage detection can be understood as a really small % of system to be surveyed annually EP. In this case, an Intervention Frequency with a really high value would be the best way to interpret this condition: The interventions in the system are not often enough or are really separated a long time between them. The relationship between Intervention Frequencies can be understood using the following example:

Figure 4.19 shows the concept of Economic Intervention for a regular survey.

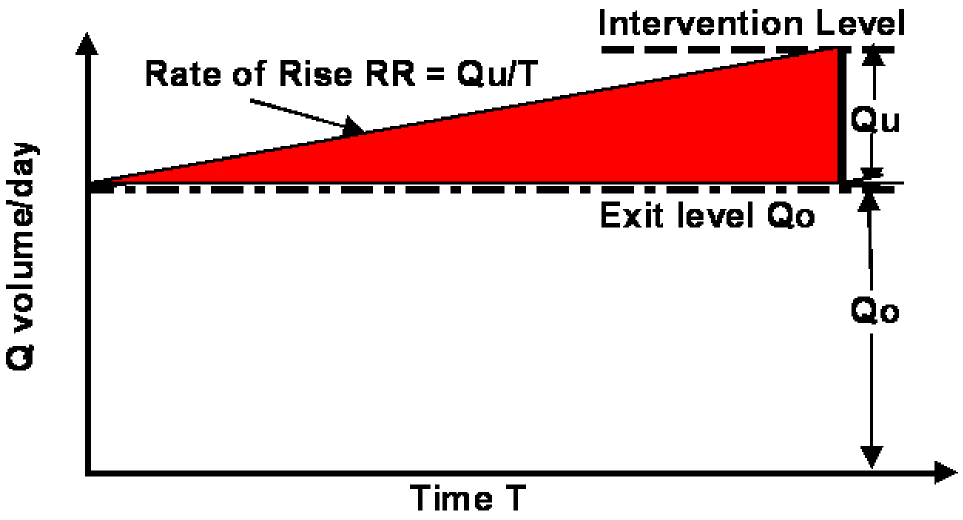


Figure 4.19: Economic Intervention for an Active Leakage Control Policy of Regular Survey (Source: Adapted from Fanner and Lambert, 2009)

As we discussed in Section 3.7 (Some Basic Concepts), if unreported leakage is rising at a rate RR, then the minimum total cost of lost water and intervention costs occurs when the accumulated value of the lost water (the volume in the triangle in Figure 4.19, multiplied by the variable cost of water CV) equals the cost of an intervention (CI).

If we assume a regular Intervention Frequency, the system's behaviour will be similar to Figure 4.20.

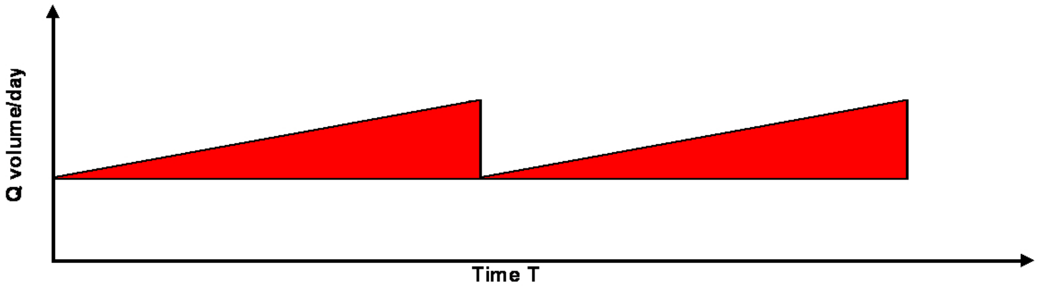


Figure 4.20: Regular Survey of a system (Source: Adapted from Fanner and Lambert, 2009)

However, if we consider a higher Intervention Frequency, which translates into a smaller percentage of the system being surveyed, and assuming the constant Rate of Rise, the behaviour of the system will be translated into a higher volume of leakage being controlled.

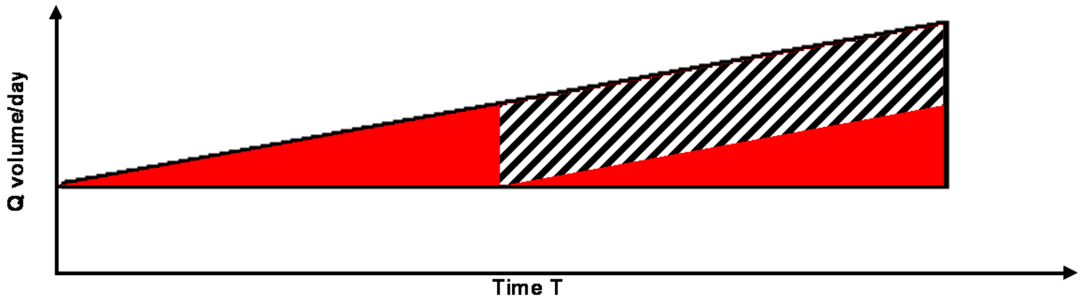


Figure 4.21: Comparison between Intervention Frequencies
(Source: The author)

But what is the difference in volume? Considering the Intervention Frequency as the double of the original Intervention Frequency, the area of the bigger triangle will be 4 times bigger than the smaller triangle

Let there be the triangle ABC with sides X and Y, showed in Figure 4.22.

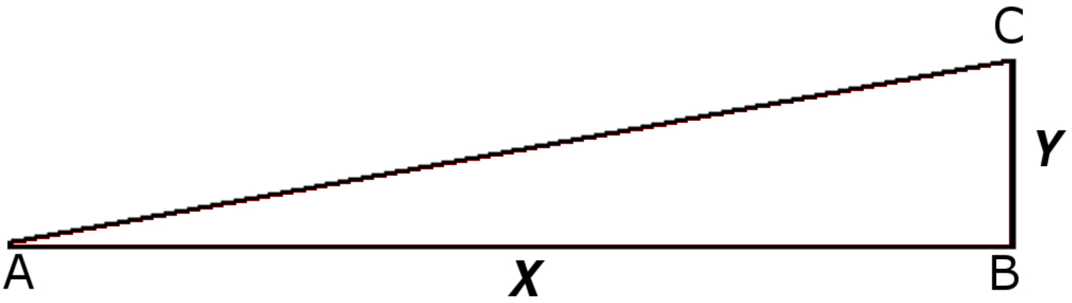


Figure 4.22: Triangle ABC
(Source: The author)

The area A1 of the triangle ABC would be:

$$A_1 = \frac{X \cdot Y}{2}$$

Equation 4.22: (Source: The Author)

The area A2 of a triangle with sides 2X and 2Y would be

$$A_2 = \frac{2 \cdot X \cdot 2 \cdot Y}{2} = 2 \cdot X \cdot Y$$

Equation 4.23: (Source: The Author)

Then the hatched area in Figure 4 will have a value of XY. That's twice the volume of leakage controlled by the regular survey. So, to generalize the difference in volume for a number K of surveys, the area of the triangle with sides KX and KY will be

$$A_K = \frac{K \cdot X \cdot K \cdot Y}{2} = \frac{K^2 \cdot X \cdot Y}{2}$$

Equation 4.24: (Source: The Author)

The difference in areas will be:

$$DifA = A_K - K \cdot A_1 = \frac{K^2 \cdot X \cdot Y}{2} - \frac{K \cdot X \cdot Y}{2} = \frac{K \cdot X \cdot Y}{2}(K-1)$$

Equation 4.25: (Source: The Author)

However the cost of intervention for the higher frequency can be higher than the cost of the recovered volume. The model calculated an economical intervention frequency.

Considering an interval of 0.25 to 5 years and 5000 simulations, the Table 4.74 shows the results for the sensitivity analysis, done using Excel.

Variables	**Correlation coefficient**
Economic Unreported Real Losses	-0.755
Estimated Background Leakage for ICF= Predicted Background Leakage	0.000
Reported Burst Volume in Distribution Mains and Service Connections	0.000
Trunk Mains and Service Reservoir Leakage	0.000
Short-Run Economic Level of Leakage	-0.755

Table 4.74: *Correlation coefficients for Economic Intervention Frequency sensitivity analysis and the different leakage components*
(Source: The Author)

There is a strong negative correlation between Economic Intervention Frequency and Economic Unreported Real Losses and between Economic Intervention Frequency and Short-Run Economic Level of Leakage. This means that an increase in Survey Frequency will result in a decrease in the values of these volumes.

This graph has a different behaviour when compared with the previous graphs. This is due to the negative correlation (-0.755409778) between Economic Intervention Frequency and Economic Unreported Real Losses. It shows than an investment in survey frequency will generate a big reduction in the first year and then the reduction in the Leakage volume will not be so notorious. This can be explained in the concept of how is easier to detect big unreported leaks at the beginning of an active leak detection work. Later the smaller leaks will be harder to detect.

Since the Correlation Coefficients for Estimated Background Leakage and Reported Burst Volume are near zero, these volumes are constant and unaffected by the change in survey frequency.

The previous information can be consolidated in tabular form in Table 4.75.

Economic Intervention Frequency EIF	**Economic Unreported Real Losses (m^3x10^3/yr)**	**Estimated Background Leakage for ICF= Predicted Background Leakage (m^3x10^3/yr)**	**Reported burst volume in Distribution mains and Service connections (m^3x10^3/yr)**	**Trunk Mains and Service Reservoir Leakage (m^3x10^3/yr)**	**Short-Run Economic Level of Leakage (m^3x10^3/yr)**
0.250593	2752.91	405.41	482.91	384.48	4025.71
0.75004	919.77	405.41	482.91	384.48	2192.56
1.25094	551.47	405.41	482.91	384.48	1824.27
1.75035	394.13	405.41	482.91	384.48	1666.92
2.25001	306.60	405.41	482.91	384.48	1579.4
2.75504	250.40	405.41	482.91	384.48	1523.19
3.2509	212.21	405.41	482.91	384.48	1485
3.75003	183.96	405.41	482.91	384.48	1456.76
4.25088	162.29	405.41	482.91	384.48	1435.08
4.75042	145.22	405.41	482.91	384.48	1418.02

Table 4.75: Sample of sensitivity analysis data for Economic Intervention Frequency (Source: The Author)

Figure 4.23 presents the information of Table 4.75.

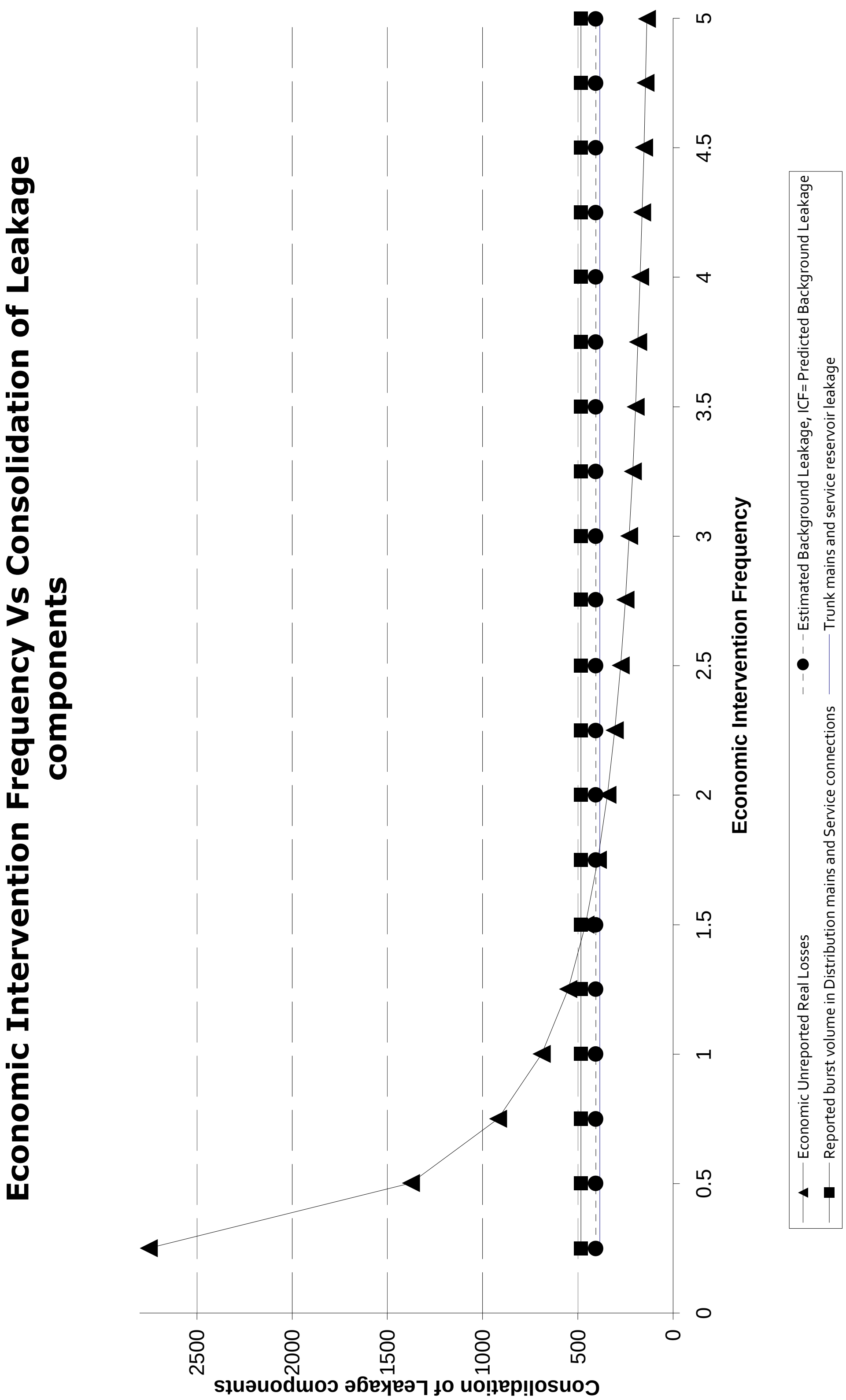


Figure 4.23: Consolidation of leakage components for Economic Intervention Frequency sensitivity analysis
(Source: The Author)

It can be showed that after 2 years, the volume of Economic Unreported Real Losses is smaller than the other components.

Finally, Figure 4.24 shows the SRELL results for this analysis.

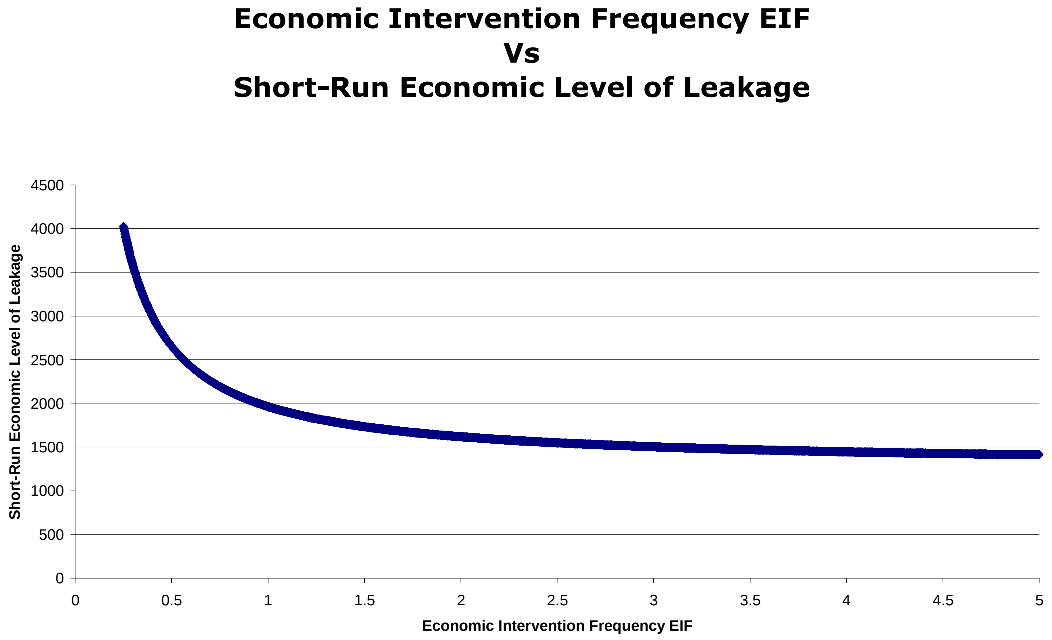


Figure 4.24: *Economic Intervention Frequency vs. Short-Run Economic Level of Leakage.* (Source: The Author).

4.11.8 N1

Section 2.3.4 (Pressure Management) explained how N1 allows to relate leakage rates with pressure according to how the cross-sectional area of the hole varies (1.5 is for the varying cross-sectional area). This means that the change in leakage rates with pressure is higher in small leaks found in pipe joints and fittings, which are normally increasing in surface area (Lambert, 2001). The value of N1 is used as an exponent of the ratio between the current pressure in the system and a condition of *50 m of pressure* (ibid) to relate the current leakage rates with the theoretical leakage rates presented in the literature.

The current value for N1 is 0.5. Farley et al (2008) gives an interval of 0.5 to 2.5 for the N1 value. Morrison et al (2007) gave an interval of 1.0 to 4.0. So the considered interval is 0.5 to 4.0 and 5000 simulations, the Table 4.76 shows the results for the sensitivity analysis, done using Excel.

Variables	Correlation coefficient
Economic Unreported Real Losses	0.000
Estimated Background Leakage for ICF= Predicted Background Leakage	-0.995
Reported Burst Volume in Distribution Mains and Service Connections	0.000
Trunk Mains and Service Reservoir Leakage	0.000
Short-Run Economic Level of Leakage	-0.995

Table 4.76: Correlation coefficients for N1 sensitivity analysis and the different leakage components
(Source: The Author)

The correlation between N1 and Estimated Background Leakage is strong and negative, just like the correlation between N1 and Short-Run Economic Level of Leakage.

In the case of the Estimated Background Leakage for ICF = Predicted Background Leakage, the analysis considers a background leakage for a condition of 50m of pressure (Section 3.12 (Estimated Background Leakage)), the values shall be adjusted for the current system pressure:

$$\mathrm{EBLPBL} = \mathrm{P}BL \cdot \frac{\left(\frac{(\mathrm{ASP})}{50}\right)^{FAVADN1} \cdot 24 \cdot Numberofdays}{10^{6}} \cdot (\mathrm{L}m \cdot \text{Background Leakage for Mains} + \mathrm{Nc} \cdot \text{Background Leakage for Service Connections})$$

Equation 4.26: (Source: The Author)

Where PBL is the Predicted Background Leakage, ASP is the Average System Pressure, Lm the Distribution and Transmission Pipe Length and Nc is the Number of Service Connections. It is important to stress that in that equation, the Background Leakage for Mains is the Background leakage @ 50m pressure and ICF = 1.0 for Mains and the Background Leakage for Service Connections is the Background leakage @ 50m pressure and ICF = 1.0 for service connections.

Deriving the equation:

$$\frac{\partial (F)}{\partial N1}=\frac{24}{10^{6}}\cdot Numberofdays\cdot \mathrm{N1}\cdot\left(\frac{\mathrm{ASP}}{50}\right)^{N1}\cdot Log_{e}\left(\frac{\mathrm{ASP}}{50}\right)\cdot$$

$$(Lm\cdot \text{Background Leakage for Mains}+\text{Nc}\cdot\text{Background Leakage for Service Connections})$$

Equation 4.27: (Source: The Author)

This explains the reason for a negative correlation coefficient since the logarithm of the division of pressure by 50 is negative since this division equals a number smaller than 1.

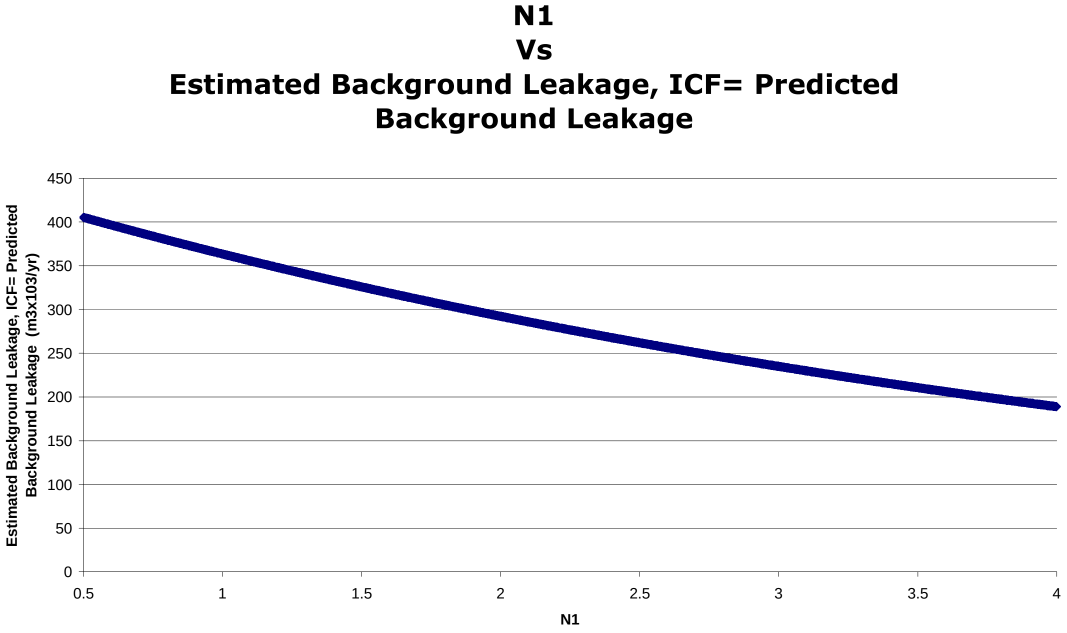


Figure 4.25: *N1 vs. Estimated Background Leakage for ICF= Predicted Background Leakage* (Source: The Author).

The volume of Economic Unreported Real Losses will remind constant during this analysis. The negative Correlation Coefficient indicates the effect of a higher N1 value in the reduction of the Estimated Background Leakage.

As it was mentioned at the beginning of this section, N1 is used as an exponent of the ratio between the current pressure in the system and a condition of *50 m of pressure* (Lambert, 2001). Since for the pressure in the system is lower than *50 m*, the ratio between current pressure and 50m will be smaller than 1. This means that the result will be smaller value when the current pressure and 50 m ratio is elevated to N1, no matter the value of N1. The previous information can be consolidated in tabular form in Table 4.77.

N1	**Economic Unreported Real Losses (m^3x10^3/yr)**	**Estimated Background Leakage for ICF= Predicted Background Leakage (m^3x10^3/yr))**	**Reported burst volume in Distribution mains and Service connections (m^3x10^3/yr)**	**Trunk Mains and Service Reservoir Leakage (m^3x10^3/yr)**	**Short-Run Economic Level of Leakage (m^3x10^3/yr)**
0.500437	364.80	405.37	482.91	384.48	1637.55
1.00215	364.80	363.34	482.91	384.48	1595.53
1.50076	364.80	325.89	482.91	384.48	1558.08
2.00038	364.80	292.24	482.91	384.48	1524.42
2.50037	364.80	262.04	482.91	384.48	1494.22
3	364.80	234.98	482.91	384.48	1467.16
3.5002	364.80	210.69	482.91	384.48	1442.87
3.99848	364.80	188.99	482.91	384.48	1421.17

Table 4.77: Sample of sensitivity analysis data for N1
(Source: The Author)

Figure 4.26 presents the information of Table 4.77.

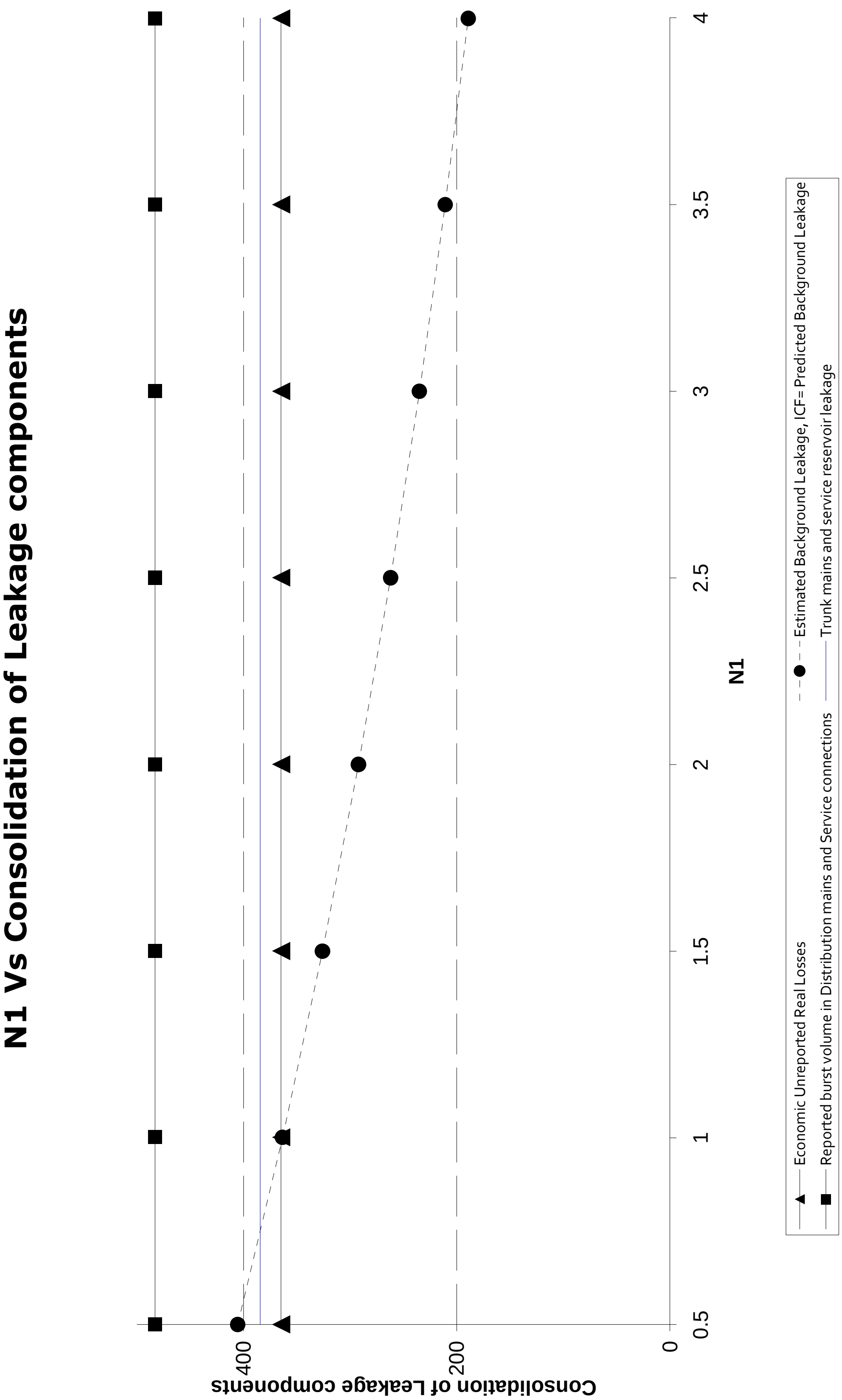


Figure 4.26: Consolidation of leakage components for N1 sensitivity analysis (Source: The Author)

For this condition, the Estimated Background Leakage becomes a volume smaller than the other components when N1 is higher than 1.0. However this is an effect of the System pressure to 50m ratio. Finally, Figure 4.27 presents the SRELL results for this analysis.

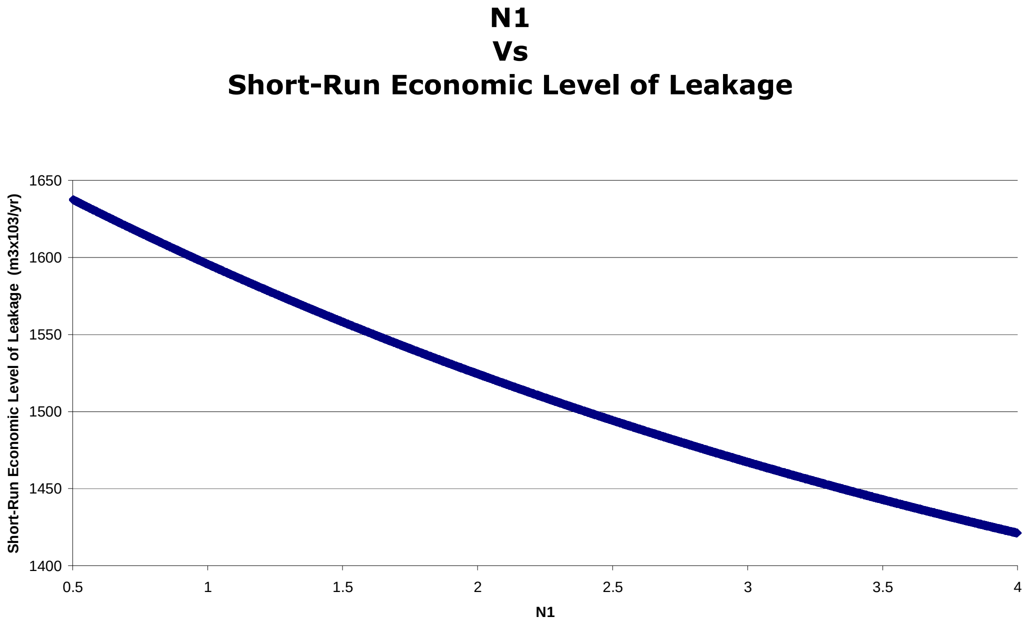


Figure 4.27: N1 vs. Short-Run Economic Level of Leakage. (Source: The Author).

4.12 Results from Sensitivity Analysis

Table 4.78 consolidates the correlation coefficients found during the analysis.

	Correlation coefficient						
Variables	**RR**	**Pressure**	**Number of Reported Burst and Leaks in Distribution Mains**	**Number of Reported Bursts and Leaks in Service Connections**	**CI**	**Survey Frequency**	**N1**
Economic Unreported Real Losses	0.991	0	0	0	0.996	-0.755	0
Estimated Background Leakage for ICF= Predicted Background Leakage	0	0.994	0	0	0	0	-0.995
Reported burst volume in Distribution mains and Service connections	0	0.994	1.000	1.000	0	0	0
Trunk Mains and Service Reservoir Leakage	0	0	0	0	0	0	0
Short-Run Economic Level of Leakage	0.991	0.994	1.000	1.000	0.996	-0.755	-0.995

Table 4.78: Summary of Sensitivity Analysis correlation coefficients for Zaragoza (Source: The Author)

Table 4.78 shows how Trunk Mains and Service Reservoir Leakage is not affected by the variables studied in the Sensitivity Analysis. This model calculates the Allowances for Real Losses from Trunk Mains (Section 3.13.2) using the Age of Trunk Mains and considering a 1.0 litre/sec detection threshold, since leaks with an smaller volume couldn't be detected. This is an argument to carry out more research and update that relation. Also the Water Utility needs to invest in the calculation of their own values for the Allowances for Real Losses from Service Reservoirs (Section 3.13.5). The following sections will describe the results from the Sensitivity Analysis.

4.12.1 Rate of Rise

There is a threshold value for the RR that indicates the Water Utility when is better to invest in the control of Estimated Background Leakage for ICF= Predicted Background Leakage, Reported burst volume in Distribution mains and Service connections and Trunk Mains and Service Reservoir Leakage. In the case of Zaragoza, that value is 1,800. When that threshold value is exceeded, the Water Utility should invest in controlling the Economic Unreported Real Losses.

4.12.2 Pressure

The concept of a minimum pressure level in the distribution network, defined by the legislation can be seen as a very basic pressure management application. Pressure has a very strong influence in several leakage components in the model so it's necessary to invest in a reliable way to measure pressure in the water distribution system.

The leakage volumes for Estimated Background Leakage for ICF= Predicted Background Leakage and the Reported Burst Volume in Distribution Mains and Service Connections are higher than the Trunk Mains and Reservoir Leakage when the pressure is higher than 38 m, such as the current conditions in Zaragoza. For pressures under 24 m, the Trunk Mains and Reservoir Leakage becomes the leakage component with the highest volume.

4.12.3 Number of Reported Burst and Leaks in Distribution Mains

There is a perfect correlation between Number of Reported Burst and Leaks in Distribution Mains and Reported Burst Volume in Distribution Mains and Service Connections and Short-Run Economic Level of Leakage. The SRELL is definitely influenced by the number of Reported Bursts in Distribution Mains. This is a way to prove that reducing the number of bursts using Active Leakage Detection has an effect in reducing the ELL.

4.12.4 Number of Reported Bursts and Leaks in Service Connections

There is a lineal relationship between the Number of Reported Bursts and Leaks in Service Connections vs. Reported Burst Volume in Service Connections and Service Connections. However, it must be mentioned that the flow for the bursts in connections is smaller than the flow for bursts in mains. The Reported Burst Volume in Distribution Mains and Service Connections will be higher than the other leakage components. However is lower than the volume considered for the change in burst in mains.

Also, an investment in the repair of burst in mains will have a higher result in the reduction of SRELL than an investment in repair of bursts in service connections.

4.12.5 Cost of Intervention

The effect of the Cost of Intervention in the Economic Unreported Real Losses is definitely not as evident in the leakage volume. During this analysis, the highest leakage volume comes from Reported Burst Volume in Distribution Mains and Service Connections.

4.12.6 Survey Frequency

There is a strong negative correlation between Economic Intervention Frequency and An investment in survey frequency will generate a big reduction in the first year and then the reduction in the Leakage volume will not be so notorious. This can be explained in the concept of how is easier to detect big unreported leaks at the beginning of an active leak detection work. Later the smaller leaks will be harder to detect.

4.12.7 N1

The Estimated Background Leakage becomes a volume smaller than the other components when N1 is higher than 1.0. This might seems strange since a higher value of N1 would indicate a worse condition of the pipes and hence a higher level of leakage. But the value of N1 is used as an exponent of the ratio between the current pressure in the system and a condition of 50 m of pressure (Lambert, 2001) and since for the pressure in the system the ratio will be smaller than 1, a higher value of N1 will result in an smaller value when this ratio is elevated to N1.

4.12.8 Conclusions from Sensitivity Analysis

The Sensitivity Analysis showed the direct effect the RR has in the Economic Unreported Real Losses. This calls for attention in the calculation of this variable. In the case of Zaragoza, the analysis of a Water Balance for the Actur area allowed the calculation of this value. Zaragoza has really new areas, with pipes in a very good condition, and areas like the town centre with severe leakage problems. Actur area was considered as an "average" condition but it would be necessary to carry RR calculations for different city areas, using field tests. A second step after the calculation of the ELL in Zaragoza could be the calculation of the RR, considering the possible changes associated with seasonality.

The Average System Pressure (ASP) (Section 3.11.1) was obtained for two sectors in the Actur area, using a field test (Section 4.2.2 and Section 4.2.6). However this field test is not representative of the city conditions for Zaragoza. The conditions reflected in the results are for spring. The analysis requires year round data, which can be collected easily implementing a pressure sensing network. Even considering that Zaragoza is rather flat, the pressure conditions of the Actur zone are not representative of the city wide system.

Section 2.3.4 mentioned that the influence of pressure on leakage is adjusted using the concept of N1 exponent. As showed in the Sensitivity Analysis in Section (4.11.8), this adds a layer of need to guarantee a reliable value. The effect of the Pressure was quantified in Section 4.11.3. Only the Trunk Mains and Service Reservoir Leakage is not affected by the pressure directly in the model.

An update of the component of the Trunk Mains and Service Reservoir Leakage is needed so, eventually, the effect of pressure will be considered. Investing in measuring is a key part for the water utility and the lack of reliable, year-long data is an important gap in Zaragoza. So the implementation of a SCADA system or investment in pressure sensors is recommended.

This brings us to the issue of the pressure reducing valve in Sector 4 (Section 4.2.1) to evaluate the effect of pressure in the leakages. The water utility has the project of analysing this data but so far they haven't got enough information. The Water Utility should make the most of this available data

The cost of lost water refers to the costs of actually producing and distributing water of an acceptable quality. The costs of leakage management are those associated with detecting and repairing the leaks. The Water Utility should have this very clear, especially for the analysis of future projections. In Zaragoza there is information about the volumes of water saved, in a very general way as it was showed in Table 4.25 in Section 4.2.11, but there is no information about costs that can be used for a projection. To relate volumes with costs or to "give a price to the lost water" allows the justification of the investment in leakage control, especially in Water Utilities with limited budget.

5 CONCLUSIONS

This research has showed the application of a model for leakage and emissions associated with the leakage control. The model is based on data that could easily be collected by practitioners. The analysis made in this study has given a theoretical ground to the model and extended it to include energy externalities associated with leakage control activities. The following sections will summarise findings, and draw conclusions and recommendations there from.

In Section 1.4 our research aims and objectives were defined. The aim was to contribute to the reduction of carbon emissions and control climate change through the development of a dynamic model for the determination of Economic Level of Leakage that considers changes in Energy Externalities associated with the Active Leakage Control activities. The use of a dynamic model is required since some of the conditions, like the energy costs and resources availability, are constantly changing. This change has an impact on the performance of the leakage control activities.

The specific research objectives were:

1) To develop a dynamic model for the determination of an Economic Level of Leakage considering the energy externalities associated with Active Leak Control, in a water distribution network.

2) To calibrate and test the validity and sensitivity of the developed dynamic model.

3) To perform the analysis of different scenarios strategies for water loss management in Economic Level of Leakage and study their effect on the active leakage control for the city of Zaragoza in Spain.

The proceeding sub-sections present conclusions for the specific objectives and research aim.

5.1.1 Conclusions on Research Objective 1

To develop a dynamic model for the determination of an Economic Level of Leakage considering the energy externalities associated with Active Leak Control, in a water distribution network

The most important result of the model is the Economic Level of Leakage (ELL). This result can include the cost of the energy externalities associated with the Active Leakage Control activities. The ELL obtained from the model can later be adapted for a Long Term ELL analysis. It is a first step that can be improved and give the Water Utility information to be used in later implementation stages to improve the system performance. After all, as it was mentioned in Section 1.3, a system failure has a direct influence on the performance, which is related with the demand. A high demand and a bad performance will result in service problems with the users while a low demand and good performance allows the water utility to focus on the future development of the system since a lower water use will reduce the energy and chemicals used in water abstraction, treatment and pumping.

The lack of data about Active Leakage control activities in the calculation of the ELL can be solved by implementing the BABE methodology. This methodology gives an accessible option compared to the data intensive methods presented by UKWIR, OFWAT and WRC. The Water Utility will be able to implement a data intensive method later, when the data has been obtained through method employed by this study.

This study found that the inclusion of energy externalities associated with active leakage management had only a minimal effect, on the ELL model. The use of the Scenario Analysis in Sections 4.5-4.10 was useful to achieve this conclusion. Therefore energy externalities can generally be ignored when estimating the ELL. However the future trend in energy and water management legislation would demand a tool that allows the quantification of the nexus between energy and water leakage management. This research makes a contribution towards covering this need.

This research allowed the quantification of the Energy Externalities associated to the leakage control tasks and in that way extended the ELL model. This calls for research on the effect of the externalities of other leakage management approaches.

This research validated the methodology and extended it with the inclusion of energy externalities associated with the Leakage Control activities. The validation process included a practical implementation in Zaragoza, Spain, providing a theoretical underpinning of that methodology.

5.1.2 Conclusions on Research Objective 2

To calibrate and test the validity and sensitivity of the developed dynamic model.

Chapter 4 showed how the model was validated and applied. However it is necessary to calibrate the data that was used to run the model. Although the quality of the data provided by Zaragoza's Water Utility is trustworthy, it might not be the case for data available in other locations. Furthermore, if new data will be included in the model, for example from new pressure measurements, it is necessary to guarantee that the measurements are made with calibrated instruments.

The dynamic model fulfilled the objectives and allowed the assessment of the impact in the water utility performance of the leakage control activities. However, it is desirable to perform more trials with data from different water utilities, and disseminate the use of the tool.

This research has showed that the use of graphical conceptualization and documentation tools, due to the use of Vensim, allows an easy way to illustrate the cause-effect relationships and the flow and interaction of the different variables.

The model needs to maintain a consistency in the units. This is critical because the model uses coefficients that relate flow rates, times, volumes and lengths. These quantities can be presented in units that are different to the ones used in the model and that can affect the results.

5.1.3 Conclusions on Research Objective 3

To perform the analysis of different scenarios strategies for water loss management in Economic Level of Leakage and study their effect on the active leakage control for the city of Zaragoza in Spain.

The comparison between the current ELL for Zaragoza and the current level of losses (Section 4.2) showed how investment in Active Leakage Control could result into reduced physical losses in the distribution network, and improve the performance of the water utility.

The sensitivity analysis showed that pressure and the number of repaired bursts in trunk mains and service connections had the biggest impact on the economic level of leakage calculations.

5.1.4 Conclusions on Overall Research Aims

This research allowed the quantification of the emissions associated with the Leakage Control activities and the effect they have in the ELL calculation. This research utilised a method that demanded less onerous data collection methods than those recommended by national agencies such as OFWAT, UKWIR and WRc. This can help out many utilities, especially those serving cities in developing countries, that lack adequate institutional capacity to collect very specific data over a long time, or data that can only be collected when certain practices or policies are implemented.

This research has used VENSIM, which is a cheap, powerful and easy to implement model platform to develop an extension of the ELL calculation. A water utility with low institutional capacity can apply this method to develop an ELL model easily and within the available economic resources.

5.2 Implications for Methodology

The use of the Burst and Background Estimate (BABE) (UKWIR/WRc, 1994) method is a valid option to help to calculate the ELL in a Water Utility without active leakage control programs. The amount of information and data needed for the implementation can be obtained by the water utility with a reasonable level of investment. As it was mentioned before, the Water Utility in Zaragoza had that data available but the need for information organization is key in the model implementation.

This methodology requires only three system-specific parameters: Cost of Intervention (CI), Variable Cost of Lost Water (CV), and Rate of Rise of Unreported Leakage (RR) (Lambert & Lalonde, 2005). Of these parameters, the most critical in the research was the RR due to the experimental nature. It is important to mention that an approximate assessment of the Rate of Rise is acceptable to get started on Economic Intervention calculations. The results obtained can be refined in a later stage.

As a premier approach to the calculation of the ELL, the use of Water Balances is good but for later stages is recommended the use of Measured Night Flows and to consider the effect of seasonality in these measurements. Furthermore, the night flow measurement facilities do not have to be continuous or permanent. The big issue with the calculation of the RR using Water Balances is the lack of good quality information to calculate the Water Balance. The implementation of a Standard IWA Water Balance appears again as the first step and need for the Leakage Management planning.

5.3 Contributions to Body of Knowledge

This research shows a real world application of a methodology for the ELL calculation in a Water Utility with no Active Leak Detection.

This research allowed the quantification of the Energy Externalities associated to the leakage control tasks and in that way extended the ELL model.

This research validated the methodology and extended it with the inclusion of energy externalities associated with the Leakage Control activities. The validation process included a practical implementation in Zaragoza, Spain, providing a theoretical underpinning of that methodology.

5.4 Recommendations for Policy and Practice

As it was mentioned in Section 2.6, in the UK, OFWAT makes compulsory the calculation of the ELL, but in the rest of the world there this is not an option. The Water Utilities in the rest of the world should understand the importance of this tool in the budget planning and make it a priority with the appropriate investments. This is also related to spreading the proper use of PI in the leakage management. For example the ILI (Section 3.12.18), CARL (Section 3.10.30) and UARL (3.12.17) are the kind of results that can be useful to identify future leakage control approaches.

The Pressure has an important influence in the model. Therefore, the investment in ways to measure or to measure and register this information is important. The equipment used for measuring and registration should be calibrated and keep calibrated to ensure quality in the measurements.

The Water Utilities should stop just storing information but make the most out of it. We believe that the main problem is not the lack of standardization between databases, since each team involved had their particular databases, but the lack of awareness of the information collected or considered by other teams inside the water utility. This awareness can be improved by sharing the access to information between teams. A centralized deposit can help solving this issue. The use of repair codes is a common practice, but sometimes they are vague. To standardize these codes can be helpful for the analysis process.

The use of Real time GPS tracking to deal with problems in the case of the Distance Driven for Leakage Control (Section 3.15.2). This information is available also as fuel volumes or fuel volumes cost, but there is always the possibility of fraud with this information. In this way, not only the utility will have the information about the current location of each vehicle but also obtain information about distances and response times. The Real time GPS tracking can even be implemented to work with a mobile phone network if necessary. This will also allow to discriminate between leak detection and leak control tasks via the inclusion of the data in the water utility GIS. This can also solve the issue of vehicles that are used for quick tasks that might not be part of leak detection and control.

The detection task and the repair tasks should be carried out by a workforce dedicated to Active Leakage Control. The tasks complement each other, and it comes down to the Water Utility to understand the tools and their effect. The calculation of the ELL helps in this stage since it reflects the effect of investment in the volume of water that can be recovered with that investment.

It is also necessary to consider the effect and scope of Apparent Losses. In the case of Zaragoza, the Apparent Losses (Section 2.2.1 and Section 3.10.28) were not an important part of the losses in the Actur area. However they tend to be an important part of losses in developing countries.

5.5 Limitations of the Research

Due to lack of data, informed assumptions were made to fill these gaps. There were no values for the Allowances for Real Losses from Service Reservoirs (ARLSR) (Section 3.13.5) and no references for the FAVAD N1 (Section 3.11.3 and Section 3.11.11). For the research we used an average condition of pipes, N1 = 0.5 for ICF = 1 according to (Fantozzi, 2007). However this does not affect the results since with the use of an average condition for the pipes, the background losses are underestimated and consequently the recoverable losses are overestimated, which balances both conditions.

This research also assumed the Pipe Length (Section 3.15.6) for the calculation of externalities. The use of a database, linked with the supply warehouse, would allow the use of a realistic value for this item. Also digging volume or work times can give a reference since they link the volume of the trench used in the repair process with the pipe length replaced. This can also be connected to the Coefficient for Emission from pipe lying (CEPL) (Section 3.15.7). In this variable the problem of considering an average pipe diameter and length after discussion was solved by obtaining data from experienced staff, involved in the repair tasks, who are reliable sources of "institutional memory".

5.6 Recommendations for Further Research

It would be also useful to investigate the effects of the other Leakage Management Approaches: pressure management, asset management, speed and quality of repairs, as mentioned in Section 2.3, on the ELL.

It would be useful to quantify the effect of the use of trenchless technology in the Leak Repair Process on carbon emissions, since they reduce the size of excavation and the restoration costs. This also can be related to the research on social disruption issue and the externalities associated.

The model developed in this study used the UKWIR estimation of the value of emissions from the use of labour (UKWIR, 2008) described in Section 2.7.3. Further research on adapting this value for tropical countries, considering no need for heating and the different travel conditions, could be carried out to estimate this value.

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6.1 Publications completed

The following published works are a result of this research

Smout, I.K., Kayaga, S.M. and Munoz-Trochez, C. “Incorporating Energy Use into the Economic Level of Leakage Model”. 2nd International Conference on Whole Life Urban Sustainability and its Assessment, Loughborough, UK, 22th–24th Apr/09

Smout, I.K., Kayaga, S.M. and Munoz-Trochez, C. “Financial and Economic Aspects of Water Demand Management in the Context of Integrated Urban Water Management”. SWITCH Scientific Meeting, Belo Horizonte, Brazil 30th Nov – 4 Dec/08

Munoz-Trochez C., Smout I.K. and Kayaga S.M. “Incorporating Energy Use into the Economic Level of Leakage Model – The Zaragoza Experience”. 4th SWITCH Scientific Meeting. Delft, Netherlands, 4th Oct - 7th Oct/09.

Munoz-Trochez C., Smout I.K. and Kayaga S.M. "Inclusion of Energy Externalities in the Economic Level of Leakage". 10th UK IWA National Young Water Professionals Conference. Cranfield, UK, 14th Apr - 15 Apr/10.

Munoz-Trochez C., Smout I.K. and Kayaga S.M. “Incorporating Energy Use into the Economic Level of Leakage Model”. 10th World Wide Workshop for Young Environmental Scientists WWW-YES 2010. Paris, France, 31th May - 4th Jun/10.

Smout, I.K., Kayaga, S.M. and Munoz-Trochez, C., ''Adapting the Economic Level of Leakage concept to include Carbon Emissions, and Application with Limited Data'', IWA, World Water Congress and Exhibition, Montreal, Canada, 19th - 24th Sep/10.

Munoz-Trochez C., Smout I.K. and Kayaga S.M. "Economic Level of Leakage (ELL) calculation with limited data. An application in Zaragoza". 35th WEDC International Conference, Loughborough, UK, 6th –8th Jul/11.