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THE RELATIONSHIP BETWEEN CONSUMER DEMAND AND PRESSURE IN A SELECTED PRESSURE MANAGED ZONE IN CAPE TOWN.

BY

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ABSTRACT

Water is a basic need and a limited resource across the world. Climate change, pollution, population growth, irrigation and urban development, among others, contribute to the issues faced with respect to availability of quality of water resources and security of water supply for consumption.

Pressure management, is the most common and feasible demand management initiative implemented by the City of Cape Town Metro. The main focus of these initiatives is to reduce water losses within the water distribution system. Influence of pressure on water consumption is also observed, but has not been as well investigated as with leakage-pressure relationships.

This study aims to assess the impact of change in system pressure on consumer water demand. To do this a pressure managed DMA and Control DMA was identified. The billed consumption data was analysed for 11 months before and 11 months after the pressure management period. A control DMA served to verify that the consumption reduction was as a result of pressure management and not any other intervention. Furthermore, this study involved the collection and analyses of the logged system flow data prior to and post commissioning of pressure management. Pressure is not fixed and varies overtime. The Average Zone Pressure was not available from logged data and was calculated by simulating the hydraulic model to reflect the system conditions prior and post commissioning of the pressure managed DMA.

Following that, an investigation into how the leakage responds to pressure was performed. Since the latter affects the demand response to pressure. It was then decided to separate the leakage from consumption. In order to do this, various leakage parameters were calculated and randomly distributed across the system. To analyse the leakage before and after pressure management, two types of models were used, namely 1) Epanet Model (based on the Orifice Equation) and 2) the Epaleaks Model (based on the Modified Orifice Equation).

N3 is the coefficient of elasticity. This coefficient represents the relationship between pressure and flow rate. Normal N3 analysis was performed on the available data. N3 was calculated for the system consumption, based on the logged data and a sample of the billed consumption records.

The power regression model suggests an N3 of approximately 0.05 to 0.06 for the system based on a sample of filtered billed consumption data. However, in the case of the entire system's end use consumption the N3 value is approximately 0.4.

Overall, the N3 values compared reasonably well with other studies in the range of 0.04 to 0.29 and in some cases ≈0.5.

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LIST OF SYMBOLS

A_0	Initial Leak Area
C	Constant Coefficient
C_d	Discharge Coefficient
g	Acceleration due to gravity
h	Pressure Head in meters
kL	Kilolitre
kL/d	Kilolitre per day
L/s	Litres per second
Lm	Length of mains
Lp	Length of underground pipe from street edge to customer meter
m	metres
N1	Leakage power law exponent
N3	Demand power law exponent
Nc	Number of service connections
Q	Flow rate
R^2	coefficient of determination
β	Elasticity of demand to pressure

LIST OF ABBREVIATIONS AND ACRONYMS

AADD	Annual Average Daily Demand
AC	Authorised Consumption
AL	Apparent Losses
AZP	Average Zone Pressure
BABE	Burst and Background Leakage
CARL	Current Annual Real Losses
CP	Critical Point
DMA	District Metered Area
DWS	Department of Water and Sanitation
FAVAD	Fixed and Variable Area Discharge
ILI	Infrastructure Leakage Index
IWA	International Water Association
MNF	Minimum Night Flow
PRV	Pressure Reducing Valve
SIV	System Input Volume
TE	Treated Effluent
UARL	Unavoidable Annual Real Losses
TARL	Targeted Annual Real Losses
WC	Water Conservation
WDM	Water Demand Management
WDS	Water Distribution System

1. INTRODUCTION

The National Water Act (1998), of South Africa, recognises that water is a scarce and unevenly distributed resource which occurs in many different forms. It also recognises that the ultimate aim of water resource management is to achieve the sustainable use of water for the benefit of all users.

Water is a basic need and a limited resource across the world. Climate change, pollution, population growth, irrigation and urban development, among others, contribute to the issues faced with respect to availability of quality of water resources and security of water supply for consumption (Gumbo, 2004; Jorgensen, Graymore and O'Toole, 2009).

Water utilities in developing countries are putting much effort into providing consumers with a reliable level of service, often through aged infrastructure and limited budgets. Factors which contribute to water losses and wastage include ageing infrastructure, high pressures, external and internal pipeline corrosion, reservoir and tank overflows, poorly designed and constructed water distribution systems (WDS's), metering errors, illegal use, poor operations and maintenance practices and wasteful usage of water within the household (Babić, Đukić, and Stanić 2014).

The ability to understand the condition and operations of water distribution systems is one of the key factors to minimising water losses and wastage (Babić, Đukić, and Stanić, 2014). Water utility operators have long known that throttling down system pressure reduces total consumption, and this strategy is sometimes used to deal with short-term water shortages (Moll, personal communication, 2016; Bemezai and Lessick 2003).

An Integrated Water Resource Planning (IWRP) study carried out in 2001 indicated that various Water Demand Management and Water Conservation (WC/WDM) initiatives are the most feasible water augmentation options to meet the growing water demand for the City of Cape Town (IWRP, 2001). Of the various demand-side initiatives, pressure management is considered a reliable and cost-effective type of demand-side intervention which achieves the desired water savings at the low cost (Fantozzi, 2015).

Influence of pressure on water consumption is also observed, but have not been well investigated as with leakage-pressure investigations. There is a need to develop more accurate methods to predict total water savings (to include savings on reduced excessive consumption) due to pressure reduction. This is of particular interest to utilities especially in the case where water wastage or excessive usage is observed (Babić *et al*, 2014) and could further impact on the expected revenue.

According to Thornton and Lambert (2005), pressure management is defined as "The practice of managing system pressures to the optimum levels of service ensuring sufficient and efficient supply to legitimate uses and consumers, while reducing unnecessary or excess pressures, eliminating transients and faulty level controls all of which cause the distribution system to leak unnecessarily". Besides holding the benefit of reducing system water losses, it also serves to ensure equitable distribution of water to end consumers (improved service delivery) and reduce inefficient water usage.

While municipalities and various water service providers are continually looking to secure future supply, and reduce the level of water losses, through repair and replacement of infrastructure, consumer behaviour is another factor which needs to be addressed when dealing with water demand. Reducing demand through the improvement of water use efficiency forces one to understand how water is used and in what ways water savings can be realized (Jorgensen et al, 2009).

Consumer demand comprises of indoor and outdoor consumption. Indoor consumption would include toilet usage, bathing, showering, cooking and cleaning while outdoor usage will include watering of the garden or filling of a pool.

Many studies (Farley and Trow, 2003; Fantozzi, 2015) around the impact and success of pressure management (as a demand management intervention) on reducing leakage and improving network performance within distribution systems are available. Many of these studies aimed to determine the relationship which occurs between pressure and the leakage rate and burst frequency. However, not many studies had focused on the impact that this pressure reduction will have on the end user consumption and even less studies attempt to determine the relationship between demand and pressure and then attempt to model relationship. In addition, those studies which do compare pressure and demand measured values, often only use the average pressure before and after pressure management and would not look at the diurnal demand and pressure variation in the system.

1.2. AIMS AND OBJECTIVES

The aim of this study was to investigate the impact of system pressure on water demand (elasticity of demand to pressure) on a select pressure managed zone in the City of Cape Town (CCT) and a control zone. This investigation aimed to analyse user consumption and logged system flow and pressure before and after pressure management. In addition to analysing the field data, this study further aimed to simulate the system conditions before and after pressure management through the use of hydraulic modelling to investigate the impact of diurnal pressure variations on the N3 factor.

The specific objectives of the study were as follows: -

- To review the latest research on the impact of pressure on demand in water distribution systems
- To select a pressure managed zone and gather the consumption data before and after pressure management
- To identify a non-pressure managed area which can act as a control for this study
- To analyse the consumption before and after pressure management and determine the impact of pressure on consumer water demand
- To analyse the leakage before and after pressure management and compare the results produced from the N1 (Epanet model) and FAVAD (Epaleaks model) model. These models were also used to model the variation of leakage overtime.
- To separate the modelled leakage from consumption in order to establish the relationship of demand to pressure.

1.3. DELINEATION AND LIMITATIONS

There are a number of factors, such climate, irrigation requirements, household income, and household size, etc., that may influence consumer water demand in a Water Distribution System (WDS). This study will only look into the impact of pressure reduction on a pre-selected, pre-existing pressure managed zone and will be based on the pressure step change which occurred at the time before and after the pressure managed zone was commissioned. The impact of other factors affecting consumer demand will not be assessed. This study will not look at the impact of pressure on the individual components of water demand within the household and will only focus on the entire average household consumption.

This investigation will focus on determining the pressure elasticity of demand, denoted by ε or N3.

1.4. ORGANISATION OF CHAPTERS

This study consists of five chapters. Chapter One provides the introduction and study proposal.

Chapter Two analyses the relevant literature in order to develop an understanding of the problem under investigation. This review provides an overview of the water distribution systems in general followed by an in-depth review of the factors which impact on water consumption and the associated relationships. The main focus will be on the impact of pressure on consumer water demand.

Chapter 3 describes the case study, methodology and system properties required for the pressure-demand analysis. A quantitative research method was chosen in order to determine the impact of pressure reduction on consumer water demand. A single pressure managed zone was selected. The data extracted included the billed consumption data and logged pressure and flow data for the period of a year before and a year after pressure management. This DMA was selected based on the fact that it had the most data available for analysis. The pressure managed zone was then simulated into a hydraulic model. The system was simulated on the N1 based hydraulic model and on the recently developed FAVAD based hydraulic model. The outcome of the two models were compared.

Chapter 4 presents the results of the study on the impact of pressure on demand at different time scales considering the impact of two different leakage models on the relationship. This section further makes the comparison between various N3 values obtained and that obtained from other studies. The limitations to the study are also summarised in this section.

Chapter 5 presents the concluding remarks on the findings followed by recommendations for further investigations.

2. LITERATURE REVIEW

2.1. GENERAL OVERVIEW

Water, more specifically, safe drinking water is a limited resource. South Africa is a semi-arid country where available water is further constrained. A sustainable water supply system, and water usage, is of vital importance for the well-being of people.

Although distribution systems, around the world, may vary according to size and complexity, they serve the same purpose which is to transport water from the source to the end consumer (Walski, Chase, Savic, Grayman, Beckwith and Koelle, 2003). Generally, water supply systems comprise of the following processes, namely, raw water extraction and transport, water treatment and storage and clean water transport and distribution (Walski et al, 2003; Trifunović, 2006). This infrastructure is of course provided at large costs. For this reason, it is important to ensure that not only the losses within the system are reduced (or even eliminated) but to ensure that consumer water usage is efficient.

The water distribution network, which supplies the consumers, consists of a network of pipes, with a number of connections, which supply water directly to the end user. The flow variation within this system varies greatly as there are more than one type of consumption patterns found within these systems. The main design objective of the water distribution systems (WDS) is to ensure that sufficient quantity of water is supplied and maintained at good quality for end user consumption (Trifunović, 2006). Badly designed systems (in terms of material type, pipe sizing, and placement) are factors which can compromise on the reliability of the WDS and quality of water delivered (Wagner, Shamir, Marks, 1988; Pieterse-Quirijns, Blokker, van der Blom and Vreeburg, 2011).

2.2. URBAN WATER DEMAND MANAGEMENT

Many definition variations of water demand management have been developed but according to (Herbertson and Tate, 2001) water demand management can be described as "the management of the total quantity of water abstracted from a source of supply using measures to control waste and undue consumption".

It has been determined and agreed, that while supply side options need to be considered in order to ensure security of supply (such as a new augmentation scheme), demand side management or rather water demand management has been considered as the most efficient and effective type of augmentation scheme to ensure security of supply. Demand-side management is performed by reducing water losses, and influencing demand to more desirable levels through the application of various interventions (Gumbo, 2004; Gumbo, et al, 2003).

2.3. TOTAL WATER DEMAND

Water demand, which is synonymous with water consumption, is the main parameter which impact on the design of WDS and is the main driving force behind the hydraulics occurring in WDS (Walski et al, 2003; Vertommen, Magini, and da Conceição Cunha, 2014). Theoretically, the term water demand (Q) coincides with water consumption, however in practice, demand is monitored at the points of supply where measurements include leakage, and volumes of water used to fill balancing tanks which may exist in the system (Trifunović, 2006).

There is a continual need to understand and predict urban water consumption particularly with the reduction of urban sprawl and the increase in urban densification. The latter is particularly important when designing water distribution systems. When designing WDS it is important to understand the quantity of water being used, by whom (or consumer type/category), the user characteristics (what drives their water usage) and time of day that water will be used (demand pattern).

2.3.1. Categories of water demand

Understanding water consumption at the end use level is critical due to the fact that the overall domestic water consumption is made up of different water end use events. According to Actcoss and Ccserac (2003, referenced in Willis, Stewart, Panuwatwanich, Williams, and Hollingsworth, 2011) water usage is categorised into two main areas: non-discretionary and discretionary. Non-discretionary water is used to define the minimum water used within the house to meet daily consumption and sanitation needs (e.g. shower, clothes washing); whereas discretionary end uses are additional non-essential use activities (e.g. irrigation, pool use).

Household consumption or typically, domestic water usage, is defined as water that is used by a household for indoor and outdoor purposes which include all things the user does at home which may include drinking, preparing food, showering, bathing, clothing washing and dishes washing, teeth brushing, water the garden, washing your car or washing your pets.

Buchberger and Wu (1995) indicated that residential water use is the largest single category water consumption often exceeding 50% of the total urban demand. Most indoor water use occurs inside the bathroom where toilets, showers and baths account for most of the average demand. SGS,2016).

Additional to being comprised of indoor and outdoor usage purposes, studies have identified that leakage, within the household plumbing, is another factor which contributes to the total consumption figure (Willis et al, 2009; Beal, Stewart, Huang and Rey, 2011; Loh and Coglan, 2003; Lugoma, van Zyl and Ilemobade, 2012).

Three basic demand types exist (Walski et al, 2006). These include:

- Consumer demand: This demand is required to meet the non-emergency needs of consumers. This is generally the metered portion of the demand which is recorded within the billing system.
- Water losses: This refers to the loss of water either through failed infrastructure or meter inaccuracies and illegal connections.
- Fire flow demand: this refers to demand required during an emergency event. The WDS is required to be designed in order to cater for such a demand event.

The consumption categories for consumer demands can be further categorised into the following (Walski et al, 2006; Butler and Fayyaz, 2006):

- Non-domestic consumption that occurs in industry, agriculture, institutions and offices, tourism and livestock (Walski et al, 2006; Butler and Fayyaz, 2006; Farley and Trow, 2003).
- Domestic consumption refers to the water used for toilet flushing, bathing and showering, laundry, dishwashing, cooking, cleaning, gardening and recreational water related purposes.

Understanding water consumption at the end use level is critical due to the fact that the overall domestic water consumption is made up of different water end use events. The Council of Social Services and the Conservation Council of the South Eastern Region and Canberra, Australia (2003) categorise water usage into two main areas: non-discretionary and discretionary. Non-discretionary water is used to define the water used within the house to meet daily consumption and sanitation needs (e.g. shower, clothes washing); whereas discretionary end uses are additional non-essential use activities (e.g. irrigation, pool use). In the case of non-discretionary water use activities, people have moved to over-use of the water volume required to meet the basic needs.

2.3.2. Demand Patterns

There are different demand patterns for different demand categories. Demand patterns are still able to vary for each of the categories depending on the activity which has taken place. Design and modelling of water distribution systems are based mostly on the expected trend in water consumption pattern (Walski *et al*, 2006, Trifunović, 2006).

In residential demand areas, the demand pattern varies from the time of day, day of week, month and season of the year. For instance, daily demand will record a different pattern to the demand at night. The demand pattern for a week day may also have a different pattern compared to the demand over a weekend or holiday period. Socio-economic factors also impact on the expected water demand pattern for residential users. The general expectation is that residential users should have early morning consumption peaks during the day, when people wake, to go to work or school they would shower, cook, clean dishes, etc., and then later in the evenings when people return home from work or school when they would possibly cook, shower, wash clothing, etc.

Diurnal patterns demonstrate the demand or consumption across a day in hourly intervals, refer to **Figure 2-1**. This pattern varies depending on the population, weather, the time of year, the day of the week (i.e. weekday versus weekends), season and residential consumption characteristics (Carragher, Stewart and Beal (2012)).

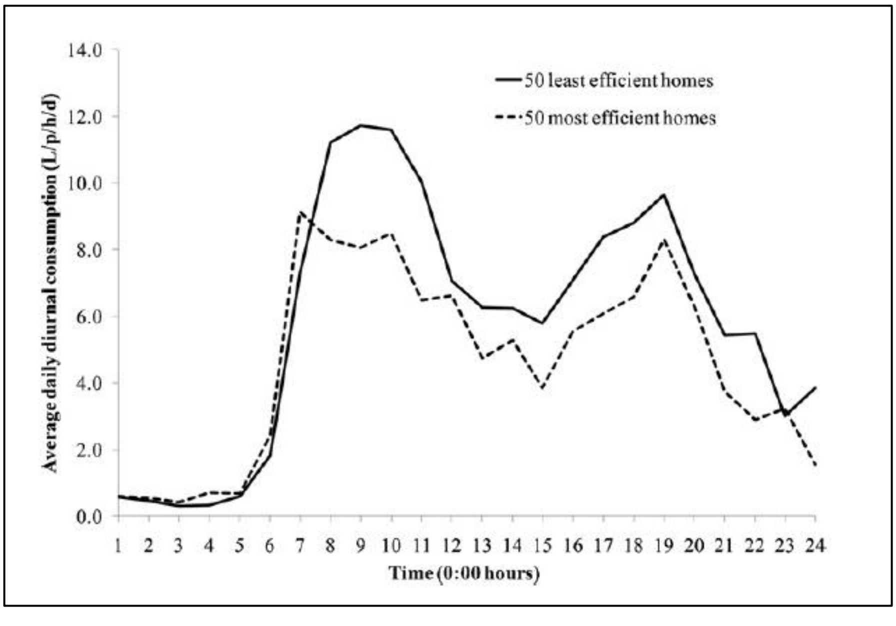

Figure 2-1: General residential diurnal pattern as shown by Carragher et al (2012)

Non-residential consumers have diurnal patterns which are completely different from residential users (Pieterse-Quirijns et al, 2011), refer to **Figure 2-2**. The demand for this type of consumer is highest when people arrive at work and remains fairly constant throughout the day until people leave for home from work. Large users, such as wet industries (or factories), may have operations which run throughout the night. Their diurnal demand pattern may display as a constant flow with minor and more frequent peaks than that of commercial.

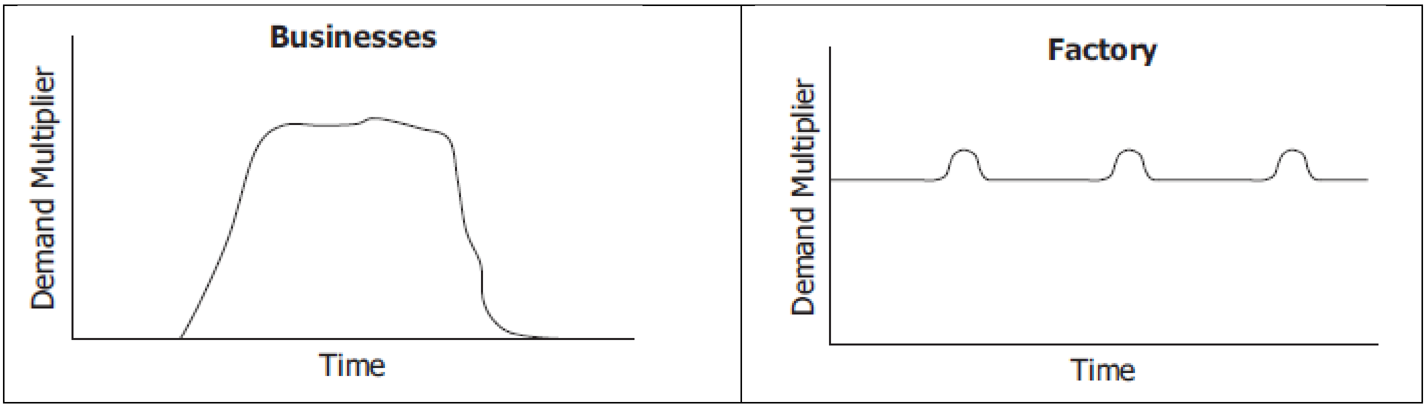

Figure 2-2: General diurnal patterns for a non-domestic user (Business and Factory) (Pieterse-Quirijns et al, 2011)

2.3.3. Drivers of Water Demand

Understanding water consumption at the end use level is critical due to the fact that the overall domestic water consumption is made up of different water end use events. According to Actcoss and Ccserac (2003, referenced in Willis, Stewart, Panuwatwanich, Williams, and Hollingsworth, 2011) water usage is categorised into two main areas: non-discretionary and discretionary. Non-discretionary water is used to define the water used within the house to meet daily consumption and sanitation needs (e.g. shower, clothes washing); whereas discretionary end uses are additional non-essential use activities (e.g. irrigation, pool use). In the case of non-discretionary water use activities, people have moved to the over-use of the water volume required to meet the basic needs.

The overall trend in water consumption varies from country to country. Increase (or decrease) in demand generally originates from increase (or decrease) in population, climate change (extreme weather conditions), drought conditions and cost of water.

There are a number of drivers for water use behaviour. Jorgensen *et al*, (2009) listed a set of drivers of water usage behaviour which are collated and summarised in **Table 2-1**. These include both direct and indirect drivers. These drivers are further discussed below **Table 2-1**.

Table 2-1: Drivers of water usage behaviour (Jorgensen *et al*, 2009)

Direct	Indirect
Climate/ Seasonal variability	Person characteristics
Incentives/Disincentives (Tariff Structure)	Institutional Trust (trust in the water provider)
Regulations and ordinances (water restrictions; Bylaws)	Inter-personal trust (trust in the consumer)
Property characteristics (area; pool; size; borehole; tank)	Fairness
Household characteristics (income; water saving and supply technology)	Environmental values and conservation attitudes
Person characteristics (direct intention to save water)	Socio-economic factors

In addition to the above, drivers for water use behaviour, pressure within the water distribution system also has an effect on pressure dependent components within household. These are further discussed in other sections of this Chapter.

The following section provides additional clarity on some of the direct and indirect drivers.

The below direct drivers are explained in slightly more detail:

- Garden or irrigation requirements depend on factors influencing vegetation growth. These factors include rainfall, runoff, infiltration, root zone storage and evaporation. (Jacobs and Haarhoff, 2004).
- Jacobs, Scheepers and Sinske (2013), indicated that household plot size has a definite impact on average annual average daily demand. Their investigation provided insights into estimating water demand based as a function of total land area.

The below indirect drivers are all linked to human behaviour characteristics and in some cases may vary.

- Fairness refers to the decision making processes, tariffs, installation of new pipelines and water restrictions implemented on specific user groups within a utility where these are being implemented. There however is no clear definition of a group or characteristic household that can be fully defined under this category (Jorgenson et al, 2009).
- Inter-personal trust refers to the belief that consumers have that other consumers are saving water which directly affects their behaviour toward being more water conservative.
- Institutional trust is the trust that the consumer has the water service authority is doing all it can to ensure there is sufficient water.
- Environmental values and conservation attitude would relate again to the individual user and their convictions to being environmental conscience.
- Person characteristics refers to one’s attitude and behavioural control toward water conservation which can be very subjective.

2.3.4. End User Demand Consumption Studies

There is a continual need to understand and predict urban water consumption particularly with the reduction of urban sprawl and the increase in urban densification (Willis, Stewart, Williams, Hacker, Emmonds, and Capati, 2011; Stewart *et al*, 2010).

A number of end-use studies have indicated that household water consumption is dependent on a number of factors such as: number of people in the household, age of residents, education levels of residents, property size, income, efficiency of water use devices (such as washing machine, shower heads, tap fittings, dishware and toilets), beliefs and pressure within the water distribution system.

Giurco, Carrard, McFallan, Nalbantoglu, Inman, Thornton and White, 2008, stated that the by having knowledge of the end use water consumption one is able to look into demand management initiatives in order to offset some of the end uses with alternative supply sources and thereby achieving savings in water usage. This end use data assists in refining and validating the design assumption parameters that influence the planning of water services infrastructure.

External consumption appears to be most affected by price of water, income and water distribution pressure.

PRICE ELASTICY

A study conducted by Viljoen, 2016, indicated that large stand sizes used more water than smaller stand sizes. This is confirmed by a study conducted by Husselman and van Zyl, 2006.

The collection of end use data also assists with verification of other demand forecast factors including diurnal patterns and peaking factors like maximum day, mean day, maximum month and maximum hour. Diurnal patterns demonstrate the demand or consumption across a day in hourly intervals. This pattern varies depending on the population, weather, the time of year, the day of the week (i.e. weekday versus weekends), season and residential consumption characteristics

INCOME

According to Loh and Coglan (2003), **Figure 2-3**, in single residential households there is a strong relationship between usage and socio-economic level of the area in which a household is located.

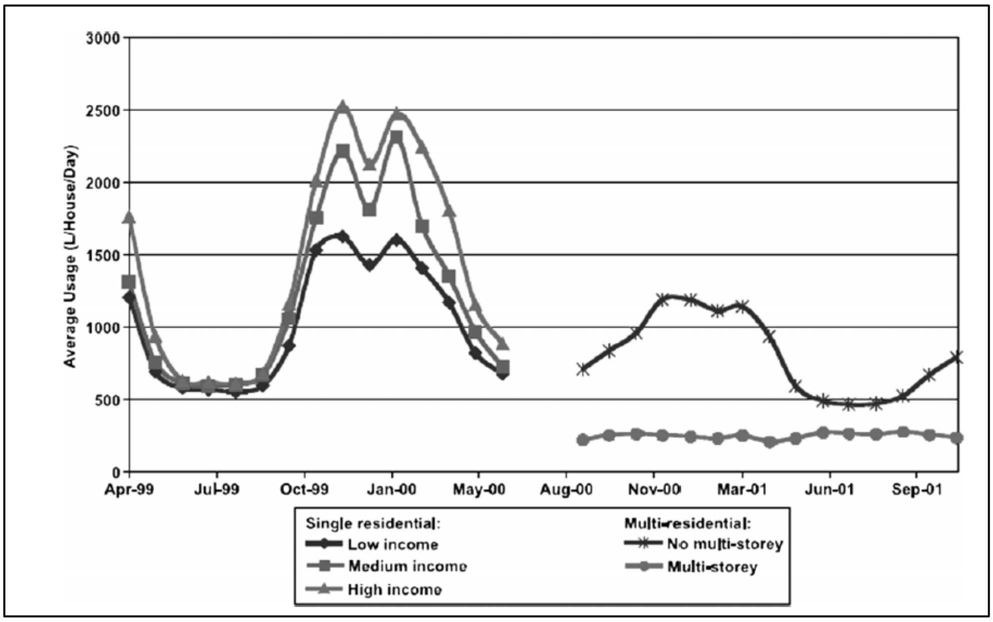

Figure 2-3 : Average monthly usage of different households (Loh and Coghlan, 2003)

CLIMATE

Viljoen (2016) also indicated that there was a correlation between water consumption and mean annual temperatures and rainfall. Areas where the mean average temperature was high and the rainfall was low, were reported to have higher water consumption.

Water usage behaviour within the winter periods remain fairly consistent with little to no variation. However, water usage behaviour in the summer period varies considerably. According to Loh and Coglan (2003) this suggests that indoor usage is similar irrespective of season, however the outdoor usage is very different in that more water will be issued in summer for irrigation purposes or filling up of pools during the summer periods.

PRESSURE

By understanding the end use components and their sensitivity to pressure, one can identify where actual potable water can be saved through pressure management as a water demand management initiative (Stewart, Willis, Giurco, Panuwatwanich and Capati, 2010). Van Zyl *et al* (2003) stated that, when one excludes on-site leakages beyond the consumer meter, the impact of pressure on demand was likely to be small but noticeable.

STAND SIZE

A study by van Zyl et al. (2007), showed that stand area can be considered as one of the most influential factors impacting on the consumer demand. Properties falling within the range of 200-300m^2 were using more water than those which fell within the 50-199m^2 range. In addition, properties of a lower property value (<R200 000) used less water than those valued between R200 000-R800 000. Properties within the range of 900 – 1299m^2 where using more than 50% more water than those which fell within the 200-399m^2 range (Viljoen, 2016).

ENVIRONEMTNAL AND WATER CONSERVATION ATTITUDES

Willis et al, 2010, completed a study which investigated, through the use of smart metering technology, the link between the environment and water conservation attitudes and observed end use water consumption. This investigation confirmed that those households with a positive outlook on the environment and water conservation used less those with a more moderate outlook.

Willis, Stewart, Williams, Hacker, Emmonds, and Capati (2011) investigated the impact of offsetting potable water usage with treated effluent (TE). This TE was used for irrigation and toilet flushing only and replaced the total consumption by 32.2% of which irrigation contributed 15.7% of the total reduction in consumption. This resulted in a significant reduction in the peak demands.

HOUSEHOLD LEAKAGE

Nguyen, Zhang, and Stewart (2013) obtained data from a sample of 252 residential dwellings located in South East Queensland (SEQ), Australia, collected from high resolution smart water meters measuring different end-use categories. Leakage was characterised at 0.167L/min.

According to Willis et al, 2009, household leakage is 1% of total consumption. Beal, Stewart, Huang and Rey (2011) determined a household leakage of 6% of total consumption. Loh and Coglan (2003) determine household leakage of 2% of total use for single and multi-residential households. A study by Lugoma, van Zyl and Ilemobade (2012) revealed that on-site leakage for residential properties and non-residential properties is approximately 25% of measured consumption. This study was conducted on sample of 233 properties which were situated in well-established suburbs in the City of Johannesburg. These properties were equipped with meters less than 5 years old. This study did not include low income areas or informal settlements. In order to eliminate the possibility that the on-site leakage measurements included legitimate water consumption, the property occupants were notified of the planned investigation and the occupants were asked to switch off all water fixtures for the duration of the test.

An initial reading was taken followed by subsequent readings. If a leak was identified the procedure was repeated. Of the 233 properties sampled for the study, only 79% of the properties (182) were accessible. From the study it was clear that the leakage was not constant but varied. 64% of the 182 properties had measurable onsite leakage. The leakage incidence was higher for residential properties (67%) than “other” properties (57%). This leakage is considered to be high when one takes into account that the suburbs were well established with fairly new meters. The average leakage rate for all properties were 23.5L/h or 17kLper month. Although “other” properties had a lower leakage incident, the average leakage rate was much higher at 40L/h or 29kL per month. In comparison to international studies, it appears that in the South African context, household leakage is well above the range of 1 to 6% of total consumption.

There are various categories that may influence end user demand, from demographics, personal behaviour, household leakage and pressure. While pressure may have a small but notable impact on demand (with no on-site leakage) it’s often the unpredictability of consumer behaviour which may over-ride this relationship.

2.4. IWA WATER BALANCE

Although regular pipeline inspections seem like a preferred direct method to understand what the condition of infrastructure is and the areas that require targeting for demand side management, it can be costly and unaffordable. Indirect assessments of water distribution system condition based on the water balance and certain performance indicators are more practical.

Water efficiency is described as the ability to do as much as possible with every "drop" of water and applying the least amount of effort per "drop" ("Water efficiency, n.", 2017). Therefore, one can conclude in order to reach this level of efficiency, one would need to account for every drop of water treated and supplied. The ability to account all of the water used within the distribution system provides one with a good interpretation of how well the system is operating.

In order to manage water efficiently, a standard water balance was proposed by the International Water Association (IWA) as given in **Table 2-2**. The components are discussed following the table. The components in the **Table 2-2** are aligned, sequentially, to the corresponding definition. The standard water balance methodology, developed by the IWA, and wide range of performance indicators (such as the Infrastructure Leakage Index (ILI)) for benchmarking utilities provides good and practical guidance on where to target your WDS in order to notice improvements within both consumption wastage and network water losses.

The IWA have developed a standard water balance, which measures the efficiency of your water distribution system by subtracting the system input volume from the billed water delivered to consumers (termed revenue water). The balance is termed Non-Revenue Water (NRW).

Non-revenue water consists of unbilled authorised consumption (such as water for firefighting, flushing or informal settlement usage), apparent losses (such as meter reading inaccuracies, illegal connections, and data transfer issues) and real losses. Real losses include tank overflows, leakage on mains, distribution network and service connections (Babić et al, 2014; Lambert and Hirner, 2000; Wegelin et al, 2010).

Table 2-2: Generic Non-revenue Water Balance

System Volume Input (1)	Authorised consumption (2)	Billed Authorised Consumption (4)	Billed Metered Consumption (8)	Revenue Water (17)
			Billed Unmetered Consumption (9)	
		Unbilled Authorised Consumption (5)	Unbilled Metered Consumption (10)	Non-Revenue Water (18)
			Unbilled Unmetered Consumption (11)	
	Water losses (3)	Apparent losses (6)	Unauthorised Consumption (12)	
			Consumers Meter Inaccuracies (13)	
		Real losses (7)	Leakage on transmission and distribution mains (14)	
			Leakage at overflows on storage tanks (15)	
			Leakage on service connections up to the point of consumers meter (16)	

IWA Water Balance Table Definitions

(1) **System Input:** Volume treated water supplied to consumers
(2) **Authorised Consumption:** Volume metered and authorised unmetered water taken by consumers.
(3) **Water Losses** (unaccounted for water): Volume lost through the system as either apparent or real losses.
(4) **Billed Authorised Consumption**: Volume billed including “Free Basic Water” which is billed at a zero rate.
(5) **Unbilled authorised consumption:** Volume authorised water consumed but not billed or paid for.
(6) **Apparent losses:** Losses due to theft, illegal use; meter inaccuracies or billed data transfer discrepancies.
(7) **Real losses:** Physical losses from the pressurised system up the point of consumers use.
(8) **Billed metered consumption:** Consumption from formal consumers (internal & external) obtained from SAP billing data.
(9) **Billed unmetered consumption:** Refers to the consumption billed at a zero rate. Always zero for Cape Town.
(10) **Unbilled metered consumption:** Informal settlement consumption & estimated unbilled metered formal consumption (e.g. new developments not yet on the system).
(11) **Unbilled unmetered consumption:** Estimated consumption from unmetered formal developments (e.g. new formal development that do not yet have a meter installed).
(12) **Unauthorised Consumption:** Theft or illegal use (estimated).
(13) **Consumers Metering Inaccuracies:** Due to consumer meter under-reading (estimated).
(14) **Leakage on transmission and distribution mains:** Physical losses from leaks or bursts.
(15) **Leakage and overflows at storage tanks:** Physical losses from reservoirs & reservoir cleaning.
(16) **Leakage on service connections up to point of consumer’s meter:** Physical losses on the service connections up to the consumer’s meter. For the CCT this is **c**alculated based on IWA Infrastructural Leakage Index (ILI) standards.

A number of tools have been developed in order to assist Utilities in determining their level of losses, within their municipalities, to a greater level of accuracy. The Water Resource Commission (WRC) has been active in initiating and supporting research that is looking and experimenting on efficient ways to manage the demand on the water resource. Tools identified to better manage demand are described as follows:

2.4.1. Burst and Background Estimate (BABE)

The Burst and Background Estimate (BABE) methodology has formed the pillars under which WRC has developed their models. It provides an approach of developing and quantifying background leakage. The main components of the BABE procedure include:

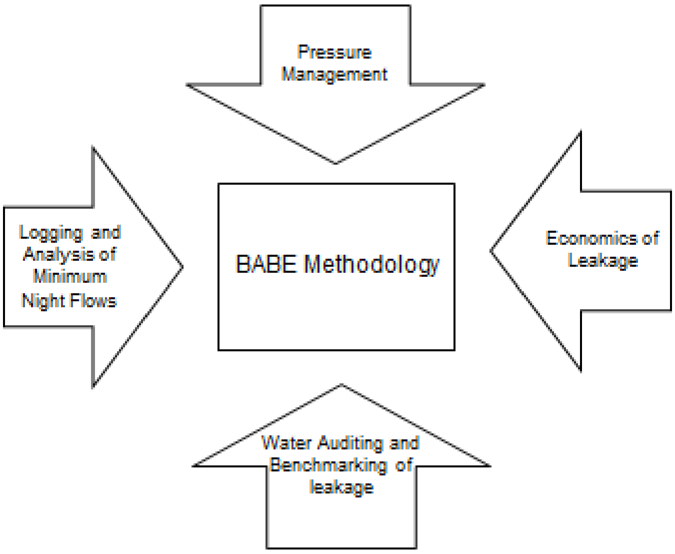

Figure 2-4 Components of BABE methodology (McKenzie and Lambert, 2002)

From **Figure 2-4**, it can be seen that the four main elements of BABE include:

- Water auditing and benchmarking of leakage
- Logging and analysis of minimum night flows
- Economic levels of leakage
- Pressure Management

Based on the above, four models were developed by the WRC. These include:

2.4.2. Benchleak Model (Benchmarking of leakage)

This model represents the current “best practice” when determining the acceptable level of leakage within a WDS (McKenzie, Lambert, Kock, Mtshweni, 2002). This model carries out several basic functions.

The model provides guidance on estimating Current Annual Real Losses (CARL). This estimate is based on the top-down approach where the CARL can be calculated from **Equation 2-1.**

$$CARL = SIV - AC - AL \tag{2-1}$$

It provides a formula on how to estimate the Unavoidable Annual Real Losses (UARL) occurring from the system. UARL is the lowest level of achievable losses, for any combination of mains length, number of connections, consumers meter location and average operating pressure. This methodology is described, in **Table 2-3** and can be calculate using **Equation 2-2**.

Table 2-3 Components of UARL

On Mains:	**18 litres/km mains/day/metre of pressure**
On service connections (up to property boundary)	0.8 litres/service connection/day/ metre of pressure
On service connections (property boundary to consumers meter)	25 litres/ km/ day/ metre of pressure

$$\text{UARL} = (18 \times \text{Lm} + 0.80\text{Nc} + 25 \times \text{Lp}) \times \text{P} \tag{2-2}$$

Where:

UARL = Unavoidable annual real losses (L/d)

Lm = Length of mains (km);

Nc = Number of connections;

Lp = Length of underground pipe from street edge to customer meter (km);

P = Pressure (m)

Once the CARL and UARL has been calculated, the severity of the leakage in the system can be evaluated. The ILI, a non-dimensional index, is used to compare the current leakage (CARL) with the theoretical minimum leakage (UARL). Represented by **Equation 2-3.**

$$\text{ILI} = \frac{\text{CARL}}{\text{UARL}} \tag{2-3}$$

Where the theoretical low limit is one. The higher the ILI the higher the leakage in the system.

The target annual real leakage (TARL) for the system, is then developed by selecting an appropriate multiplier or Target Loss Factor (TLF). For example, it may be appropriate to set the acceptable leakage at three times the UARL. In that case, a demand multiplier of three would be used.

The difference between the CARL and TARL, provides the estimated potential savings in leakage (PSL).

2.4.3. SANFLOW Model (Background Night Flow Analysis Model)

McKenzie, 1999, developed a model which applies a standardised approach to evaluate burst and background losses in WDS in South Africa. This model is based on the techniques used in the Burst and Background Estimate (BABE) principle. This is illustrated in **Figure 2-4**.

This model measures the minimum night flow by suppliers, into district metered areas (DMA's). The leaks are identified as it is assumed that there is very little to no consumption during the night period. Generally, minimum night flow occurs between midnight and 4am in order to evaluate the level of leakage in a particular DMA. According to **Figure 2-5**, minimum night flow can be split into various components.

2.4.4. ECONOLEAK Model (Economic level of leakage model)

This model gives suppliers a platform to operate within their limited budget as well as attending to any leakages or bursts that occurs on the WDS (McKenzie and Lambert, 2002). The urgency/ priority to attending to a leak or burst is identified by the model and the supplier is notified along with how much funding should be allocated to leak detection and repair per annum.

This model was designed to complement the SANFLOW Model. It uses similar information such as number of service connections, length of transmission mains, length of distribution mains and estimated monthly losses.

2.4.5. PRESMAC Model (Pressure Management Model)

The PRESMAC pressure management model is used to determine the likely savings (in financial terms) of various pressure reduction options (e.g. Fixed-outlet and time-modulated PRV's) in a selected district metered area. This model allows the user of the program to gauge the potential for pressure management very quickly and effectively without requiring a full detailed pipe network analysis. The analysis is undertaken based on the general concepts of the Burst and Background Estimate (BABE) principle. Data required include number of connections, length of mains, number of properties, population, expected leakage rates from connections, property mains, pressure exponent for the system as a whole and details of commercial consumers. In addition, three 24-hour pressure and flow profiles need to be collected (McKenzie, 2001). The hourly values need to be collected at the following points:

- Pressure at the inlet point
- Pressure at the average zone point,
- Pressure at the critical point: This represents the point or node in a district metered area (DMA) where the pressure is expected to be the lowest. It often serves as a reference point to report excess pressures within the system.
- Inflow to the zone

These models, described above, form the basis for the development of successful demand management strategies.

2.4.6. Minimum Night Flow Analysis

The minimum night flow (MNF) is usually found to occur sometime between midnight and 4am, when the consumption is the lowest in the network (McKenzie, 1999) as represented by **Figure 2-5**. It assumes that most people will be asleep during this period. MNF is made up of 1) normal night use, 2) background leakage 3) Excess night flow.

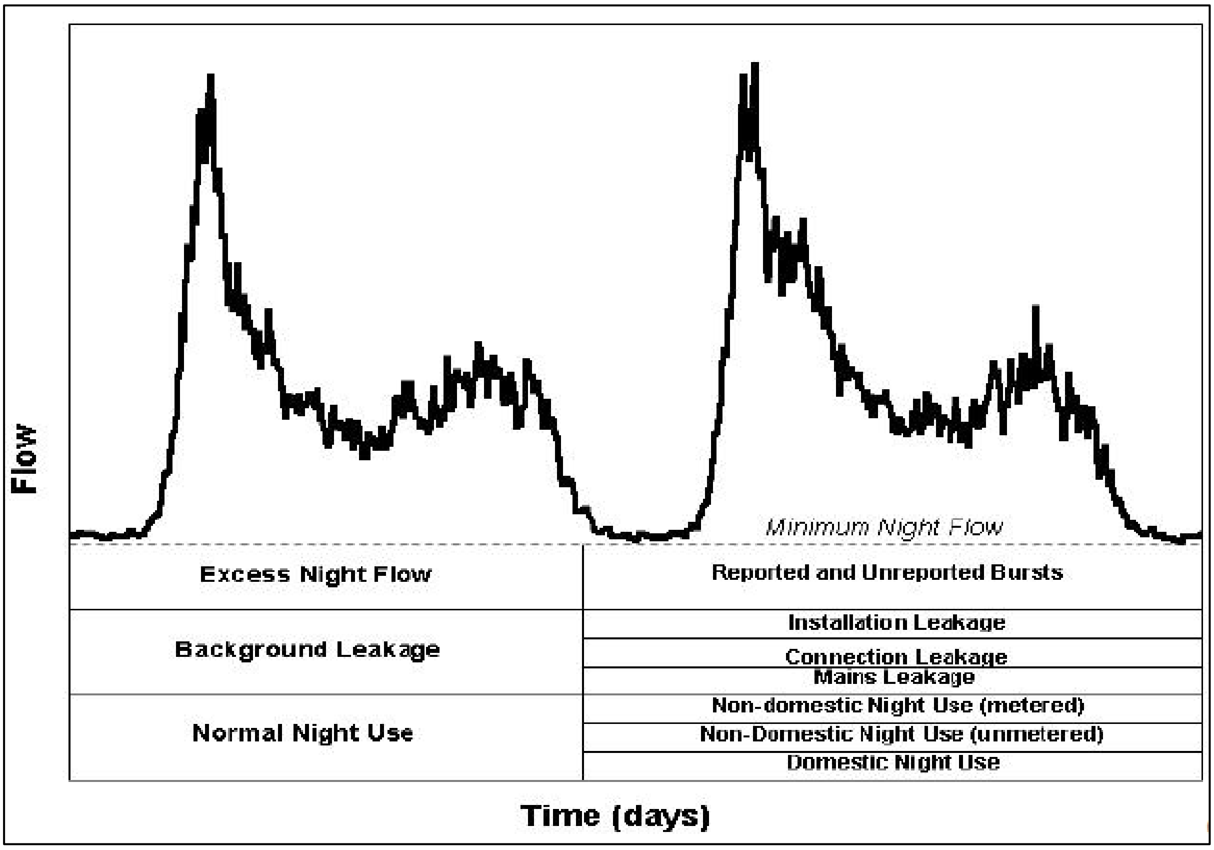

Figure 2-5 Components that make up minimum night flow which forms the basis of the BABE analysis (McKenzie et al, 2000)

2.4.7. Night Day Factors

It is incorrect to assume that the minimum night flow leakage is consistent across 24 hours. Therefore, it would be incorrect to assume that daily leakage can be converted to hourly leakage by dividing by 24 hours/ day (and vice versa). Leak flow rates vary with average pressure. The multiplier in hours/day is known as the Night Day Factor (NDF) (Lambert and Water Loss Research & Analysis Ltd (WLRA), 2017).

The methodology presented by Lambert and WLR&A (2017), calculates the NDF using the assumption that N1 is constant at 1.0, then applies a correction for variable area leakage using a Correction Factor (CF). The latter is dependent on the ration between the average AZP/AZP at the MNF hour (AZPave/AZPmnf) and N1. NDF is calculated based on **Equation 2-4**.

$$\text{NDF(hours/day)} = \text{CF} \times 24 \times \text{AZPave}/\text{AZPmnf} \tag{2-4}$$

Where:

NDF = Night Day Factor (hours/day)

CF = Correction Factor

AZPave = Average Zone Pressure of the system (m)

AZPmnf = Average Zone Pressure at the MNF hour (m)

The calculation steps are as follows:

Step 1: Calculate the AZPave/AZPmnf for a particular zone

Step 2: Calculate the N1 for the system

Step 3: Get the values of CF from **Figure 2-6**

Step 3: Apply **Equation 2-4**

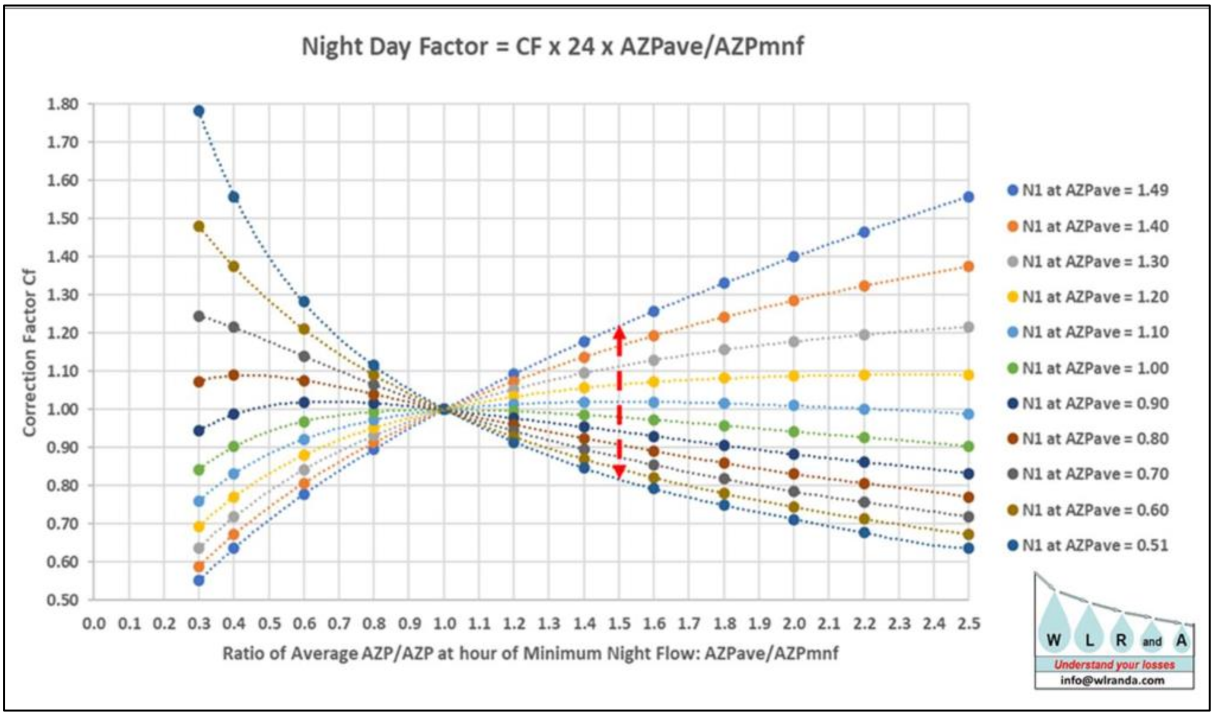

Figure 2-6: Correction Factor vs Ratio of AZP/ AZP at hour MNF (Lambert and WLR&A, 2017)

The NDFs can be read directly (but less accurately) off **Figure 2-7**, for different values of N1 at the average zone pressure.

Alternatively, the NDF's can be read directly (but less accurately) off **Figure 2-7**.

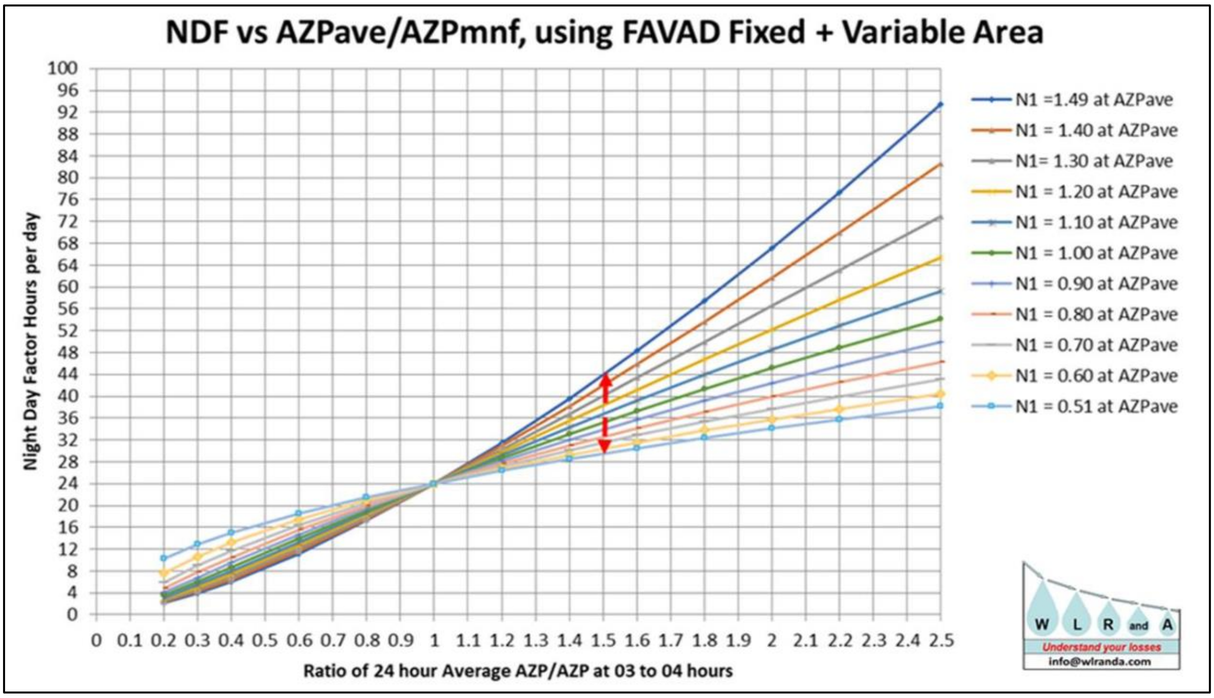

Figure 2-7: NDF vs AZPave/ AZPmnf, using Fixed and Variable Area (FAVAD)

2.5. PRESSURE MANAGEMENT

2.5.1. Introduction

Water reticulation systems are generally designed to provide for local demands, including fire demands, at a minimum working pressure at all points in the system. Minimum pressure (generally specified by local bylaws or design guidelines) occurs at some critical point in the system which is often either the highest point in the system or furthest point from the main supply as shown by **Figure 2-8** (McKenzie, 2001).

WDS experience significant fluctuations in diurnal demand with morning and evening peaks coupled with periods of low demand during the night and early afternoons. Systems also experience seasonal fluctuations, generally caused by climatic factors that influence irrigation requirements or by holiday migrations which significantly impact on demand for a number of days (McKenzie, 2001).

WDS are designed to provide a set minimum pressure throughout the day, in order to meet the pressure requirements including fire demands, during periods of peak demands when friction losses are highest and inlet pressure is at their lowest. As a result of this, during periods of off peak periods, WDS experience higher pressures than is needed which often results in increased leakage and bursts.

Each water distribution system includes different components such as pipes, pumps, tanks, hydrants and valves. Leaks occur in all these components, however leakage from the piped network is considered most considerable due to the size and number of pipes found within the water distribution system (Nazif, Karamouz, Tabesh and Moridi, 2009).

Water pressure management is introduced in order to adjust the water pressure levels within a WDS in order to improve the level of service of consumers, protect infrastructure and save water. Pressure regulating valves and system monitoring are the tools required in order to achieve suitable pressure management in order to achieve stable pressure levels across the supply network (Farley and Trow, 2003; Thornton and Lambert, 2005; McKenzie, 2001).

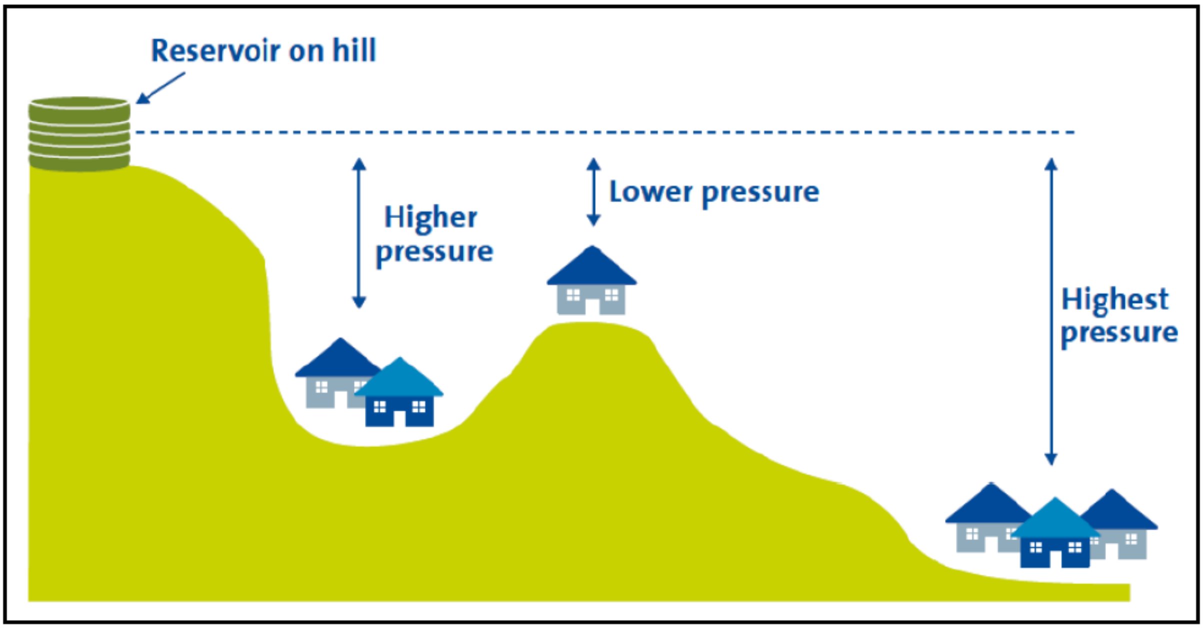

Figure 2-8 Varying water pressure in a WDS (McKenzie, 2001)

The benefits of pressure management within WDS go beyond water conservation, it includes reduction of leakage flow rates (burst and background), and reduction of pressure-related consumption, improved service delivery and consumers benefits (Farley and Trow, 2003).

Pressure management comprises of a number of different techniques which include (Farley and Trow, 2003):

- Pump Control

Slow-start control are useful on pumping sets to prevent pressure surges.

- Combined booster and PRV

Areas of high ground may be boosted by an in-line pumping installation in order for the lower-lying area to be pressure reduced.

- Trunk main control

This involves the installation of pressure-reducing valve, or electronically-controlled valves on trunk mains in order to control pressures over a widespread area of supply.

- Rezoning

This involves the installation of link mains and line valves in order to supply the areas in different manner. This could allow areas to be transferred to adjacent lower pressure systems. Alternatively, some properties in an area could be transferred to a higher pressure supply area in order to allow the remainder of the supply area to be pressure reduced.

- Introduce a break pressure tank

A break tank can be installed in a main in order to break the hydraulic grade.

- Reservoir inlet control

Valves on the inlet to service reservoirs can be used to control the flow. The valves can be fitted with pilots or electronic controls to prevent pressure surges when they shut off as the reservoir fills.

- Reservoir outlet control

In some instances, it may be possible to install control valves on the outlets of service reservoirs to make a small reduction in pressure which will have an effect over a large area.

- Day/night districts

This method of pressure management requires that some valves be shut permanently, and other valves be fitted with electronically-controlled valves which are only shut at night. This allows the day-time demand to be supplied without excess head loss, and at night the flow passes through a single feed via a pressure-reducing valve in order to reduce leakage.

- Installing a pressure reducing valve (PRV)

PRV's are designed to create a head-loss which reduces pressure on the outlet side. The type of valve used will depend on its function in the network.

2.5.2. Using Pressure Reducing Valves in distribution systems

Pressure reducing valves are widely used in managing pressure in WDS. This is done without compromising the quality of water supply in the system and the demand that is to be met even after pressure reduction valves are introduced into the system. Furthermore, it should not compromise on the needs of special cases such as fire-fighting. **Figure 2-9** is an example of a pressure during peak demand periods when there has been an introduction of pressure reducing valves. For illustration purposes, the minimum required pressure has been assumed as 20m.

In **Figure 2-9**, the pressure reduction valve is introduced upstream on the system and reduces the pressure from 100m just upstream of the PRV to 60m just downstream of the installed PRV. At the critical point, the required minimum pressure of 20m is maintained.

Pressures in a WDS increase during off-peak periods and the system operates at pressures higher than is required. From **Figure 2-9**, the importance of pressure reduction is illustrated as leaks and pipe bursts increase with an increase in system pressure. **Figure 2-9** illustrates a situation where the demand is at minimum and the pressure (at the critical point) rises from 20m, as illustrated in **Figure 2-10**, to 55m. This illustration shows how leakages and pipe bursts are affected by the excessive pressures in a WDS during off-peak periods (McKenzie, 2001; McKenzie and Wegelin, 2009).

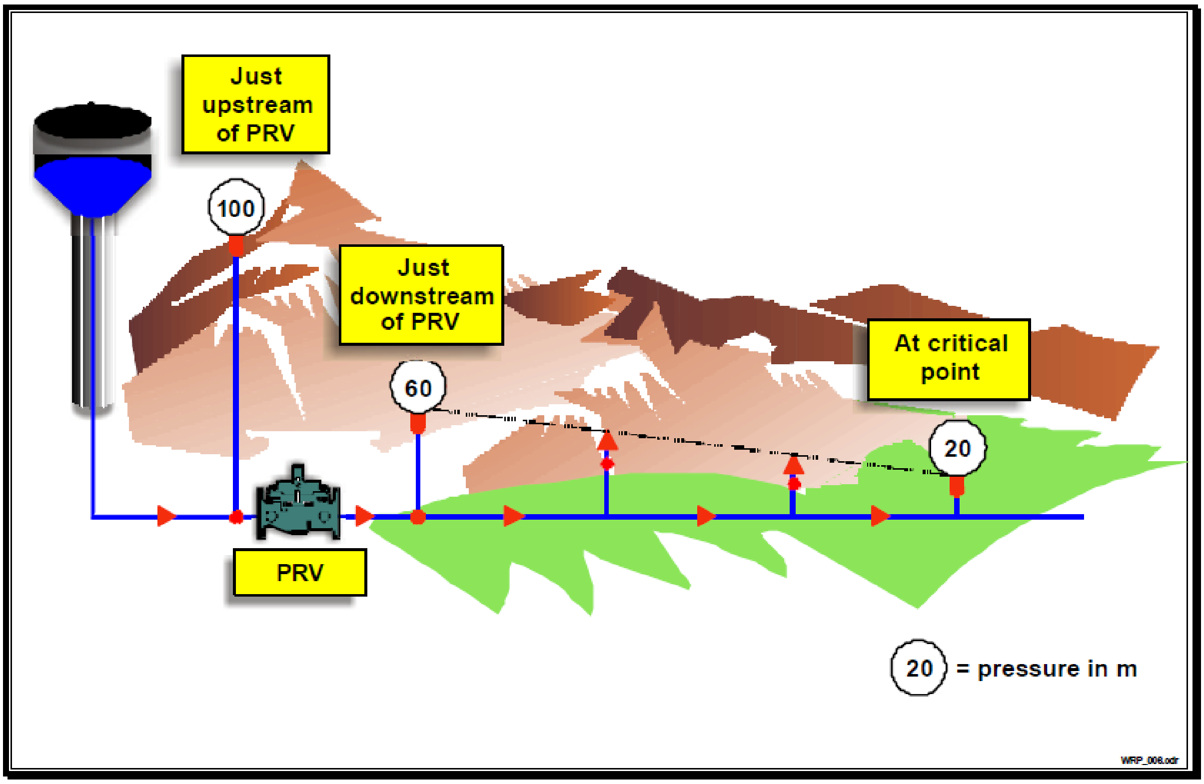

Figure 2-9: Pressure during peak water demand period (McKenzie, 2001)

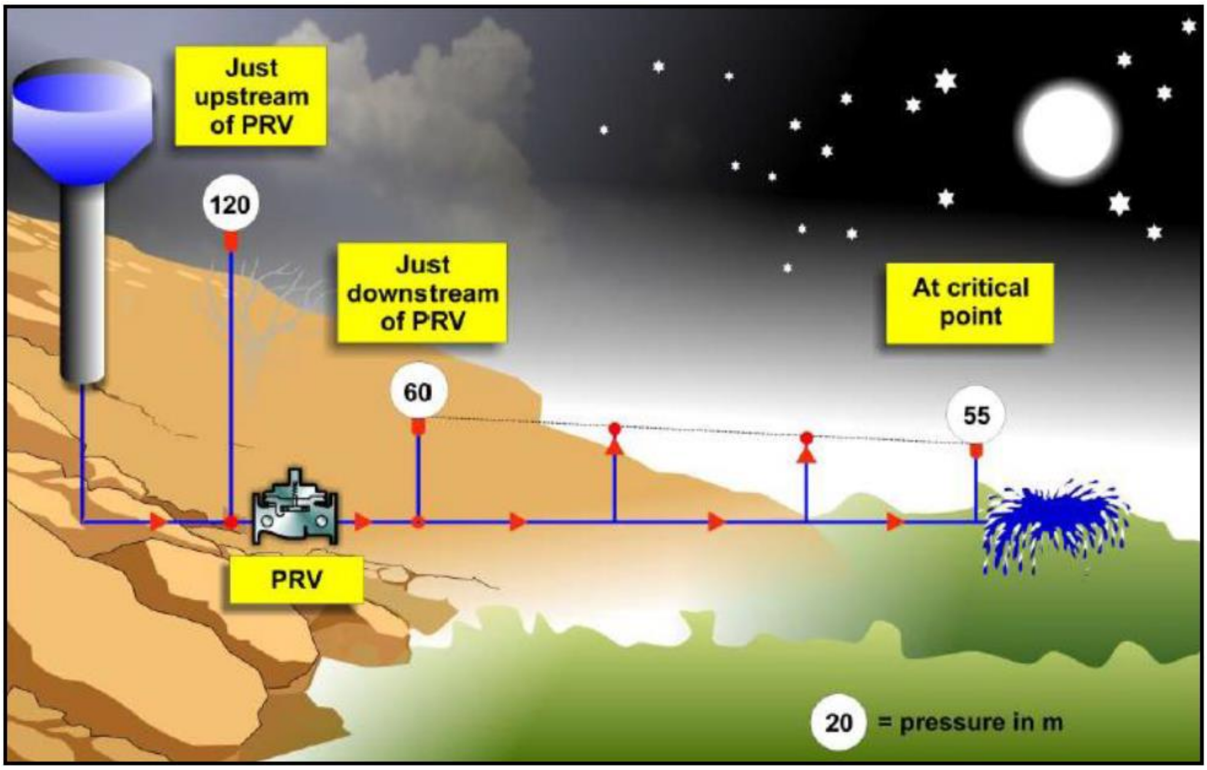

Figure 2-10: Pressure during off-peak demand (McKenzie and Wegelin, 2009)

2.5.2.1. Fixed Outlet Pressure Control

This type of pressure control is done through the use of a pressure reducing valve (PRV). For a fixed outlet PRV, there is a single working condition (the head downstream is always the same) (Gomes, Marques, and Sousa, 2011). This valve is required to control the maximum pressure entering a certain zone. The fixed outlet pressure control requires the use of a PRV without any additional equipment. **Figure 2-11** illustrates a typical layout of the fixed outlet pressure control.

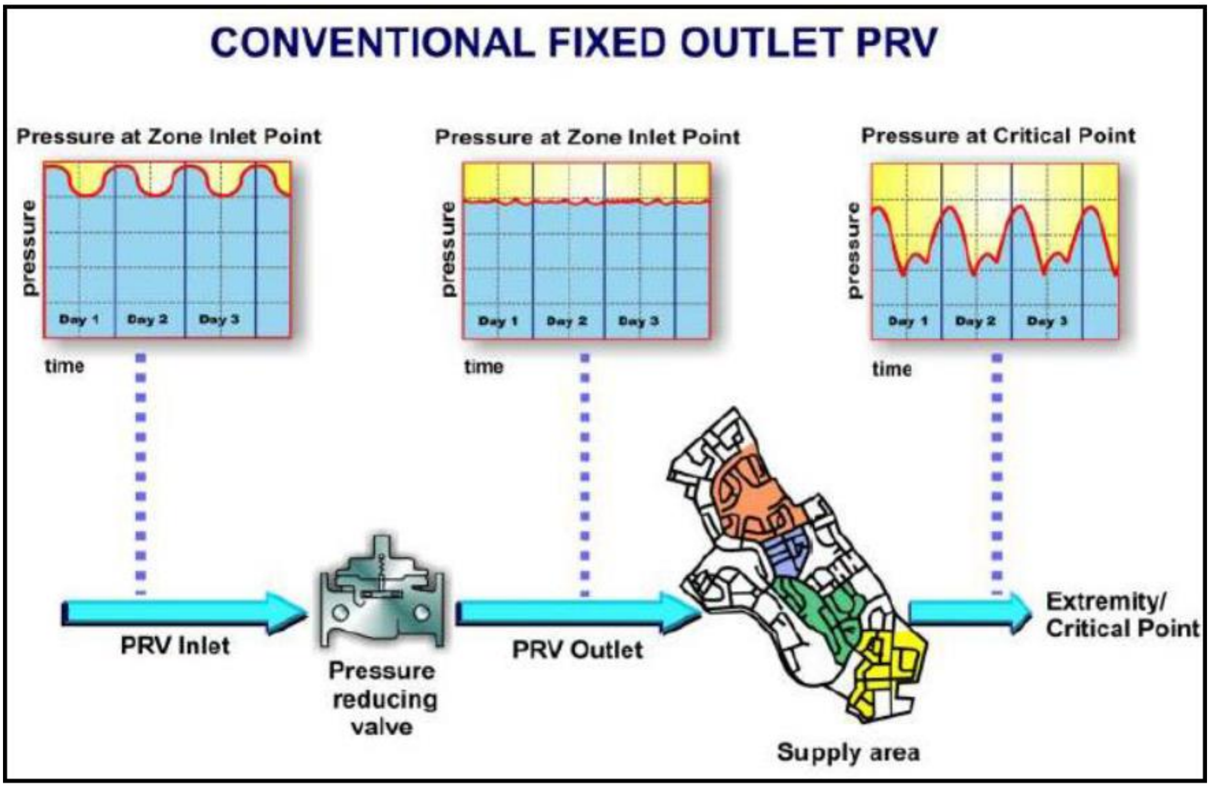

Figure 2-11: General layout of fixed outlet pressure control (McKenzie and Wegelin, 2009)

Advantages of Fixed Outlet Pressure Control include (McKenzie and Wegelin, 2009):

- Simple to install
- Relatively low costs, no electronic equipment required
- Simple maintenance and operation

Disadvantages of Fixed Outlet Pressure Control include (McKenzie and Wegelin, 2009):

- Maximum possible savings cannot be attained
- Lacks flexibility in that water pressure cannot be adjusted at different times of the day

Figure 2-12 illustrates how a fixed outlet PRV can be used to ensure that the pressure at the critical point is limited to the minimum required pressure (15m as illustrated) at the period of maximum demand. It can further be seen that there is a considerable amount of excess pressure in the system during most of the day, denoted by the grey shaded area representing excess pressure at the critical point (Wegelin, 2001).

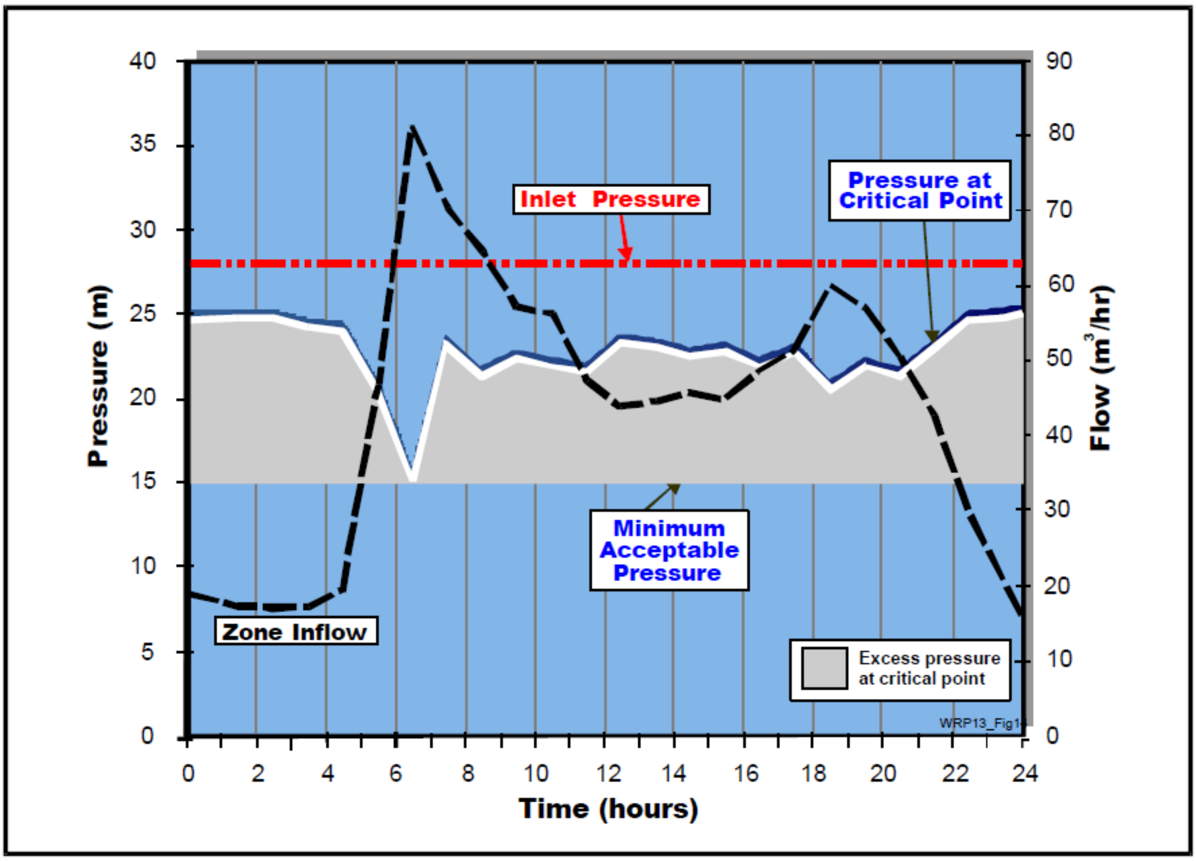

Figure 2-12: Illustrates a typical zone with fixed outlet pressure control (Wegelin, 2001)

Another type of pressure control, known as time-modulated pressure control, can be used to further reduce excess pressure.

2.5.2.2. Time Modulated Pressure Control

Time-modulated Pressure Control is different to the Fixed-outlet Pressure Control in that it has an additional device. The device allows for a further reduction of pressure during off-peak demand periods. For a time-modulated PRV there can be several working conditions which are all defined by a time period (for instance, one at night and another during the day) (Gomes, et al, 2011). This type of pressure control is more suitable to areas where pressures during off-peak demand periods increase rapidly. **Figure 2-13** illustrates the layout of a typical zone with Time-modulated Pressure Control. From the figure below one can see that the upstream pressure is much higher than the downstream pressure. Once the water enters the PRV (with time modulated control), from the flow profiles presented, one can see that during day time a certain fixed pressure (less than the upstream pressure) will be maintained along with a stable critical point pressure. During the night time when there is little to no demand, pressure is the highest and losses also increase. The time-modulated PRV will be set to reduce the pressures at night resulting in reduced pressure at the critical point.

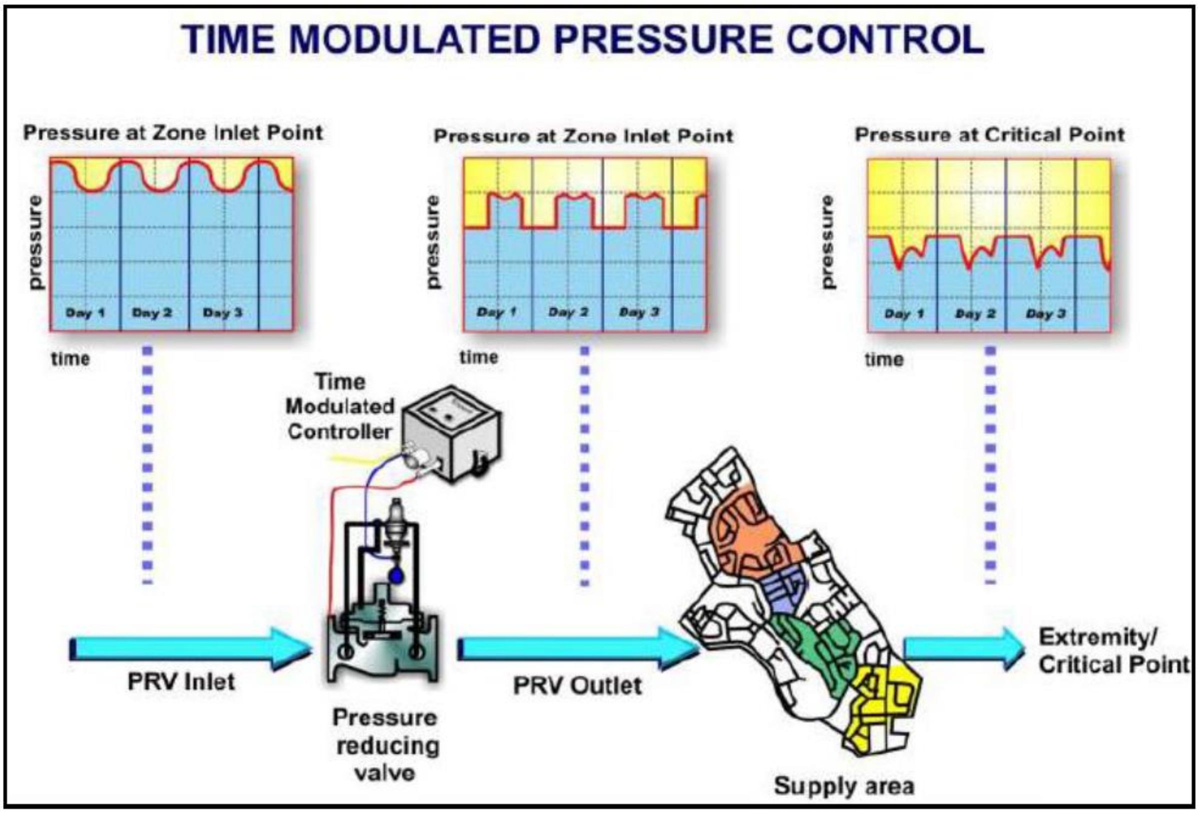

Figure 2-13: General layout of time-modulated pressure control (McKenzie and Wegelin, 2009)

Advantages of Time-modulated Pressure Control includes (McKenzie and Wegelin, 2009):

- Allows for pressure to be reduced at specific times
- Electronic controller is cheaper
- Easy to setup and operate
- Installation does not require a flow meter

Disadvantages of Time-modulated Pressure Control includes (McKenzie and Wegelin, 2009):

- Does not react to demand for water (independent of demand requirements)
- More expensive than fixed-outlet pressure control

Figure 2-14 further demonstrates how time-modulated pressure control can further reduce the excess pressure that was present during the Fixed-outlet pressure control (illustrated by **Figure 2-12**).

From **Figure 2-14**, it can be further seen that Time-modulated pressure control has resulted in a significant reduction in the system excess pressure (indicated by the grey shaded area).

Considering **Figure 2-14**, from the flow profile denoted by the black dashed line, one will notice that the profile is more or less representative of a domestic area where two peaks are presented namely a morning peak (from 4am to about 12pm) and the evening peak (between 4pm until about 9pm). The minimum night flow is between 0 to 4am and low demand requirements are between 12pm and 4pm and again at 10pm until 4am. During this period the pressure is set at around 20m (denoted by red-dashed line) while ensuring that the minimum acceptable pressure is maintained for the system (which is set at 15m – denoted by the greyed out area). During the peak periods (morning and afternoon peaks), starting at around 4am until just before 12pm and again at 4pm until about 9pm), the demand on the system increases (denoted by the black dashed line) and the controller on the PRV adjusts the pressure settings to a higher pressure at around 27m (denoted by red dashed line) during the same period and consequently raising the critical point pressure in order to meet the demand.

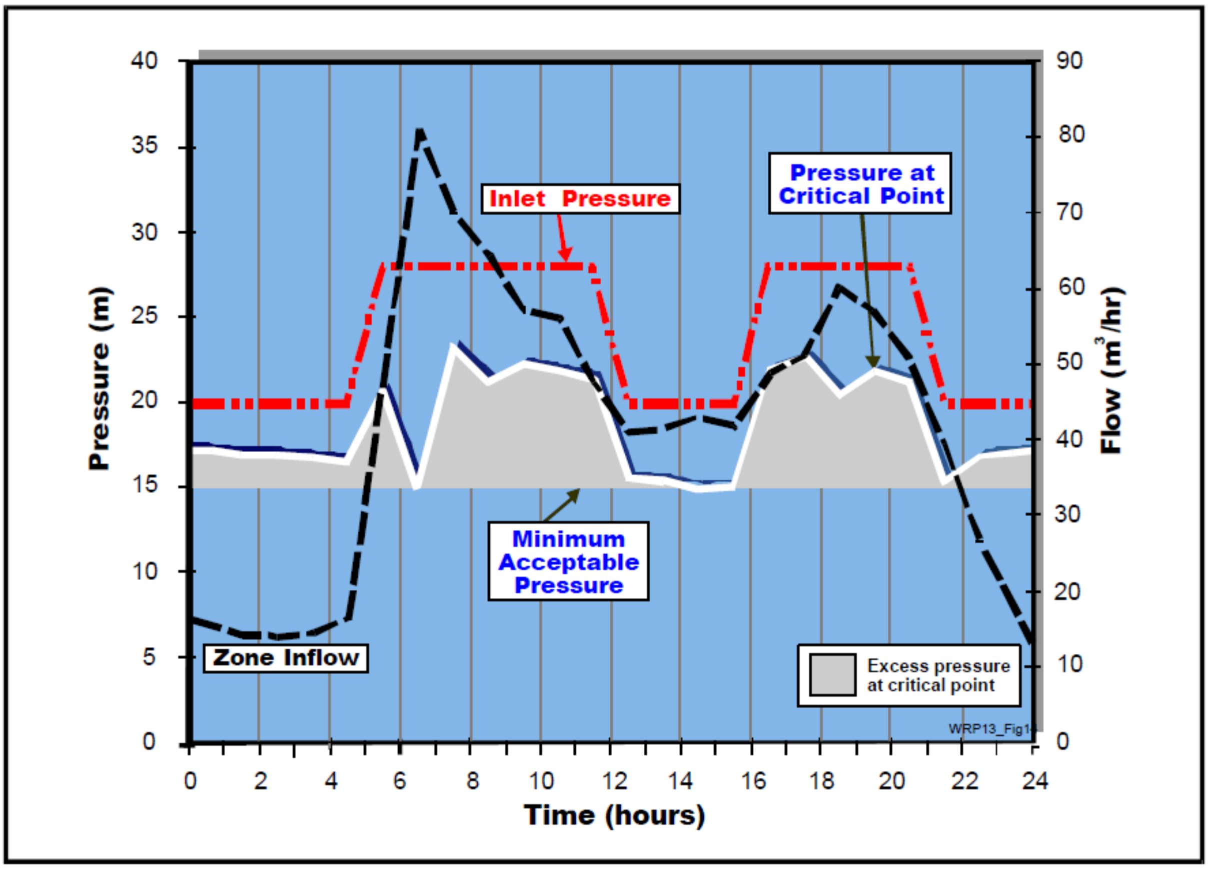

Figure 2-14: Illustrates a typical zone with time-modulated pressure control (Wegelin, 2009)

Although, time-modulated pressure control resulted in a significant improvement to reducing the excess pressures, further improvement can still be attained. This can be done through the use of a more sophisticated type of pressure control known as Flow-modulated Pressure Control.

2.5.2.3. Flow Modulated Pressure Control

Flow-modulated Pressure Control allows for more flexibility than the fixed outlet pressure control and the fixed outlet and time-modulated pressure control. The pressure-modulated PRV adjust the working conditions in order to always reach minimum pressure required (Gomes, et al, 2011). In addition to having a PRV, this type of control requires an adequately sized meter. **Figure 2-15** illustrates a general layout for a flow modulated pressure control (McKenzie and Wegelin, 2009).

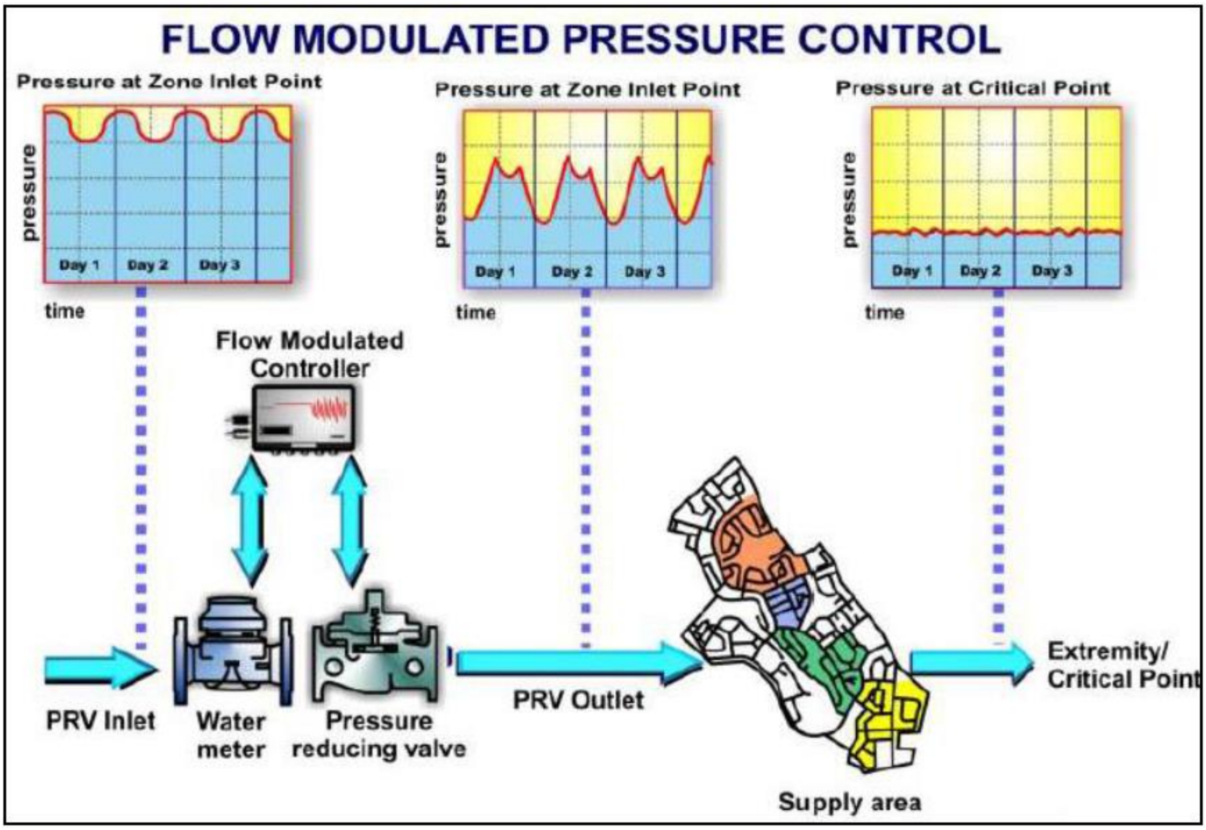

Figure 2-15: General layout of a Flow-modulated Pressure Control system (McKenzie and Wegelin, 2009)

Advantages of Flow-modulated pressure control include (McKenzie and Wegelin, 2009):

- Does not impact on water supply during a fire event
- Greater flexibility

Disadvantages of Flow-modulated pressure control include (McKenzie and Wegelin, 2009):

- Highly expensive
- Needs to be carefully considered before implementing flow-modulated control

Figure 2-16 illustrates how flow-modulated pressure control was able to further reduce the excess pressures within the specific WDS zone.

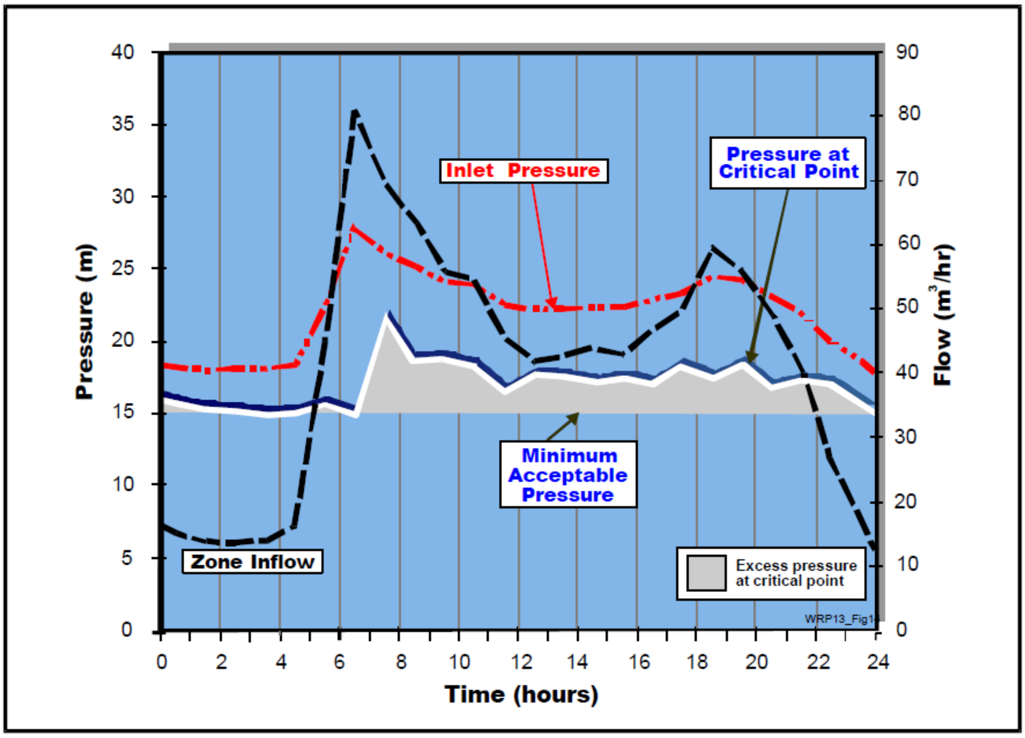

Figure 2-16: Illustrates a typical zone with Flow-modulate pressure control (McKenzie, 2001)

Pressure management, and its impact on the level of real losses, including consumer demand is governed by certain principles which will be discussed in the following sections.

2.5.3. Theoretical pressure-leakage relationship

One of the major factors influencing leakage, within a WDS, is pressure. It can be mainly described through the Orifice Equation which describes the relationship of the flow of water through an opening. The flow of water is caused by the pressure head of the water level relatively to the opening with a closed perimeter. **Equation 2-5** describes this relationship (Walski et al, 2003):

$$Q = AC_d\sqrt{2gh} \tag{2-5}$$

Where:

Q = Flow rate

C_d = Discharge coefficient

A = Orifice Area

g = gravitational acceleration

h = pressure head differential over the orifice

Equation 2-6, can be rewritten into a form which is suitable for practitioners for leakage and modelling practice analysis. This equation is defined as (van Zyl and Clayton, 2000):

$$\mathrm{Q} = \mathrm{Ch}^{\mathrm{N1}} \tag{2-6}$$

Where:

Q = leak flow rate

C = leakage coefficient

N1 = leakage exponent

h = pressure head differential

Practitioners apply Equation **2-6** in a form which will assist them in identifying the impact of pressure reduction within a designated District Metered Area (DMA). It is applied as a ratio of leakage flow before and after pressure management (McKenzie et al., 2003; Wegelin and McKenzie, 2010; Meyer et al, 2009). This is displayed in **Equation 2-7**:

$$\left.\begin{aligned} \mathrm{Q}_{\mathrm{before}} &= \mathrm{Ch}_{\mathrm{Before}}^{\mathrm{N1}} \\ \mathrm{Q}_{\mathrm{After}} &= \mathrm{Ch}_{\mathrm{After}}^{\mathrm{N1}} \\ \frac{\mathrm{Q}_{\mathrm{After}}}{\mathrm{Q}_{\mathrm{Before}}} &= \frac{\mathrm{Ch}_{\mathrm{After}}^{\mathrm{N1}}}{\mathrm{Ch}_{\mathrm{Before}}^{\mathrm{N1}}} \\ \frac{\mathrm{Q}_{\mathrm{After}}}{\mathrm{Q}_{\mathrm{Before}}} &= \left(\frac{\mathrm{h}_{\mathrm{After}}}{\mathrm{h}_{\mathrm{Before}}}\right)^{\mathrm{N1}} \end{aligned}\right\} \tag{2-7}$$

The main parameter of the equation is the leakage exponent, N1. This exponent is widely used by practitioners to determine the pressure leakage relationship in WDS. It is also used in laboratory studies to in order to describe the behaviour of individual leaks which subject to certain causative factors of leakage (soil hydraulics, pipe material, leak hydraulics and water demand) (Greyvenstein and van Zyl, 2007; Lambert, 2001; van Zyl and Clayton, 2007).

Various N1 values have been determined. Analyses of a number of field tests on sections of distribution systems in a number of countries have confirmed that N1 exponent typically lies between 0.5 and 1.5 but occasionally reaches much higher (Farley and Trow, 2003; Thornton and Lambert, 2005).

Greyvenstein and Van Zyl (2007) investigated the impact of different types of leak openings and pipe material on the leakage coefficient. The three types of leak openings included round holes, corrosion holes and longitudinal holes. It was found that the leakage coefficient varied between 0.5 for round holes, 0.67 to 2.30 for corrosion holes and between 0.79 to 1.85 for circumferential cracks. Furthermore, Cassa and Van Zyl (2011) determined, using Finite Element Analysis, the following leakage coefficients, 0.91, 0.85 and 0.64 for long longitudinal, spiral and circumferential cracks but will vary depending on pressure range.

May (1994) adopted the orifice equation to produce the Fixed and Variable Area Discharge (FAVAD) equation. This equation is made up of two expressions: a flow expression where the area does not expand as a function of pressure, and a flow expression that considers the change as a function of pressure.

The FAVAD equation was derived by defining the relationship between area and pressure as being linear as shown in this equation:

$$\mathrm{A} = \mathrm{A}_0 + \mathrm{mh} \tag{2-8}$$

Where A_0 is the initial area of the leak, m is the pressure-area slope and h is the pressure head. Replacing equation **2-5** into equation **2-2** gives equation **2-6**.

$$\mathrm{Q} = \mathrm{C_d}\sqrt{2\mathrm{g}}(\mathrm{A}_0\mathrm{h}^{0.5} + \mathrm{mh}^{1.5}) \tag{2-9}$$

Where $h^{0.5}$ describes the flow through the initial fixed area of the leak and the $h^{1.5}$ describes the flow through the expanded area of the leak. **Equation 2-9** is not new and had been used by different researchers in the past. Most of these investigations assumed that leaks were either fixed or variable and could not have both expressions at the same time (Piller and Van Zyl, 2014).

2.5.4. Hydraulic network modelling

General hydraulic network modelling software, specifically the Epanet software package (Rossman 2000), uses a power equation (**Equation 2-6**) to model pressure-dependent outflows such as leakage. As previously discussed, studies on pressure leakage relationships have realised that leakage does not adhere to the theoretical orifice equation (a power equation with a fixed exponent of 0.5) and has resulted in values much higher (Cassa and Van Zyl (2011); Greyvenstein and van Zyl, 2007; Lambert, 2001; van Zyl; Clayton, 2007; Farley and Trow, 2003; and Thornton and Lambert, 2005). The latter is as a result that leak areas are not fixed however vary with system pressure.

Kabaasha, Piller and van Zyl (2017), incorporated and tested the inclusion of the modified orifice equation into the standard hydraulic model (now known as Epaleaks). Three network types were tested on this model, small, medium and large network with a total pipe length of 19.3, 60 and 103.8 km respectively. The application of the modified orifice model showed similar results for the total system leakage flows and volumes under normal diurnal pressure variations. The leakage lows at individual nodes at elevations different from the AZP were found to differ significantly.

2.6. PRESSURE-DEMAND RELATIONSHIP AND ELASTICITY

Water consumption is considered pressure dependent. When one considers the volume of water used by consumers in DMA’s over a period of time (e.g. 1 day), certain categories of water consumption may be considered as pressure-independent (such as toilet tanks, washing machines, dishwashers, etc.). This means that under high pressure the appliances consume water faster but the volumes of consumed water remain the same (Babić *et al*, 2014). One also needs to consider that despite the volume consumed by the individual appliances remaining the same, however filling at a different rate, that the flow rate, will affect the overall flow rate into the system.

2.6.1. The analytical approach

Although demand is not classified as leakage, it is often impossible to separate actual water consumption from leakage. The empirical formula used to describe the relationship which exists between pressure (h) and demand (Q_{dem}), can be described as follows:

$$Q_{dem} = Ch^{N3} \tag{2-10}$$

Where C is the discharge coefficient and N3 is the coefficient of elasticity. The theoretical relationship between pressure and flow rate dictates that the flow rate should be proportional to the square root of the pressure, in other words, N3 = 0.5.

Pressure affects the flow rate through an opening in a pipe (hence the leakage rate within a water distribution system). The theoretical relationship between pressure and flow rate dictates that the flow rate through a fixed opening should be proportional to the square root of the pressure (hence a ε value of 0.5). However, experience in actual systems indicates much higher values for ε measured in terms of volume (e.g. a bath or toilet cistern), but in terms of time taken to fill these volumes based components. Wasteful water consumption (such as taps being left open for unnecessary long periods) was assumed to have theoretical ε values of 0.5. Since irrigation consumption can be controlled by time or volume, the elasticity value will typically vary between 0.5 and 0. Based on the latter information argued by Van Zyl, Haarhoff and Husselman (2003), it was assumed that the elasticity for household consumption would vary between 0.15 and 0.25.

Pressure-dependent consumption, if the initial pressure, P_0, is reduced to P_1, consumption changes from QC_0 (initial consumption) to QC_1, and the extent of that changes depends on the exponent N3. This is represented by the following equation (Gomes *et al.*, 2011):

$$\frac{QC_1}{QC_0} = \left(\frac{P_1}{P_0}\right)^{N3} \tag{2-11}$$

It is noted that part of the consumption can be classified as pressure-independent (e.g. toilet flushing, roof tanks, washing machines, dishwashers) and the remainder is classified as pressure-dependent (e.g. shower use, hand washing, watering gardens).

Pressure-independent consumption ($QC_{indep,0}$), analytically, is not affected by pressure fluctuations, (unless one considers the sociological drivers as described in section 2.3.3). The volume stays the same however the flow-rate is a function of pressure. The excess pressure (above which is required to meet consumption without affecting duration of the consumption) increases the pressure-dependent ($QC_{dep,0}$), thereby affecting the total consumption after pressure reduction (QC1). Gomes *et al.* (2011), went further to define the following equation (slightly modified to only refer to consumption and exclude system leakage):

$$QC = QC_{dep,0} \times \left(\frac{P_1}{P_0}\right)^{\varepsilon} + QC_{indep,0} \tag{2-12}$$

2.6.2. Effect of Pressure reduction on demand

This section provides an overview of published and unpublished investigations on the impact of pressure on water demand.

A study by Girard and Stewart (2007), which involved implementation of pressure and leakage management strategies in Gold Coast, Australia was conducted in order to investigate the impact of pressure management on leakage and consumption. A consumer survey was conducted after the introduction of pressure management. Results of the consumer survey indicated that pressure management had the greatest impact on the garden irrigation and showering during the period of 3pm to 8pm.

Gebhardt (1975) investigated the impact of pressure, within the reticulation system, on water wastage related to excessive water usage and water loss such as leakage. One of his objectives was to determine the extent to which pressure contributed to overall water wastage (or excessive household usage). His methodology involved a field experiment which tested three pressure managed DMA's. Within these DMA's he varied the pressure. The DMA's included one high income area comprising of asbestos cement laid pipes and galvanised steel connections to consumers, and two low income DMA's, one of these areas (Diepkloof, Soweto) was comprised of steel piping with galvanised steel connections to centre blocks and toilet facilities outside the house. The second low income area was in Hillbrow which is a densely populated area served by steel mains with steel connections.

His field test took on four phases.

Within the **first phase** he recorded three demand records on three consecutive Sundays. The pressures were altered on the preceding Thursday of each Sunday. In seeking a mathematical relationship between pressure and the rate of flow, it was assumed that each outlet point in the system i.e. tap, ball valve, leak, etc. acts as an orifice under pressure and the total flow may be expressed by general formula $Q=kh^x$ (or Equation 2-10), where Q is the flow rate in cubic metres per hour, k is the parameter depending on the characteristics of the orifice, h is the pressure head at the orifice, in metres and x is the constant (or coefficient) for any particular type of orifice.

In phase one he identified that consumption increased or decreased in relation to pressure.

Within the one test area, described as a mixed use well-developed area, he determined that an approximate 64% reduction in pressure resulted in approximately 30% reduction in water usage with $\mathcal{E} = 0.54$.

During **phase two** of his investigation, Gebhart (1975) was concerned with the effect of short period pressure change on the same system. The PRV setting at the outlet was set to an initial setting of 49.4m. One week later is was then set to 74.7m. The pressure was then dropped in three intervals over a period of 15 to 20 minutes between the hours of 10:00 to 11:00 am. He then raised it in reverse sequence. The flow rate in reverse order did not conform to the similar steps as when it was dropped. Gebhart (1975) indicated that it could be due to localise demand fluctuations.

In **phase three** he describes the effect of limited garden watering restrictions on consumption in the same system. Garden watering depends to a large extent on the season or amount of rainfall. The restrictions limited the use of sprinklers to the hours of 8:00 to 10:00 and 19:00 to 21:00. On a typical dry day, the consumption was 20% less than the corresponding day in September.

The consumption types identified within the various DMA’s include the use of a bucket to collect water (fixed volume), gardening using sprinklers (variable with Pressure) and various indoor household usage consumption types.

Phase 4 described the consumption pattern after rainfall. He determined that consumption reduced by more than 50% of peak September consumption in September. The latter refers to the difference between total consumption and household consumption in September. The difference came about as there was less water used on gardens.

Gebhart (1975) concluded that his tests describe that the rate of flow through taps, and various other components, in the domestic system, is proportional to the pressure head in the system.

The Fixed and Variable Area Discharge (FAVAD) concept introduced by May (1994) is versatile in that a simple power law can be applied to elements of consumption (Thornton and Lambert, 2005). An investigation on the impact of pressure on the flow rate through toilet cisterns was performed which resulted in elasticity exponents of Exponents of 0.07 and 0.25.

Cullens (2004) investigation applied the accepted method of quantifying leak sensitivity, the orifice equation concept to elements of domestic consumption. This study focused on irrigation systems. He tested six different types of irrigation system devices on a range of operating pressures between 10 and 900kPa, and their discharge behaviour recorded. Applying the orifice equation to these results generated a sensitivity value for each device.

The devices tested were split into two categories, rigid and non-rigid. It was found that non-rigid devices were more sensitive to pressure than rigid devices. The latter is due to the expandable nature of flexible devices discharge paths. The results unpacked a number of observations, including the large amounts of excess water discharged by irrigation systems overnight, during periods of high night flow pressures. He determined that rigid devices tend to generate an N3 close to 0.5 and non-rigid devices generate values between 0.6 and 0.8. the latter means that non –rigid orifice devices have a discharge path that is more sensitive to pressure.

For rigid devices, a pressure reduction of around 50% resulted in a flow rate reduction of approximately 30%. However, for non-rigid devices, a pressure reduction of around 50% resulted in a flow rate reduction of about 40%. Cullen determined that a definite relationship exists between outdoor consumption and pressure, and that due to high levels of water that are being discharged, pressure reduction will serve as a good method to reduce wasted irrigation water.

van Zyl *et al* (2003) performed a study on end-use water demand. The study was limited to a pilot study to illustrate the difficulties and the potential application of end-use modelling as a water demand predictor. The study focused on a restricted number of variables where pressure is considered as one of them. They developed an end use model. They further performed a sensitivity analyses in which each of the elasticity parameters were varied between a minimum, normal and maximum expected values. Various data sources were used to determine the elasticity exponents. Elasticity values were estimated based on stand meter readings thus excluding the effect of leakage in the municipal pipe networks.

In their sensitivity analyses the following assumptions were made, where suburbs were assumed to use 50% of their consumption outdoor and townships 20%. The sensitivity analysis was performed by plotting the consumption response to normal, minimum and maximum values for each parameter. The sensitivity analyses provided an indication of how much water demand would be affected by a changing a single parameter at a time.

Pressure affects certain aspects of water demand in which time is generally used as a measure instead of volume (e.g. irrigation). The pressure elasticity's in this study were based on the estimated effect on actual consumption and specifically exclude losses in the system. Due to the latter, the elasticity values are much lower than normally used in pressure management investigations.

They determined that 50% reduction in pressure will result in a consumption decrease of between 10% and 16% for suburbs and between 7% and 13% for townships respectively. van Zyl *et al* (2003) concluded that the effect of pressure reduction on demand is expected to be small, although the main benefit of pressure control will be in the area of leakage reduction.

Bemezai and Lessick (2003) investigated how effective pressure optimization as a potential best practice intervention, is in terms of water savings and increased consumer complaints. They did not evaluate the impact of the reduced pressure on lowering water lost to leakage.

The impact of reduced pressure on consumption was analysed and consumers service calls were examined in Irvine Ranch Water District service area mainly because they had the following in place, namely, household billing history, daily system pressure history and an electronic consumer complaint logging system. In the two test areas, University Park and Racquet Club, pressure was reduced on average by 17.6% and 6% respectively during the experimental one-year period. Savings were determined by comparing weather-normalised consumption during the experimental period to two years of pre-experimental (or baseline) billing histories. A similar comparison was made when assessing whether pressure related consumer complaints increased during the experimental period.

Basic laws of fluid mechanics indicate that flow rates through circular pipes are exponentially related to headloss. In other words, if one doubles the flow rates, pressure differential over the pipe must increase fourfold, all else being equal. Or, on the other hand, decreasing pressure by 10%, for example, will possibly reduce flow rates by 5%. The latter however does not mean that consumption will decrease by 5% if the system pressure is reduced. Indoor household fixtures, such as toilets, dishwashers and laundry machines only result in increase in time to fill these devices when the flow rate is lowered without affecting consumption. However, showers and faucets may respond to certain degree. It is expected that automatic irrigation is likely to respond to pressure reduction (as indicated by Cullens (2004)). Bemezai and Lessick (2003) indicated that irrigation systems respond well to pressure reduction for two reasons, namely because the irrigation offshoot is generally taken before the residents' pressure regulating vale (that's provided they have such a valve), and consumers generally over-irrigate and therefore generally do not notice any significant change to their landscapes as a result of pressure reduction. Bemezai and Lessick (2003), go on further to say that if one assumes that irrigation is about one third of the residential consumption, it is possible to expect total consumption reduction of one to two percent when the pressure is reduced by 10%.

They selected two neighbourhoods for pressure reduction and three DMA's were used as a control group. These two neighbourhoods system pressure was being maintained at 70 to 85 pounds per square inch (or in other words 48.2m and 58.6-meter head). Irvine Water District considers 41.4metres (60pounds per square inch) acceptable minimum pressure. A pressure regulating valve was fitted to each supply system for each of the test areas and they were remotely tracked and controlled through the Supervisory Control and Data Acquisition (SCADA) system.

They analysed the billing data over a three-year period of the residents living in the same house only. The billing histories were matched with daily weather data and then statistically weather normalised to estimate water savings.

Their findings demonstrated that reducing system pressure can significantly reduce residential water consumption, especially irrigation, without causing any significant costs in terms of increased consumer complaints. In University Park DMA, where the pressure was reduced by 17.6%, single-family consumption reduced by 1.9% overall and by 4.1% among residents with greater than average landscapes. They could not detect any notable savings within the Raquet Club DMA probably because of the low magnitude of pressure reduction.

Examining savings from the larger than average accounts proved useful for two reasons as they were able to prove their hypothesis that pressure reduction largely works because of its ability to reduce the irrigation demand and secondly, the savings estimates are reliable statistically, as they are based on accounts where the owner had been residents for the entire test period.

Once they completed their analysis they developed a conceptual model to estimate water reduction potential for weather and other unobserved time-variant factors across the households. Two models were developed. The first model was based upon all households meeting the three-year residency criteria and the second model introduced the subset of households also having outdoor usage. It was identified that the behaviour of the comparison group could affect the estimated savings estimated through the first model. It was identified that consumption had increased by 1% during the intervention period relative to the baseline period. The latter, however, did not impact the second model as it offers stronger evidence supporting the hypothesis that pressure reduction reduces water consumption. Bemezai and Lessick (2003) went further on to estimate the pressure elasticity of demand. For this approach only data from the test groups were used because daily pressure histories were not available from the comparison neighbours. The estimated elasticities ranged between 0.1 and 0.2 but were significant only at the 10% pressure reduction level.

Bemezai and Lessick (2003) concluded that pressure reduction serves as a valuable intervention in conserving water.

Bartlett (2004) performed a study to investigate pressure dependent demands. The study looked into a distribution network which was supply Student Town Housing. Data was recorded on a weekly basis using loggers attached directly to the inlet of the distribution feeding the study area. The pressure was altered on a weekly basis by adjusting a pressure regulating valve on the system. The conclusions of the study indicated that higher pressures results in higher demands. The study did not exclude minimum night flow leakage. The demand exponents calculated were 0.2157 (for Wednesdays only) and 0.198 (for Wednesdays and Tuesdays only).

Fantozzi and Lambert (2010) utilised the FAVAD approach and weighted average to determine the impact of pressure reduction on consumption. Assuming that your consumer consumption (denoted as C) varies with average pressure (denoted as PN3) the FAVAD concept holds true in order to predict C. It is important, in the case of the latter to split the consumption into indoor and outdoor consumption components as the exponent for the inside consumption is considered to be much smaller than for outside consumption.

Fantozzi and Lambert (2010) also indicated that for direct pressure systems, without consumers storage tanks, some components of in house residential consumption (example, toilet flushing, and some types of toilet cistern leaks and use of showers) can be influenced by pressure reduction.

Limited info from Australia indicated typical indoor exponents of 0.04 (denoted as N3i) was obtained, zero was obtained for houses which were serviced by roof tanks. Typical outdoor exponents (denoted as N3o), using sprinklers and hosepipes, yielded 0.5. However, households which contain flexible seepage hoses with multiple holes yielded an exponent of 0.75 (Cullens, 2004). Households which contained a swimming pool yielded an exponent of 0 for outside water usage and pressure relationship.

Fantozzi and Lambert, have concluded that methods for predicting metered consumption reduction, based on percentage split between indoor and outdoor consumption, is now also available through the application of the FAVAD concept.

The percentage reduction in consumption is represented by the following equation:

$$\% \text{ Reduction in consumption} = 1 - OC\% \times (P1/P0)^{N3o} - (1 - OC\%) \times (P_1/P_0)^{N3i} \qquad \textbf{2-13}$$

where OC refers to outside consumption.

A value close to 0.5 for outside elements suggests that in such scenarios, as consumption depends fully on pressure, the FAVAD equation can be applied. Conversely, a value close to zero for domestic consumption may indicate that it is independent or less dependent from pressurhe (Vicente, Garrote, Sanchez and Santillan, 2015).

Babić, Aleksander and Stanic (2014) investigated the potential of available pressure management methodologies and their implementation in developing countries using a case study of the Kotež-Serbia DMA. This DMA is mostly residential with supplied by 150mm diameter pipelines. The secondary pipelines are made of asbestos cement pipelines of 100mm in diameter. A fixed outlet PRV was installed in the main inlet pipeline to the DMA. The flows and pressures were collected by data loggers. The data was logged every 15min. They further went on to develop a hydraulic model of the DMA using Epanet software. The model was developed to select nodes that will be used as representative for the Average Zone Pressure (AZP) and critical point pressure however they could not calibrate the model. Readings of the consumer meters were taken before and after the completion of the experiment. An hourly water demand pattern was determined according to registered flow data. The experiment occurred during a wet weather period and it can be concluded that no water was used for garden watering.

They applied three methods in order to assess the amount of water saved. These methods include the Leakage index, Presmac model and their own method which was based on a new method which assumes that both leakage and consumption are dependent on pressure. This name of this method is the Leakage-Consumption-Pressure (LCP). The latter method has greater significant for this paper. The basic assumption of this method is that the total system inflow (both leakage and consumption) is pressure dependent. The following pressure-water/consumption equation is utilised as the foundation for the analysis:

$$\frac{L_1}{L_0} = \left(\frac{p_1}{p_0}\right)^{N1} \text{(based on Equation 2-7)}$$

Where L_0 (m^3/h) is initial water loss in at initial pressure p_0 (m); L_1 (m^3/h) is new water loss at new pressure p_1 (m) and N1 is the pressure exponent. In this study, Babić *et al* (2014) assumes that there will be different exponents for water losses upstream of the meter, N1, water consumption (N2) and leakage inside the building (N3). The LCP method describes water used by consumers and leakage inside the building. Input data for the model include the total number of consumers, number of service connections and measured inflow into the DMA. Unknown parameters in this method include the water used by consumers, leakage rate in the building, N1, N2 and N3 values. The first three are calculated from the data collected; however, N2 and N3 estimated using recommendations from literature namely 0.5 and 1.0 respectively. The pressure reduction from 63m to 29.5m (approximately 53% reduction) resulted in a system input volume reduction of 2 457 m^3/d to 1 590 m^3/d. Total estimated savings under reduced pressure was 94%.

The authors investigated the hourly demand pattern experienced on a Sunday before pressure management was introduced. This day was used for comparison with the monitoring results at reduced pressure on the same day of the week (for three days). Water usage types investigated include leakage in the distribution system, night time usage, night time wastage, household leakage and consumer indoor usage. The pressure was reduced from an unregulated pressure of approximately 63m to 29.5m inlet pressure (approximately 53% reduction). The water used reduced from 1 484 to 990m^3/day (approximate 33% reduction).

Table 2-4: Variables and associated results based on outcomes of investigation by Babić *et al* (2014)

Variable	Value
Initial Unregulated Pressure (m)	63
Final Reduced Pressure (m)	29.5
Overall N3 (Power regression Model)	0.5228
Flowrate Reduction after 53% reduction in Pressure	33%

Lambert, personal communication, 2017, stated that consumption exponents of 0.5 for indoor household generally relate to high levels of leakage within the building.

Gomes, Marques, and Sousa, (2011) estimated the benefits yielded by pressure management especially with respect to water production reduction. This method proposed in this paper uses a head-driven network simulation model and the pressure/leakage and pressure/consumption relationships during minimum night flow to estimate the reduction achieved from pressure management. In phase 1 of the investigation Gomes *et al* (2011) estimate the water consumption and water losses at each node and the pressure/leakage and pressure/consumption relationships during minimum night flow. Afterwards, in phase 2, the pressure is reduced and the corresponding consumption and water loss estimates are adjusted by adjusting phase 1 values to phase 2 pressure conditions. In order to assume good consumption conditions, the service pressure must reach or exceed the minimum pressure required. For the modelling exercise an exponent of 0.5 was used for the consumption.

Two case studies were used. In the first case study a fixed outlet PRV was used to analyse the importance of pressure-dependent and pressure-independent consumption. The second case study shows the influence of different PRV types and the influence of the pressure available at the DMA entry point. With a pressure reduction of 45.74m to 22.45m (50.92% reduction) the water consumption reduced from 1476.62m^3/h to 1464.42m^3/h (0.83% reduction).

It was determined that there was a definite reduction in water sales (although minor).

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Tabesh and Hoomehr (2009) developed a genetic algorithm to manage water consumption through optimizing pressure reducing valves settings.

In this procedure, nodal pressure pressures were set to their optimum magnitude (in relation to minimum standard pressure) by using reservoirs, valves and suitable pressure zones. Uncontrolled pressure reduction, although leads to consumption reduction, may also cause reduction of the system reliability. The optimal situation is when the nodal heads approach to design values as much as possible. The latter is obtained by using optimization procedures. Tabesh and Hoomehr (2009) first determined the real condition of the network, by means of network hydraulic analysis, before finding the real consumption volume. In this method, they assumed that the amount of demand remains constant at each node and it can be supplied at any normal and abnormal situation. In order to consider both controlled consumption and leakage a full head driven model was considered.

It was stated that pressure reduction and optimal pressure settings (in relation to minimum standard pressure) will reduce the total consumption of water within the system by 15 -25%. This can be observed in **Figure 2-17.** This graph reflects the total water consumption before and after pressure management. This investigation by Tabesh and Hoomhr (2009) indicated that only head driven hydraulic models are capable of modelling such pressure reductions because demand-driven models cannot recognize the pressure dependent nature of demand.

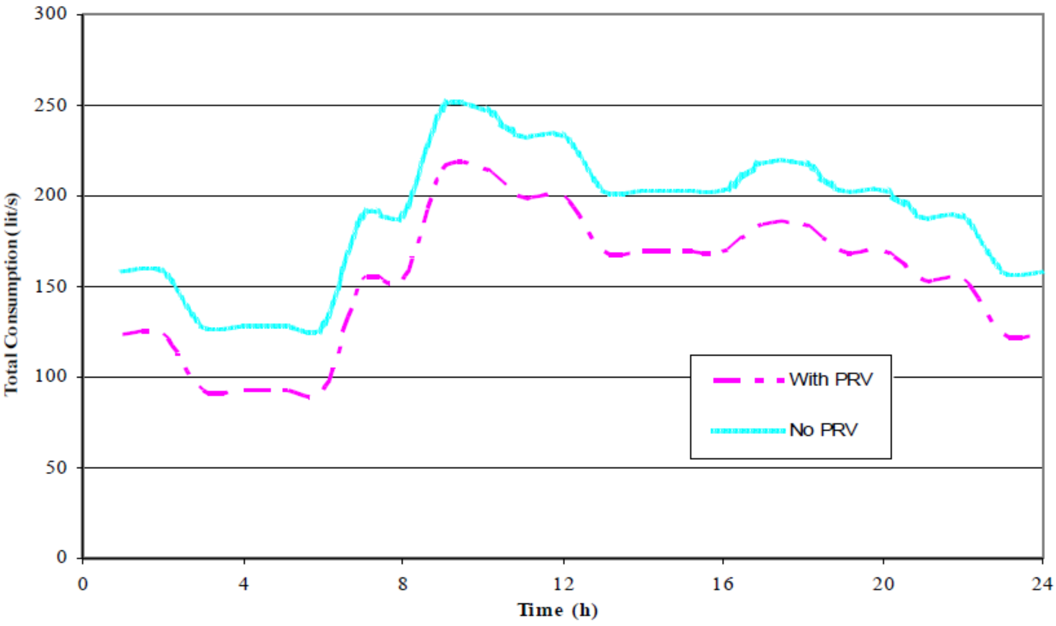


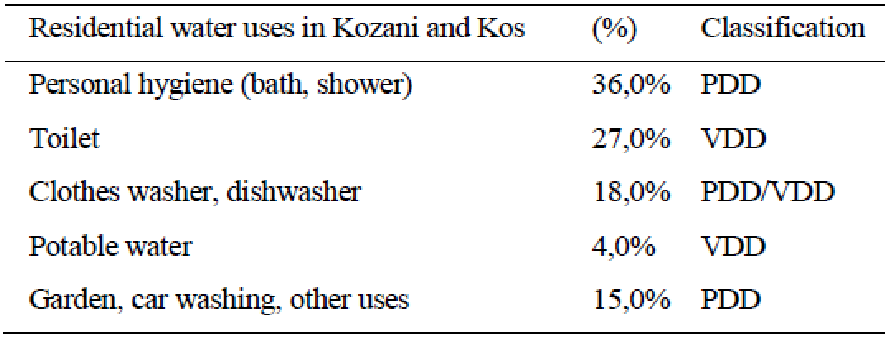
Figure 2-17: Comparison of total consumption before and after consumption management (Tabesh and Hoomehr, 2009)

Kanakoudis and Gonelas (2014) applied pressure management to reduce water losses in two Greek Cities. The purpose of the study was to assess options of pressure management and its impact and benefit to both a modelled and real investigation.

In Greece, the operating pressure of WDS is usually quite high (7-8 atm or ≈70 -80 m) often exceeding 10 atm (≈100m). Pressure management will reduce part of the consumption which is pressure dependent and in medium-term postpones future expansions of the system's supplying capacity and thus saving money.

Volume driven demands are considered to have water consumptions which depend on the required volume of water and are independent of pressure, such as washing machines, bath tub, toilet, etc. Pressure driven demand considers consumption components which depend on pressure, such as the use of showers, in-house leakage, and sprinklers. The pressure driven demand or consumption was 70% of total household consumption.

Table 2-5: Classification of water use in PDD and VDD (Kanakoudis and Gonelas, 2014)



Residential water uses in Kozani and Kos	(%)	Classification
Personal hygiene (bath, shower)	36,0%	PDD
Toilet	27,0%	VDD
Clothes washer, dishwasher	18,0%	PDD/VDD
Potable water	4,0%	VDD
Garden, car washing, other uses	15,0%	PDD

This study dealt with the implementation of “virtual” DMA’s and installed PRVs in a simulated model of Kos Town WDS and Kozani WDS.

The field experiment involved the gradual decrease of the outlet pressure over two to three days. Author only considers reduction in SIV which does not focus on only consumer demand but takes into consideration losses which may exist within the system. Water consumption reduction ranged between 12% for scenarios with fixed PRV’s installed and up to 25% for scenarios with 24hr PRVs and pump installed. However, in the pilot areas savings were up to 60%.

Figure 2-18 represents the correlation between SIV reduction and pressure driven demand and the associated exponent within the demand-pressure relationship. The greater the percentage reduction in SIV the higher the exponent value. The more consumption sensitive demand components to pressure the higher the exponent (Cullens, 2004).

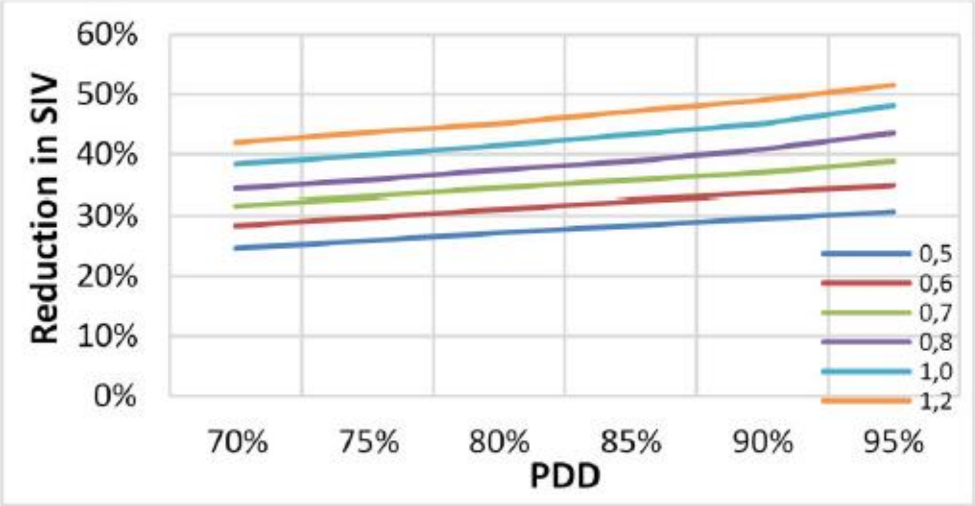


Figure 2-18: Correlation between SIV reduction with pressure driven demand and the exponent in the demand-pressure relationship

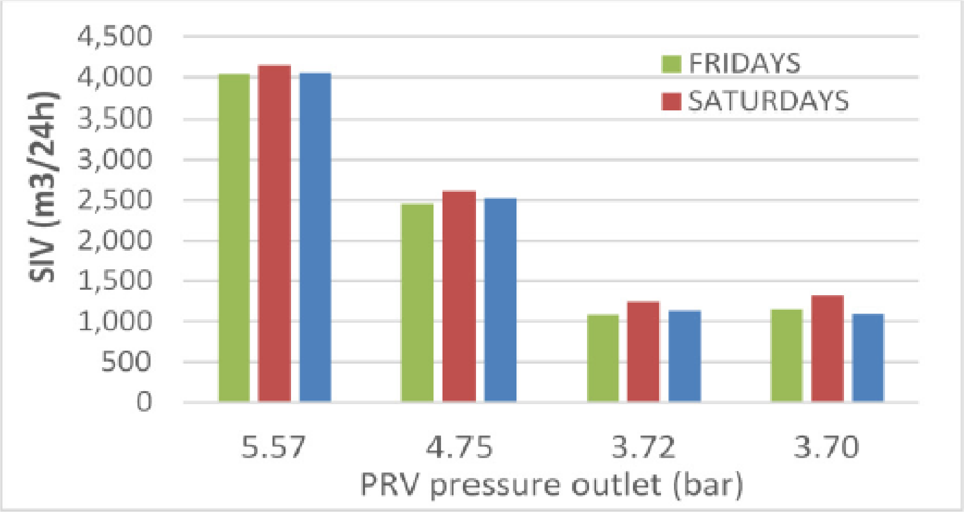


Figure 2-19 above reflects the SIV reduction over a three-week period. SIV decreases with a decrease in pressure.

Figure 2-19: SIV reduction over three weeks (Kanakoudis and Gonelas, 2014)

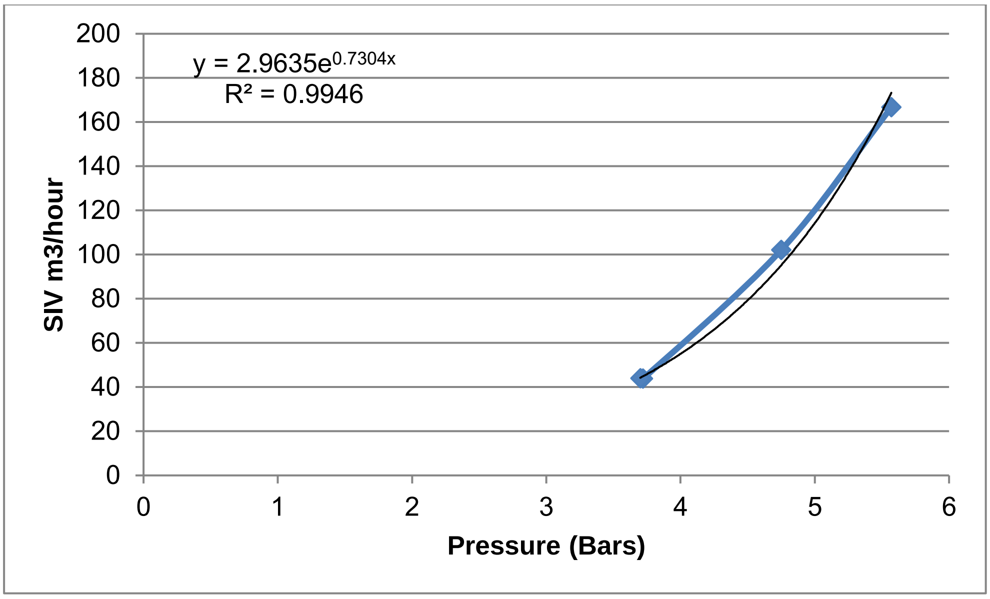


Figure 2-20: System Input Volume Consumption versus pressure records over a three week period for three consecutive Fridays only (data extracted from Figure 2-19)

In **Figure 2-20**, the exponent, 0.73, represents the impact of pressure reduction on the system input volume. Even though they were able to indicate that there was an effect of pressure reduction on consumption, the distinction between the impact on the leakage and the end user consumption was not clear. Especially in the case where they partially validated the impact of the pressure reduction, on the end user consumption reduction, based on the large percentage of variables within the household consumption which was considered sensitive pressure fluctuations. However, if it is found that many households have a high degree of leakage within the home, the indoor household exponent values can reach around 0.5 (Lambert, personal communication, 2017).

A study by Tuhovcak, Suchaek and Rucka (2018), investigated the sensitivity of changes in water consumption with changing pressure conditions in a specific office building. This paper is based on a real-life study which monitors the influence of pressure on water consumption over a period of time. This study utilized a number of input parameters to monitor this relationship. This included the number of people in the building during working time, the water meter pulse value and the time step length in the characterization of the water consumption using demand coefficients. The supply pressure to the building was controlled using a pressure regulating valve on the water service connection. The building had three levels with maximum number of workers of 35. In determining the demand coefficient (N3) the most important input parameter was the number of people working in the building. According to the study, the most accurate value obtained, for an office building, was 0.150 with a pulse value of 1 litre (where the number of workers were monitored continuously).

Meyer (2018) as part of his research investigated the pressure-demand relationship by performing pressure adjustments in three operational district metered areas (DMA's). Three DMA's formed part of this study. DMA1 is a medium to high income group, DMA2 is a low income group and DMA3 is a medium income group. Pressure was varied at the PRV inlet and flow recordings were placed at random consumers within the DMA. Pressure and flow data was available from 76 different households. The analysis spanned over approximately 2 weeks for each DMA. For DMA 1, the increments of pressure reduction ranged from 4m to 13m per step, DMA 2, the increments of pressure reduction ranged from 3m to 10m per step. For DMA 3 the increments of pressure reduction ranged from 4 to 12 m per step.

For all three DMA's the PRV downstream pressure and critical pressure reduced with each test. In DMA 1 the flow rate reduced for the first three pressure reductions however after the next three step pressure test the consumption increased. It was explained that this was likely as a result of increased irrigation, which is common for high income users. In DMA 2 and DMA 3 the MNF reduced with reduced pressure in each period. In DMA 1, after a few days of pressure step testing there was an unforeseen drop in consumption. this pattern was similar observed in the control DMA where the pressure was kept constant. The latter suggested weather related patterns could have impacted on the recorded flow.

Meyer (2008) indicated that legitimate night use, in a residential DMA, can be calculated however it is expected to be small and mainly due to toilet use which is pressure independent. He therefore went on to say that the legitimate night use should remain constant under pressure.

The elasticity of demand to pressure was approximately 0.05 for DMA 1 (High to medium) and DMA 3 (Low income) and in the range of approximately 0.25 for DMA 2 (Medium Income).

The study concluded that the relationship was not consistent between various periods and in some cases remained the same. Meyer, 2018, indicated in his unpublished thesis, that the power regression model suggested an elasticity of demand to pressure in the range of ≈0.15 to ≈0.30 where on-site leakage was included, and in the range of ≈0.05 to ≈0.25 where on-site leakage was excluded

2.6.3. Summary of Demand Elasticities obtained through various studies

Table 2-6 represents the summary of the demand elasticities obtained through various studies. It further compares the exponents, data sources and limitations.

Table 2-6: Summary of Demand Elasticity obtained through various studies

Author	C/ L/ B	M/ F	Exponents	% Reduction in Pressure	% Reduction in Consumption	Indoor/ Outdoor/ Both	Consumer Type	Comment
Gebhart, 1975 (Phase 1)	C	F	0.54	64%	30%	Both	Mixed	
***Gebhart, 1975	C	F	0.26	52%	25%	Both	Flats	Calculated from results in presented in the study
***Gebhart, 1975	C	F	0.87	52%	48%	Both	Schools	Calculated from results in presented in the study
***Gebhart, 1975	C	F	0.62	52%	38%	Both	Shopping Centre	Calculated from results in presented in the study
***Babić *et al*, 2014				53%	33%			
Thornton and Lambert, 2005	C	F	0.07 and 0.25	-	-	Indoor	Residential	Only performed on toilets
Barlett, 2004	C	F	0.2	-	-	Indoor	Student housing	
Cullens, 2004	C	F	0.5 – 0.8	50%	30%-50%	Outdoor	Irrigation Systems	Outdoor consumption, typically garden irrigation, is time based with higher exponents of 0.5. Soaker hoses were found to have the higher exponent of around 0.75 – 0.80
Van Zyl *et al*, 2003	C	M	-	50%	10-16%	Both	Domestic Suburbs	
Van Zyl *et al*, 2003	C	M	-	50%	7-13%	Both	Domestic Townships	
Bemezai and Lessick, 2003	C	F	-	17.6%	1.9%	Both	Domestic	
Bemezai and Lessick, 2003	C	M	-	6%	None detected	Both	Domestic	Pressure reduction may be too low to notice significant change
Bemezai and Lessick, 2003	C	M	0.1 – 0.2	10%	-	Both	Domestic	Pressure reduction may be too low to notice significant change
Fantozzi and Lambert 2010	C	F	0.04	-	-	Indoor	Domestic residential	Limited insight (data from Australia)
Fantozzi and Lambert 2010	C	F	0	-	-	Both	Domestic	Households with roof tanks
Fantozzi and Lambert 2010	C	F	0	-	-	Outdoor	Domestic	Household with Swimming pool
***Babić *et al*, 2014	C	F/ M	0.53	113%	49.9%	Indoor	Domestic	Authorised Consumption
*Gomes *et al*, 2011	C	M	0.5	-	0.83%	Both	Mixed	estimate
Tabesh and Hoomehr, 2009	C	M	-	-	15-25%	Both	Domestic	

Author	**C/ L/ B**	**M/ F**	**Exponents**	**% Reduction in Pressure**	**% Reduction in Consumption**	**Indoor/ Outdoor/ Both**	**Consumer Type**	**Comment**
Kanakoudis and Gonelas, 2014	B	M	0.5-1.2	-	12-25%	-	Domestic	
***Kanakoudis and Gonelas, 2014	B	F	0.73	50.5%	>200%	-	Domestic	Calculated
Tuhovcak *et al* , 2018	C	F	0.150	-	-	-	Commercial Building	Does not consider leakage in the building
Meyer, 2018	C	F	0.13	-	-	Both	Domestic Medium to High Income	All Consumers in the DMA
Meyer, 2018	C	F	0.23	-	-	Both	Domestic Medium to High Income	High MNF Excluded
Meyer, 2018	C	F	0.26	-	-	Both	Domestic Medium to High Income	Medium and High MNF excluded
Meyer, 2018	C	F	0.29	-	-	Both	Domestic Low Income	All Consumers in the DMA
Meyer, 2018	C	F	0.27	-	-	Both	Domestic Low Income	High MNF Excluded
Meyer, 2018	C	F	0.25	-	-	Both	Domestic Low Income	Medium and High MNF excluded
Meyer, 2018	C	F	0.19	-	-	Both	Domestic Medium Income	All Consumers in the DMA
Meyer, 2018	C	F	0.06	-	-	Both	Domestic Medium income	High MNF Excluded
Meyer, 2018	C	F	0.04	-	-	Both	Domestic Medium Income	Medium and High MNF excluded

C = Consumption after the meter; L= System Leakage; B = Combined Consumption and network Leakage analysis; M= Model and F= Field Investigation

*refers to estimate **Obtained ***Calculated from data within paper

3. STUDY AREA AND METHODOLOGY

3.1. INTRODUCTION

This Chapter describes the method undertaken in order to achieve the objectives listed for this study. The process included a detailed literature study on the topic of pressure and water demand, collection of end user water consumption and the collection of logged pressure and flow data. This data was then analysed using the power equation (Epanet) and the modified orifice equation (Kabaasha; Piller and van Zyl, 2017) hydraulic modelling software, Epaleaks, to determine the water demand elasticity.

3.2. METHOD OVERVIEW

In order to test the impact of pressure management on end user demand it was important to identify a Pressure Managed DMA. A Control DMA was selected in order verify the impacts of pressure management on the end user consumption. Various analysis was performed on the billed consumption for these two DMA's. These include:

- Overall Average Day Demand Comparison a year before and a year after pressure management
- Monthly Average Demand Comparison a year before and a year after pressure management

The analysis included a comparison of the consumption for the non-domestic users for both the Pressure Managed and Control DMA. However, these users were not a core focus of the study.

Two sets of system flows and leakage flows data was available for the pressure managed DMA. This information was available from the Completion Report (City of Cape Town, 2009) and the logged flow data. The Completion Report Data reflects the Average system flows and MNF a week before and a week after pressure management. The Logged Data was available for a longer period of time and reflects the flows before and a year after pressure management. The logged data was filtered, cleaned and analysed. Information available for this study is as follows:

- Completion Report
    - MNF and Average Flows (based on the system a week before and a week after pressure management)
- Logged Data
    - MNF and Average flows (based on the system a year after pressure management)

In order to calculate the AZP for the system at the Completion Report conditions (City of Cape Town, 2009) and the Logged Data conditions, it was required to develop two models. These models were based on the information set under the two scenarios. From these models, the flow profiles were generated and compared. In addition, the AZP for both systems were calculated and compared.

Furthermore, the Night Day Factor was calculated for the system. This value was used to convert the leakage flow into a daily flow rate. This information was later used in the Water Balance where the following information was calculated:

- Non-revenue water for the system before pressure management
- Non-revenue water for the system after pressure management
- Infrastructure Leakage Index (ILI) for the system before pressure management
- Infrastructure Leakage Index (ILI) for the system after pressure management
- Billed Authorised Consumption before pressure management
- Billed Authorised Consumption after pressure management

It was then decided to separate the leakage from consumption. In order to do this, various leakage parameters were required to be calculated. To analyse the leakage before and after pressure management, two types of models were used, namely 1) Epanet Model (based on the Orifice Equation) and 2) the Epaleaks Model (based on the modified orifice equation). In order to do this modelling the following leakage parameters were calculated using the official Completion Report MNF and Average Flows calculated. Leakage parameters include the following:

- For the N1 Equation
    - Constant Coefficient
    - Leakage Exponent
- For the Modified Orifice Equation
    - Initial Leakage area
    - Head-Area Slope

These parameters were calculated for the system based on the data a week before and a week after pressure management. To calculate the leakage parameters for the system a year later the Excel Solver function assisted with adjusting these leakage parameters. The following leakage parameters were adjusted:

- For the N1 Equation
    - Constant Coefficient
- For the Modified Orifice Equation
    - Initial Leakage area
    - Head-Area Slope

Once the adjusted leakage parameters were available they were applied as follows:

For the N1 Model (based on the orifice equation), the constant coefficient was distributed across each node based on the weighted average of demand.

For the FAVAD Model (based on the modified orifice equation), the initial leakage area was distributed across the system at each node based on the weighted average of demand. The head-area slope was calculated for each node.

The relevant leakage parameters were inserted into the models. The demand pattern was calibrated. The following comparisons were made between the two models:

- Total Demand over 24-hours
- Total Consumption over 24-hours
- Total Leakage over 24 hours
- AZP

To determine the impact of pressure on consumer demand the demand elasticity to pressure was calculated. A number of scenarios were tested. These included:

- N3 based on Billed data (domestic only)
    - Average annual demand
    - Monthly demand
- N3 based on Billed Authorised Consumption
- N3 based on the N1 and FAVAD model outputs
    - Average Consumption (excluding leakage)
    - For every hour over the 24-hour demand profile

To verify that this was consistent with other studies, a graph illustrating the various studies N3 values from other studies was plotted with the calculated values from this study.

3.3. PRESSURE MANAGED AND CONTROL DMA SELECTION PROCESS

In order to ensure that the reduced demand was not as a result of any other water saving interventions a Control DMA was selected. The purpose of the Control DMA was to test whether there had been alternate activities which may have influenced the reduced demand in the pressure managed DMA as opposed to pressure management.

The following section describes the pressure managed DMA and Control DMA site selection process.

3.3.1. DMA Selection Process

The DMA was selected based on the following criteria:

- The DMA had to be mostly domestic (more than 90% of households defined as domestic and total domestic consumption should be larger than the total non-domestic consumption)
- It must be fed through a single metered connection fitted with a pressure reducing valve (PRV).
- There must be at least 11 months' worth of reliable consumer billing data both before and after pressure management. Ideally, 12 months of data would have been preferred, however, on extracting the 12-month data prior to pressure management it was found that the dataset was not complete. It was only possible to access 11 months of valid data. This was required in order to identify the possibility of seasonal changes having an impact on the change in consumption.
- There must be at least three weeks of logged pressure and flow data before and after pressure management. Most logging results for the system prior to pressure reduction are only available between two and four weeks.

3.3.2. Control Selection Process

The control area was selected based on the following criteria:

- It must be near the DMA under investigation
- It must be similar in network length, number and type of consumers
- There must be at least 11 months' worth of reliable consumer billing data before and after pressure management.

From **Table 3-7**, summarises and compares the criteria between that of the pressure managed and Control DMA. It further highlights the similarities and minor differences between the sites. The Control DMA is approximately 8km away from the pressure managed DMA.

The approximate network length of the pressure managed DMA is 86km and the Control DMA is 63km. There are approximately 4 825 and 3 946 stands in the pressure managed and Control DMA respectively (obtained from the SAP records). The average size is approximately 285m^2 and 397m^2 respectively where the pressure managed DMA has a slightly smaller average stand size. The number of connections per km are similar in that the pressure managed DMA has 56 connections per km and the Control DMA has 61 connections per km. The income level is middle to low income for both DMA's. Logged data is not available for the Control DMA. Only SAP billing records are available for the Control DMA. These records were used to compare if the consumption reduction in the test DMA was as result of pressure management or possibly other factors.

The Critical Point Elevation, for the pressure managed DMA is 23.46m (furthest point in the DMA from the PRV). The topography is fairly flat ranging from a high of 26.63m to 12.84m which is sloping upwards from the PRV for the pressure managed DMA. For the Control DMA topography is also fairly flat ranging from a high of 57.6m to 39.2m.

Table 3-7: Summary and Description of pressure managed and control DMA

	Pressure Managed DMA	Control DMA
Income Level	Mid-low	Mid-low
No. Stands	±4 825	±3 946
No. Occupied Stands	±4 560	±3 946
Average Stand Area (Domestic Only)	285 m^2	±397 m^2
Length of mains (km)	±86	±63
Connections/ km	56	61
No. feeds into DMA	One Inflow	-
Commissioned	August 2009	-
Billing data before Pressure Management	12 months	11 months
Billing data after pressure Management	12 months	11 months
Logged Data Before Pressure Management	±2 weeks	-
Logged Data After Pressure Management	±2 weeks	-

3.4. PRESSURE MANAGED DMA DESCRIPTION

In 2009, Exeo Khokela Civil Engineering Contractors (Pty) Ltd in association with sub-consultants WRP Consulting Engineers (Pty) Ltd and Kantey and Templer Consulting Engineers (Pty) Ltd, were appointed to design, construct and commission a sustainable pressure management solution for the study area. The solution involved the construction of a single pressure management installation on the main supply pipeline and making discreet of the supply area to ensure that all water supplied to the area is regulated through the pressure management installation.

3.4.1. PRV Installation

The 2009 commissioned pressure managed zone consists of a single feed, 250mm, PRV installation. **Figure 3-21** provides a schematic overview of the pressure managed zone and its network configuration.

Figure 3-21: Schematic Layout of Pressure Managed DMA Water Supply Network (City of Cape Town, 2009)

As detailed in **Figure 3-22**, the 250 mm PRV installation connects onto a 300mm asbestos cement supply pipeline onto the 400mm reticulation main. A 300mm isolating valve was installed onto the existing 300mm asbestos cement pipeline. This valve is normally isolated to force flow through the PRV installation. The existing pipeline then serves as a bypass for the installation with no interferences on the water supply to the area. The PRV is fixed outlet and modulated through a single pilot and no controller is installed. The installation consists of a (a) 250mm isolating valve enclosing a (b) 250mm strainer, (c) meter and (d) Bermad PRV all housed in a (e) five by two meter reinforced concrete chamber. The PRV is modulated through a single pilot and no controller are installed (City of Cape Town, 2009). **Figure 3-22,** provides an overview of the installation configuration.

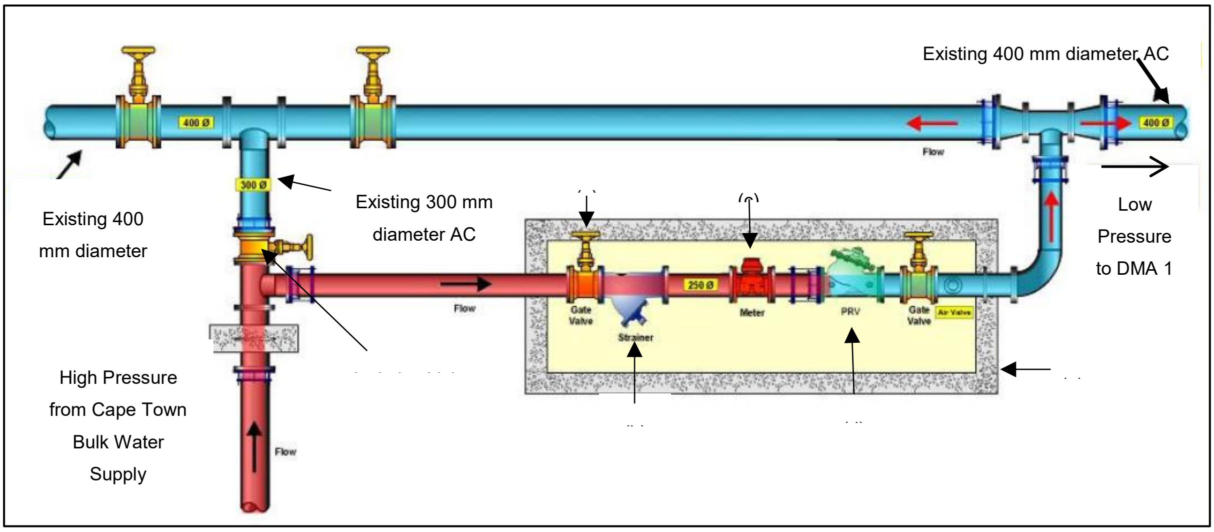


Figure 3-22: Layout of Pressure Managed DMA Installation (City of Cape Town, 2009)

3.4.2. Loggers

GSM Loggers

MyCity, as with Zednet, is a web-based monitoring system. This system gives the users access to data parameters such as flow level, pressure, or other fluid properties. A Global System for Mobile Communication (GSM) data logger is used to record these data parameters. Recorded data is transferred to the server by means of the GSM network. This server can be accessed through a website on which data can be accessed in the form of graphs, tables, or can be downloaded as CSV files (Pretorius, 2016).

As part of the installation One Cello XO GSM logger with two pressure sensors (i.e. upstream and downstream pressure of the installed PRV) and one flow sensor, was installed

Prior to the installation of the PRV, one Flotron GSM logger was installed in order to monitor the pressure and flow profiles.

3.4.3. Logged Flow and Pressure Data

Flow logging results for the Study Area prior to and post commissioning of the pressure management project are included in **Figure 3-24**. The minimum night flow reduced from 158m^3/hr to 47m^3/hr. The pressure was reduced from an average upstream pressure of 88m to 47m as presented in

Figure 3-23. It is clear that the up-stream pressure fluctuates from a high of 96m to a low of 79m. The PRV outlet pressure remained stable at an average of 47m varying slightly by one or two meters. These pressure readings only reflect the pressure readings up-stream and downstream of the PRV.

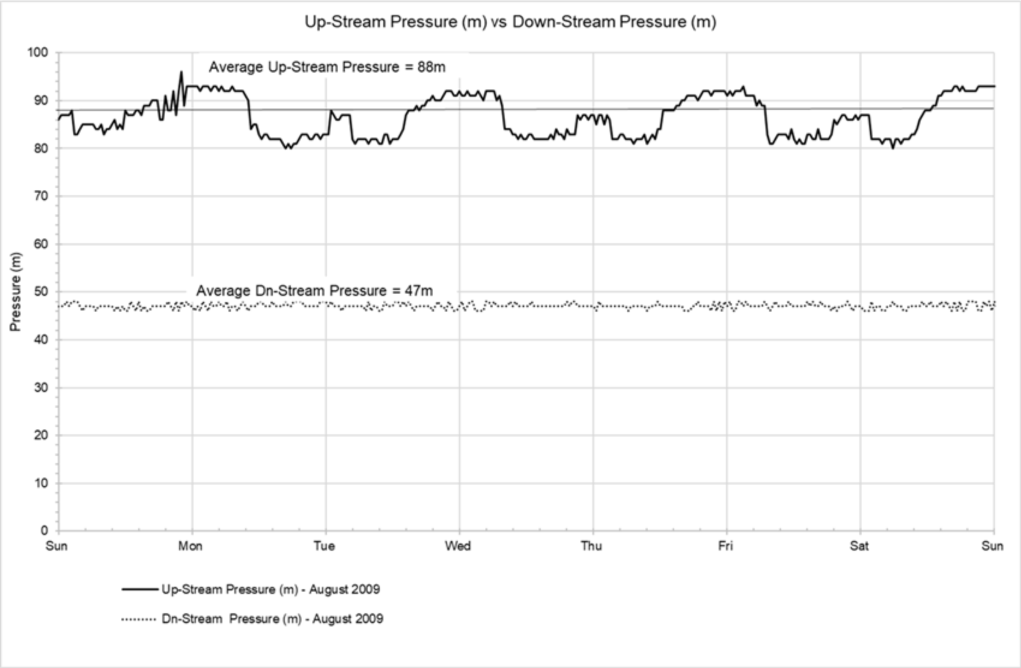


Figure 3-23: One week pressure logging results for the study area

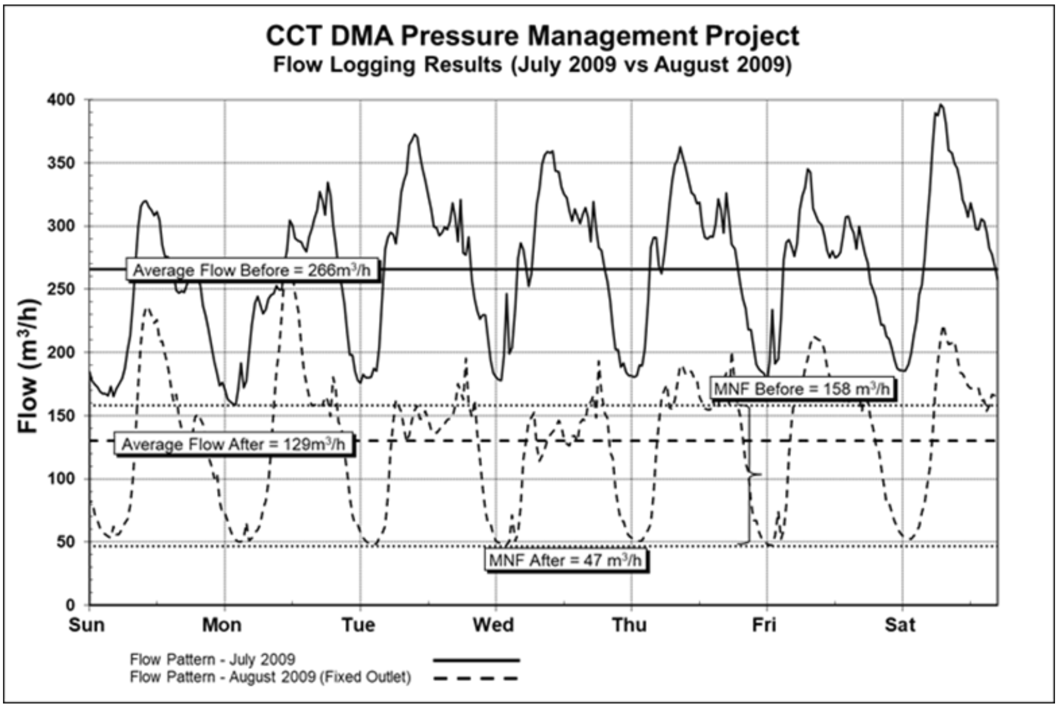


Figure 3-24: One Week Flow logging results (before and after pressure management) (City of Cape Town, 2009)

3.4.4. Diurnal Demand Pattern

The recorded data used for this study was retrieved from a web-based monitoring system, and is based on a past pressure management installation commissioned in 2009. Additional logger installations were not required as part of this study.

MyCity, as with Zednet, is a web-based monitoring system. This system gives the users access to data parameters such as flow level, pressure, or other fluid properties.

3.4.5. Extraction of Logged Data (before and a year after pressure management)

Data supporting the commissioning report and presented in **Figure 3-24,** as requested from WRP Consulting Engineers, was extracted. This data was provided in Excel format for the period 5 July 2009 to 12 July 2009 which represented the system before pressure reduction. The Completion Report (2009) logged approximately one week's worth of data. This data was logged at 30 minute intervals. In addition to the latter data, Data for 7 June 2009 until 20 June 2009 was available from the MyCity portal and was extracted at 30-minute-intervals.

Figure 3-25 and **Figure 3-26** represent the raw flow data extracted from the respective sources.

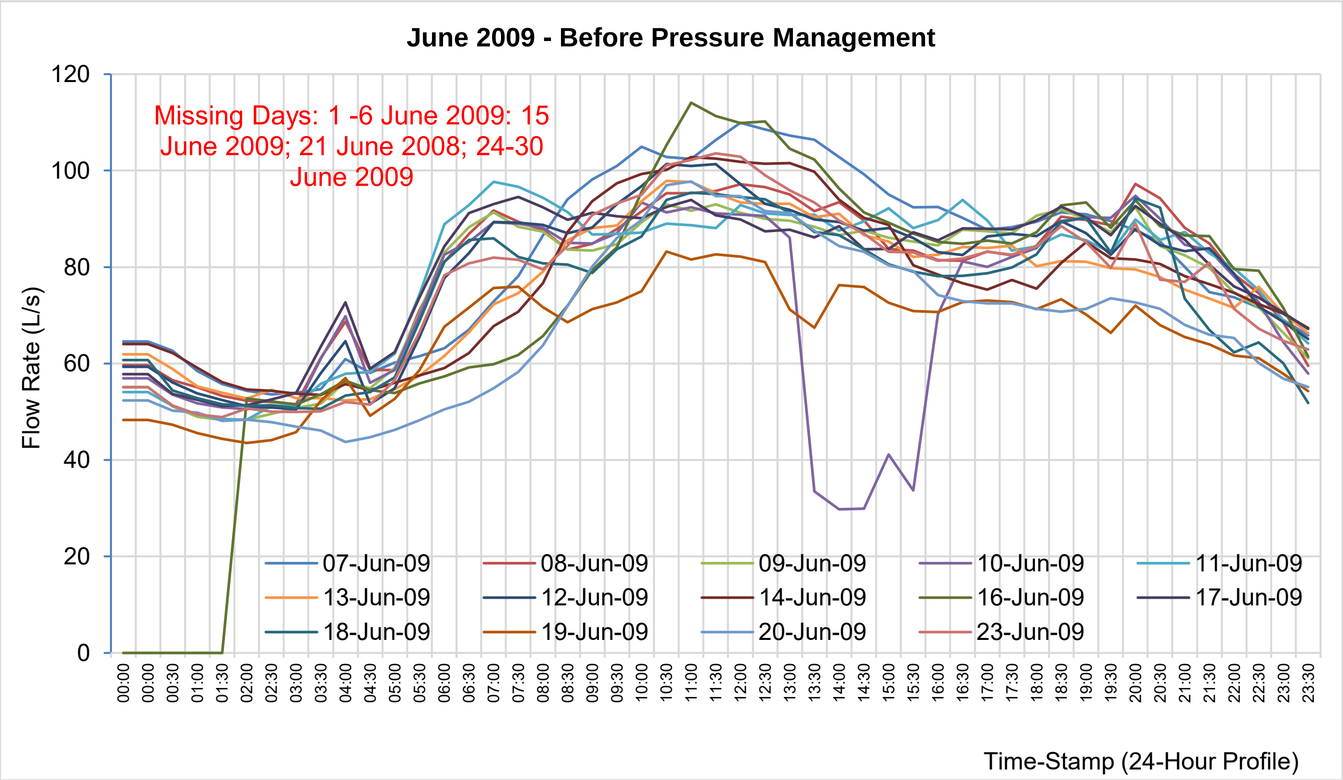


Figure 3-25: Raw logged, 24 hour flow data at 30-minute-intervals, for the period before pressure management (My City Portal, 2009)

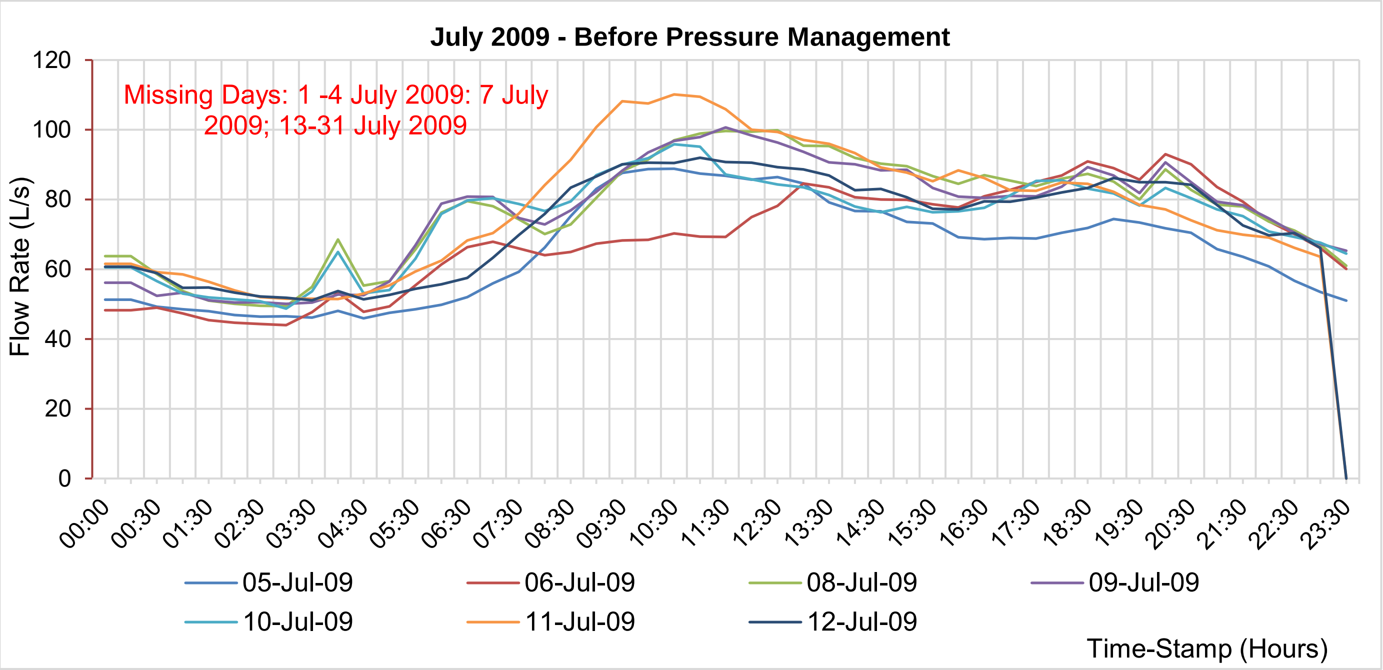


Figure 3-26: Logged, 24 hour flow data at 30 minute intervals, for the period before pressure management (City of Cape Town, 2009)

Due to limited data available for the scenario before pressure management a decision was then made to extract, analyse and compare the logged results for June/ July 2009 with the logged results for the month of June/July 2010 (one year later). This was to ensure that the data sets were comparable with each other. **Figure 3-27** and **Figure 3-28** represent the flow logged raw flow data profiles logged at 15-minute intervals.

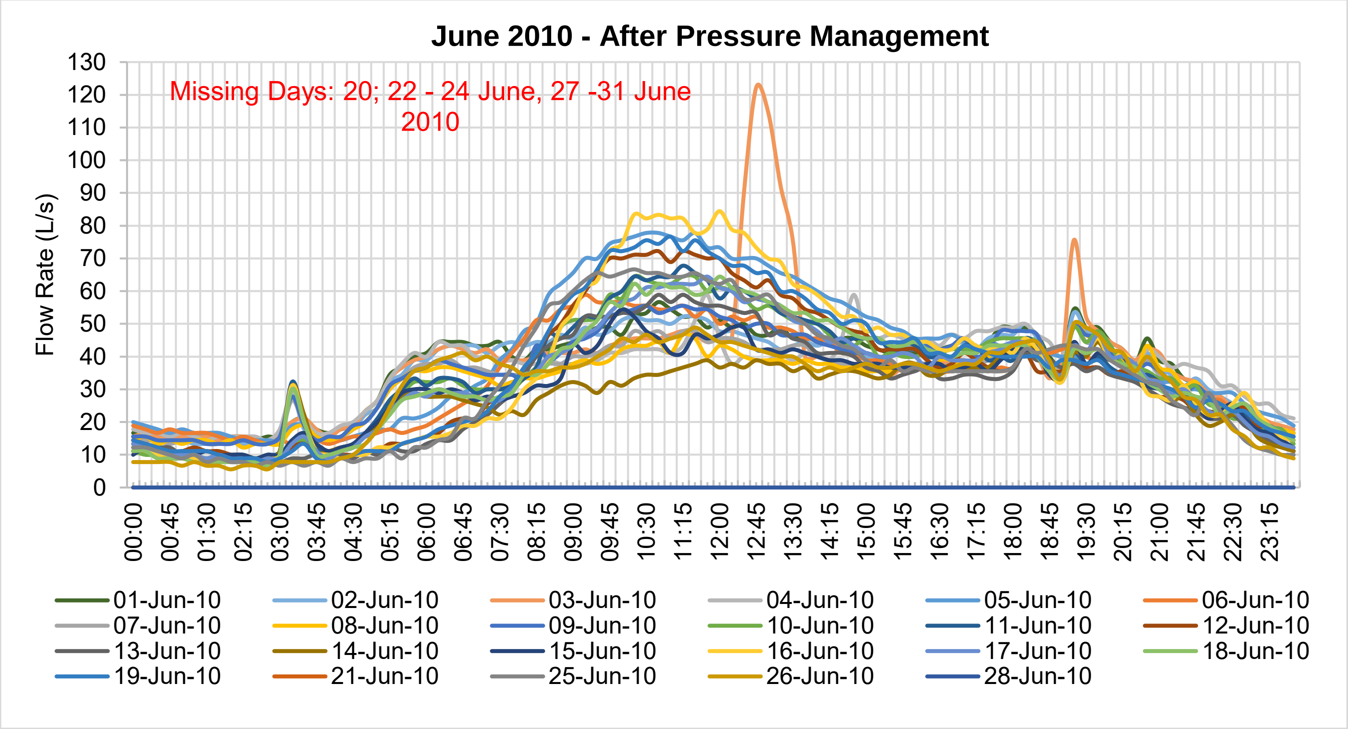


Figure 3-27: Raw logged, 24-hour flow data at 15-minute intervals, for the period after pressure management (My City Portal, June 2010)

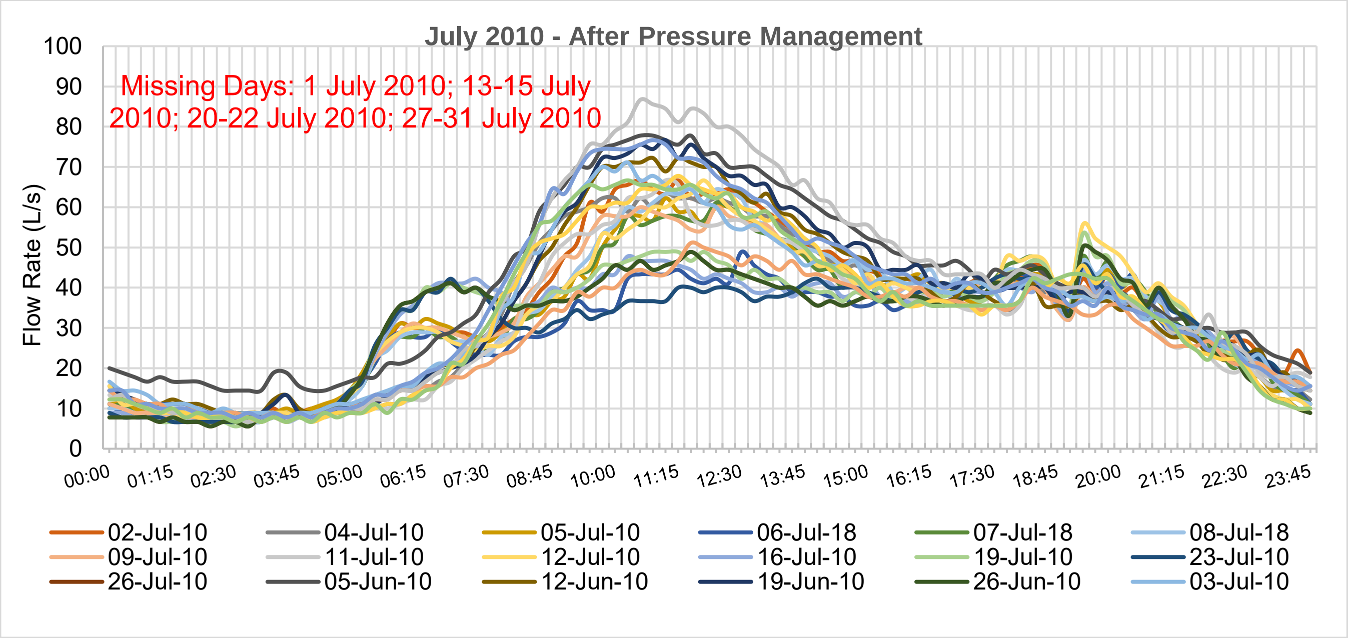


Figure 3-28: Raw logged, 24-hour flow data at 15-minute-intervals, for the period after pressure management (My City Portal, July 2010)

3.4.6. Filtering of The Logged Flow Data

From the raw logged data presented **Figure 3-25**, **Figure 3-26**, **Figure 3-27** and **Figure 3-28**, it was found that a number of the logged readings had either daily missing readings or individual 15-or 30-minute interval records missing. The following filter process was applied.

Missing daily records

Records which had zero readings for the whole day or for more than five consecutive readings were removed.

Missing 15 or 30 minute records with in the daily data

In the event that less than five (for 15-minute intervals) or two consecutive (for 30-minute intervals) readings were missing, these were replaced with an average value of the two previous days of the same logged interval.

Summary of filtered flow data

The number of daily profiles available (for the system before pressure management), before the filter was 22. After the filtering process it was reduced to 21 daily profiles. **Table 3-8** represents the summary of 30-minute interval records available, where 48 intervals refers to 1 day (logged at 30-minute intervals).

Table 3-8: Summary of records filtered for the system before pressure management

	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday
Max Intervals generated within a day (i.e. number of 30 minute intervals in a day)	48	48	48	48	48	48	48
No. daily profiles averaged per day	3	3	3	3	3	3	4
No of missing records	44	5	0	0	1	0	0
No of days removed	1	0	0	0	0	0	0

The total number of daily profiles available, before the filter, was 42. After the filtering process it was reduced to 39 logged daily. **Table 3-9** represents the summary of 15-minute interval records available, where 96 intervals refers to one day (logged at 15-minute intervals).

Table 3-9: Summary of records filtered for the system after pressure management

	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday
Max Potential Records within a day (number of 15 minute intervals in a day)	96	96	96	96	96	96	96
No. daily profiles averaged per day (used to generate the average weekday profile)	8	4	4	4	8	8	6
No of missing 15 minute records within daily profile	96	0	0	0	96	96	0
No Days Removed	1	0	0	0	1	1	0

3.4.7. Demand Patterns

Determine the flow profile over 24-hours

The following steps were followed in obtaining the 24-hour flow profile based on one-hour intervals:

- Calculate the summation of the 15-minute interval (four records per hour) or 30-minute intervals (two records per hour) system flows.
- Divide the summation by the number of records per hour.
- Plot the average flows (y-axis) for each hour.

The above methodologies were applied to the system before and after pressure reduction.

An average of the hourly daily flows was used to generate the new profiles for before and after pressure reduction, represented by **Figure 3-29**. From **Figure 3-29**, it is clear that the demand profile for the system before pressure management is higher that of the system before pressure management. This change can be evidently seen in the Minimum Night Flows at hour 3. **Table 3-10** represents the change in flows, for the system before pressure management and after pressure management. As expected from theory, the MNF flow values appear to be most influenced by the pressure difference.

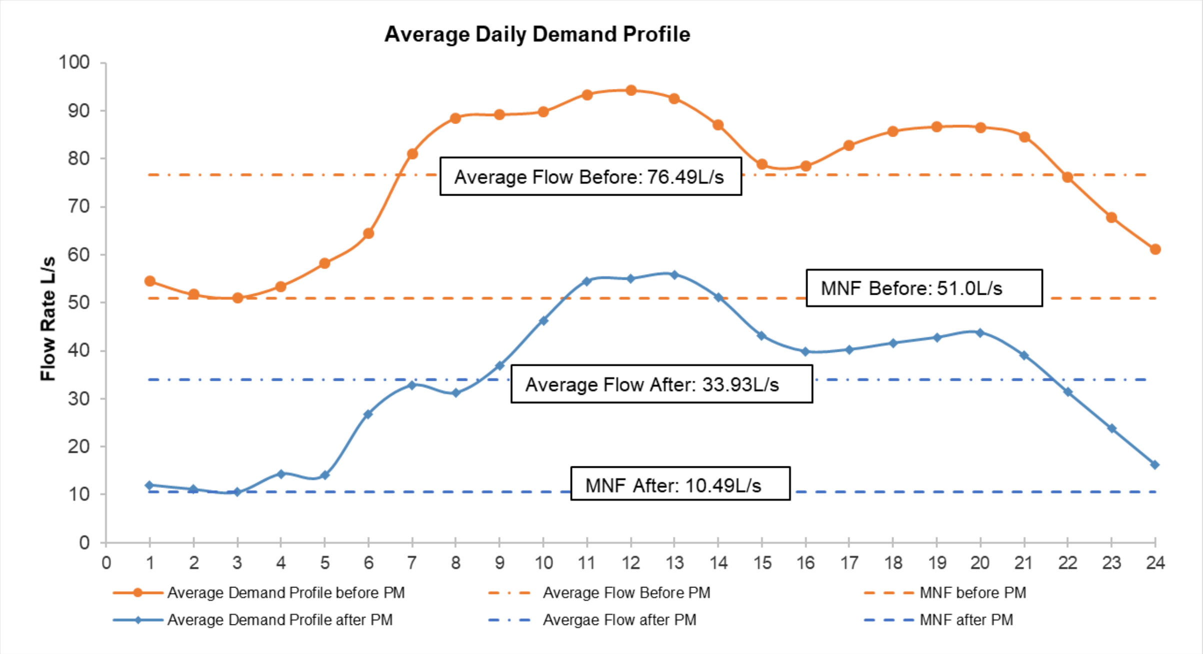


Figure 3-29: Average Daily Demand Profile based on logged data

From the above profiles the following information was obtained:

Table 3-10: Summary of flows before and year after pressure management (June/ July month)

Parameter	Before	After
Average Flow (L/s)	76.5	33.9
Max Flow (L/s)	94.2	55.9
MNF Flow (L/s)	51.02	10.49

Dimensionless 24-hour pattern

The flow profiles, in **Figure 3-29**, were used to develop the demand pattern (or dimensionless 24-hour pattern) for the system before and after pressure reduction scenario. This was done by applying following the following steps:

- Calculate the sum of the 24 hour flows and divide by the number of hours, 24, in order to obtain the average daily flow for the system.
- Divide the average flows of each hour by the total daily average.
- Plot the demand pattern ratio (y-axis) against each hour (x-axis)

The above methodologies were applied to the system before and after pressure reduction.

An average dimensionless 24-hour demand pattern was derived for the system before and after pressure management. This demand pattern was developed initially in order to be able to model the 24-hour profile and thereby, according to the methodology, obtain the initial AZP values.

These demand patterns are representative of the same shape and size of the flow profiles plotted in **Figure 3-29**.

Table 3-11 compares the demand profile in liters per second and the dimensionless demand pattern profile for the system before and after pressure management. The demand profile, presented in **Table 3-11,** was then displayed graphically, and illustrated in **Figure 3-30**. The diurnal pattern for the period before pressure management is fairly flat however starting at a much higher factor during hour 1 and 5 and again during hour 22 and 24. Between the period 9 and 16, there is an increase in the demand profile for the period after pressure management.

Table 3-11 Summary of the average flows per hour based on logged data and corresponding demand pattern

	Before Pressure Reduction		**After Pressure Reduction**	
Hour	**Demand Profile (L/s)**	**Demand Pattern 1**	**Demand Profile (L/s)**	**Demand Pattern 1**
1	54.48	0.71	12.02	0.35
2	51.71	0.68	11.11	0.33
3	51.02	0.67	10.49	0.31
4	53.44	0.70	14.31	0.42
5	58.14	0.76	14.05	0.41
6	64.42	0.84	26.76	0.79
7	80.96	1.06	32.75	0.97
8	88.44	1.16	31.23	0.92
9	89.13	1.17	36.85	1.09
10	89.85	1.17	46.30	1.36
11	93.38	1.22	54.44	1.60
12	94.21	1.23	55.02	1.62
13	92.56	1.21	55.88	1.65
14	87.01	1.14	51.20	1.51
15	78.85	1.03	43.22	1.27
16	78.53	1.03	39.86	1.17
17	82.73	1.08	40.23	1.19
18	85.67	1.12	41.57	1.23
19	86.63	1.13	42.75	1.26
20	86.58	1.13	43.77	1.29
21	84.62	1.11	39.05	1.15
22	76.17	1.00	31.37	0.92
23	67.87	0.89	23.80	0.70
24	59.47	0.78	16.27	0.48
Average	**76.49**	**1.00**	**33.93**	**1.00**
Min	51.02		10.49	
Max	94.21		55.88	
MNF	51.02		10.49	

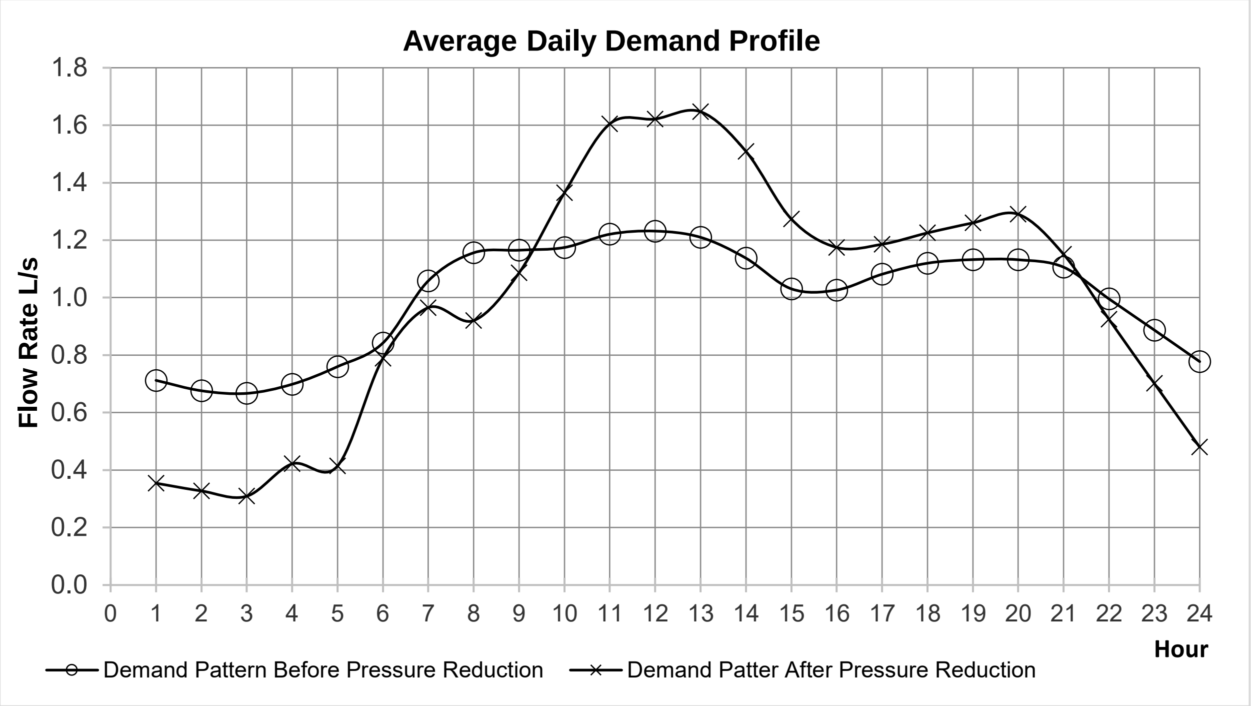


Figure 3-30: 24-hour Demand Pattern before and after pressure management

3.5. BILLED WATER DEMAND DATA AND FILTERING PROCESS

The billed water demand data used within this research was obtained from the City of Cape Town (CCT) Revenue SAP Raw Database.

The total number of records extracted for the Pressure Managed DMA, between the period 2008 and 2010, was 4 825 (which includes both residential, industrial, commercial properties, educational buildings, parks and government buildings). The period for which the data was extracted was at least 12 months before the commissioning month of the PMZ and 12 months after the commissioning of the PMZ (from August 2008 to August 2010 and excluding the commissioning month which was August 2009).

The total number of records extracted for the Control DMA was 3,946. The period over which the data was extracted was 11 months before the commissioning month of the test zone and 11 months after (from September 2008 to September 2010).

The pressure managed and control DMA extraction period were slightly different (offset by a month) due to the Control DMA not having valid data for the August period specifically in the 2008 period. The reason for this is uncertain.

3.5.1. Data Filtering Process

This section is used to discuss the filtering process which was necessary to ensure that there were no errors in the data and further establish the level of the data's integrity.

The consumption data, over the same period, was analysed and compared with the consumption data of the pressure managed DMA. **Table 3-12** provides an summary of the total number of stands (or consumer records) after each filter step.

Filter 1: Remove non-domestic users.

The Pressure Managed DMA is predominantly domestic. 81 non-domestic users (where 23 were rated as standpipes or miscellaneous water) were identified in the data set. This amounts to 1.6 % of the total SAP records with a monthly average day demand of 14kL/day.

The Control DMA zone is predominantly domestic. 82 non-domestic users were identified in the data set. This amounts to 2 % of the total SAP records with a monthly average day demand of 77kL/day.

The non-domestic users were removed in order to ensure the end results are more comparable with other studies.

Filter 2: Remove Zero and Negative Records

Negative records relate to estimates. In some cases, it is possible that readings may have been estimated and then, when an actual reading is taken, it is then confirmed as being over-estimated. In order to rectify the over-estimated reading, it will be deducted from the next billing period. Zero records relate to system errors or capturing delays. Records where consumption was zero or negative for two months or more were identified and removed.

For the pressure managed DMA The total number of records meeting this criterion were 4120 records. No conclusive reason exists as to why there were so many records meeting this criterion. It could be as result of system errors, meter change overs or replacements or poor capturing.

For the Control DMA total number of records meeting this criterion were 2,294 records.

Filter 3: Remove records greater than or equal to 50kl/day

Records where two or more records where equal to or greater than 50kl/day were removed.

A number of household's water usage exceeded 50kL/day up to six-digit consumption figures. These figures are no realistic for domestic consumption users. Details concerning the reason for these figures were not available. It was then decided to excluded these records.

The 50kL/day was selected as a starting point for eradicating records which appeared to be unrealistically high for domestic properties.

For the Pressure Managed DMA these records equated to 113 where the Control DMA had a similar result of 114 records.

Filter 4: Replace remaining outliers (or blank months)

Replaced remaining outliers with average of two months either before or after the month being calculated.

For the Pressure Managed DMA about 64 readings spread over 22 months were replaced with an average of two months' readings. This was almost double the records replaced for the Control DMA at 37 readings.

The final cleaned data was then analysed in various ways, plotted, compared and further analysed.

Filter 5: Non-Domestic Billed Records

The non-domestic users were separated from the domestic users. Non-domestic users included parks, government and municipal facilities and commercial properties. The same filtering process applied from 1 to 4 was applied to the non-domestic users. Of the 65 occupied stands only 17 records were suitable for analysis. This represents 26% of the total non-domestic consumers.

For the Control DMA, of the 82 records only 28 records were suitable for analysis. Notwithstanding that May 2009 months' data was incomplete over a number of records. This represents 34% of the total non-domestic consumers.

The non-domestic user consumption was compared, on a graph annually and then monthly.

Table 3-12: Summary and Comparison of the number of consumption records before and after the filter process

Filter Step	**Final Total After Each Filter Step**	
	Pressure Managed DMA	Control DMA
Total Number of Stands	4 825	3 946
Filter 1: Remove non-domestic users	81	83
Filter 2: Remove Zero and Negative Records	4120	2294
Filter 3: Remove records greater than or equal to 50kL/day	113	114
Final Total	**511**	**1455**

3.6. DESCRIPTION OF THE HYDRAULIC MODEL

The water hydraulic model provided by the CCT was not representative of the demand scenario for 2009. The model was then adjusted in order to represent the system conditions as of 2009.

Extracting the Model

The hydraulic model of the water distribution system under investigation was exported from the Wadiso Hydraulic Model version 6.1 into Epanet as an .inp file.

The characteristics of the model imported were as follows:

- Average peak demand as at 2015/16 Financial Year = 211.5 L/s
- Number of Nodes/ Junctions = 1 030
- Number of pipes = 1 249
- One 250mm PRV
- Total pipe length = 85 903.97m or ≈85.90km

Figure 3-31 represents the configuration of the network within the hydraulic model.

Figure 3-31: Snapshot of the Analysed Pressure Managed Zone Hydraulic Model. Extracted from Epanet

There was no model available at the baseline of 2009. Initial hydraulic models and master planning models only came into effect after 2011. Due to there not being a model available at the baseline of 2009, the model provided by the City of Cape Town Municipality was adjusted in order to represent the system before and after pressure management.

Two sets of models were developed. One set (includes two models before and after pressure management) is based on average flows and the minimum night flows as calculated in the DMA Completion Report (City of Cape Town, 2009). The second set (includes two models before and after pressure management) is based on the average flows and minimum night flows as calculated from the logged data extracted before and one year after pressure management.

For simplicity,

- *Completion Report Data* refers to the data a week before and a week after pressure management.
- *Logged Data* refers to the data extracted before and one year after pressure management. Average flows and MNF supporting this model is illustrated in **Figure 3-29**.

The following steps were undertaken in order to set up the model:

Step 1: Check

Verify that the number of nodes imported into Epanet match the nodes exported from Wadiso 6.1. This is done by selecting the summary report in Epanet.

Confirm that the Flow units are set to Litres per second and that the Head-Loss Formula is set at the Hazen-Williams method.

Check that the demand patterns are set to default demand pattern of 1.

Check that the demand multiplier is set to the default demand value of 1.

Step 2: Replace the PRV with a Reservoir

The PRV was replaced with a reservoir for ease of adjusting the pressure. A dummy pipe was inserted in order to connect the reservoir to the system.

Step 3: Set the Total Head of the Reservoir

By adjusting the total head of the reservoir, it was possible to simulate the behaviour of the PRV. The reservoir levels, for the system before and after pressure management, was set at 88m and 47m, respectively. These values match the PRV setting pressure prior to and post commissioning of the PMZ. The intention was to simulate the model to represent the conditions at the time of the installation.

Step 4: Balance the model under static conditions

In the Epanet model the duration was adjusted from 24 hours to 0. This was done in order to balance the model at static conditions. Once this was done, the model was balanced.

Step 5: Calculate Demand Multiplier

Once the model was balanced, select the reservoir and obtain the outflow at static conditions. Adjust the out flow by applying a demand multiplier. The demand multiplier was adjusted in order that the net flows represent the average flows determined in Table 3-11.

An overview of the net flows are found in **Table 3-13**.

Table 3-13: Overview of the net flow conditions (logged Completion Report Data and Completion Report Data)

	Calculated from Logged Data extracted		Completion Report Outcome	
System Condition	**MNF (L/s)**	**Average Flow (L/s)**	**MNF (L/s)**	**Average Flow (L/s)**
Before Pressure Management	51.02	76.49	43.89	73.9
After Pressure Management	10.49	33.93	13.06	35.8

The average flows represented in the original model was 211.24L/s. This was adjusted by applying a demand multiplier. The demand multiplier is a dimensionless number. The multiplier was calculated as dividing the average flows (from the completion report) by the average flow in the model.

For the system after pressure reduction, steps 1 through to 4 was repeated. In step 3, the demand multiplier was calculated as follows:

Table 3-14: Summary of Calculated Demand Multipliers used in initial model set-up

	Calculated from Logged Data	**Completion Report Outcome**
Demand Multiplier Before Pressure Management	76.49/211.24 = 0.3620	73.9/211.24 = 0.3498
Demand Multiplier After Pressure Management	33.93/211.24 = 0.1606	35.8/211.24 = 0.1696

Step 6: Add a demand pattern

Add a new pattern and label the pattern, other than that of 1 as 1 represents the default pattern. Add the relevant (i.e. for the system before or after pressure management) demand pattern presented in **Table 3-11** and illustrated in **Figure 3-29.**

The demand pattern was then applied to each node/ junction.

Before running the Model, adjust the total duration to 24 hours. Once completed, balance the model.

Step 7: Check

Graph the system flow in order to check that the modelled profile matches the profile presented in Table 3-11. Figure 3-32 illustrated the modelled flow profile compared to the calculated flow profile from the Completion Report (City of Cape Town, 2009). The profiles are very closely matched except at hour 13. At hour 13 the modelled flow is slightly higher.

Figure 3-32 illustrates the modelled demand flow profile compared to the minimum night flow as calculated in the Completion Report (City of Cape Town, 2009). The actual system pressure profile, at the MNF of 43.89 L/s (before pressure management) and 13.06 L/s (after pressure management) was not available. The latter is due to the fact that only the upstream and downstream PRV pressures were logged. This model was used to determine the system flow and pressure profile in order to calculate the AZP for the system.

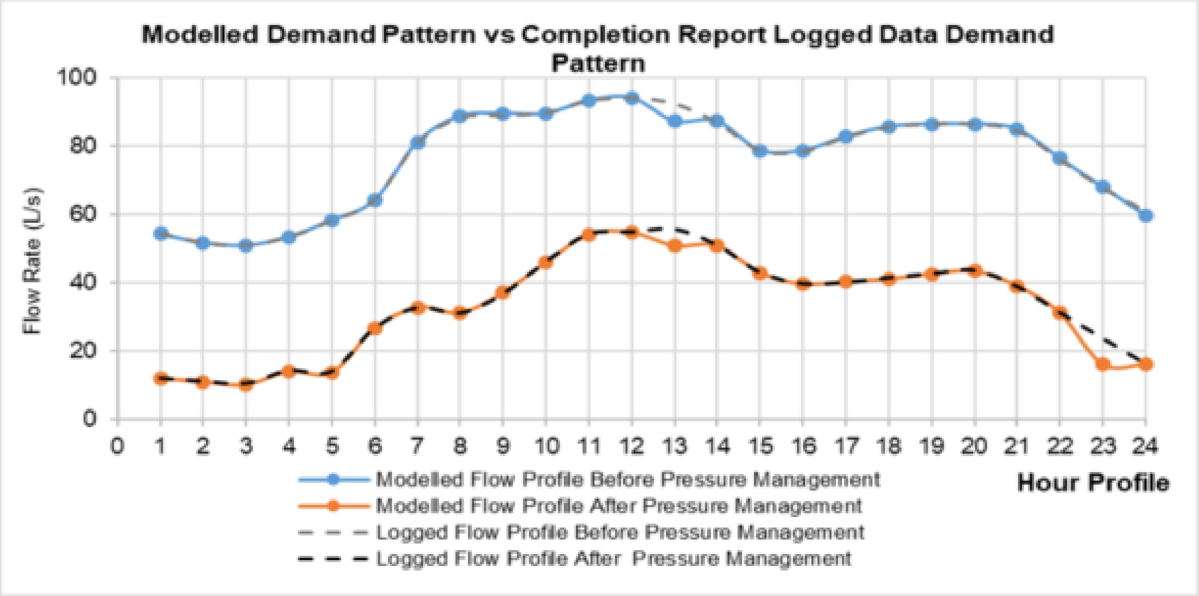


Figure 3-32: Modelled Demand Pattern vs Completion Report Logged Data

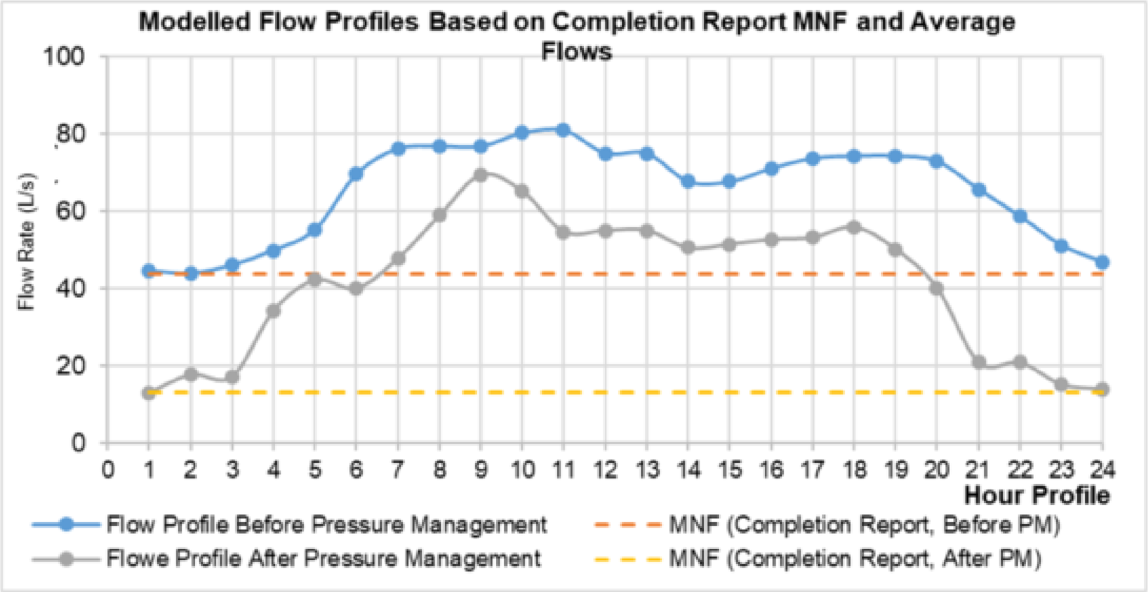


Figure 3-33: Modelled Flow Profiles Based on Completion Report MNF and Average Flows

Step 8: Extract pressure and demand represented at each node for every hour.

In the Model, from the Table Selection tab, select the type of table to create. In this case, a table for the network nodes, for the system at hour zero was selected. Then select the columns to be presented based on your selection. These columns were Elevation, Demand, Head and Pressure. Demand and Pressure were the only variables used for the calculation.

For each table generated, the data was copied into an Excel sheet. The process was repeated 24 times (1 to 24 hours).

Before calculating the AZP at each node, it was required to determine the number of stands (or connections) linked to each node.

3.6.1. Determining The Number of Stands Linked to Nodes

In order to calculate the AZP based on the weighted average against the number of connections or stands, it was required to count the number of stands linked to the specific nodes.

The stands linked to the nodes were extracted from a sqlite file. This is a spatial file containing attribute information specific to each stand. It is used specifically within the Wadiso 6.1 model and allows the link to be made from the consumers (or stands) to the model nodes. In the attribute table there are a number of fields such as stand type, AADD, Stand Area, etc. and more specifically there is a field called “Node”. In this field the node number onto which the stand will be linked is presented. Multiple stands can have the same node number.

In the Sqlite file there were 5 948 records (or stands). These records include zoning for public open space, servitudes, and transport routes. These are considered non-consumer related records and were discarded from the list. When removing these records, the total records reduce to 4 860.

The node numbers, from the Sqlite file, was extracted per record. A count of the number of stands per node was performed in excel using the countif logic function. In total, the number of nodes which linked to the model nodes were 4 855 records vs the total 4 860 Sqlite records. This was a 0.1% difference and was considered a good match.

3.6.2. System Average Zone Pressure

According to the guidelines relating to average pressure calculations (ILMSS Ltd, 2013), when the density of the connections is 20 or more per km, most of the real losses would occur on the service connections, so the preferred weighting factor would be number of service connections. However, if the converse is found, then most of the losses would be expected to occur on the mains, so the preferred weighting factor would be mains length.

For this system the number of connections per km is greater than 20 which was calculated at 56 connections per km.

The AZP at MNF conditions, as represented in the report was not available for the period before and after pressure management. Ideally, one would want to identify and log the average zonal pressure point and this was not done for the system. Only the down-stream and up-stream pressures of the PRV was logged. This study had to adapt and use those values.

The adaptation required the use of the City of Cape Town hydraulic model. This model was officially developed, based on citywide network, in 2009. Its demands are based on the billed consumption data and standard operating rules of the entire network. The model is calibrated based on measured bulk water meter outputs. This model was used to determine the pressure distribution across the system. The model was further used to determine the pressure profile over 24-hours.

In order to calculate the AZP one needs to know the distribution of pressure across the network and in order to obtain this information, a number of steps were performed. The steps are briefly listed below:

- Simulate the hydraulic model (initial hydraulic model developed), based on the logged demand patterns illustrated in **Figure 3-29**. At this point the Orifice Equation parameters, embedded in the model, were not used.
- Extract the simulated pressure results for each node at each hour over 24-hours.
- Calculate the weighted average of the nodal pressure based on the number of connections for every hour.
- Calculated weighted sum of the nodes per hour to obtain the AZP (m).

The AZP is representative of the pressure within the pressure managed zone. This pressure varies throughout the day as consumption fluctuates/ varies.

Step 1: Calculate Weighted Average Pressure at each Node

For each node, the number of linked stands were then divided by the total sum of stands for the entire system. This was done in order to determine the fraction of properties linked to each node. Once this was done, multiply the fraction by the pressure (m) reflected at the corresponding node.

The weighted average at each node was calculated using the following formula:

(Node count of Stands / Total number of Stands) x Node Pressure at hour “n“. **3-14**

Where “n” refers to hours 0, 1, 2, 3, etc.

Step 2: Calculate AZP at Completion Report MNF

The weighted average pressure, per node, was totaled for every hour. This was done in order to obtained the total AZP for the system at hour “n”. The AZP was calculated for each hour over 24-hours.

These steps were applied to the system before and after pressure management.

The AZP was calculated for the systems before and after pressure management.

From **Table 3-15**, it is evident that there is a minor difference between the two systems. This is further illustrated in **Figure 3-34**. Slight differences are seen between hour 8 and 13 for the system before pressure management and between hours 8 and 10 for the system after pressure management.

This comparison was only based on the AZP at minimum night flow conditions which was set at hour 2.

Table 3-15: Comparison AZP: Completion Report Data vs Logged Data

	AZP (m)	AZP (m)	% Difference
	Completion Report Data	Logged Data	
Before PM	66.82	66.48	0.51
After PM	26.67	26.79	0.45

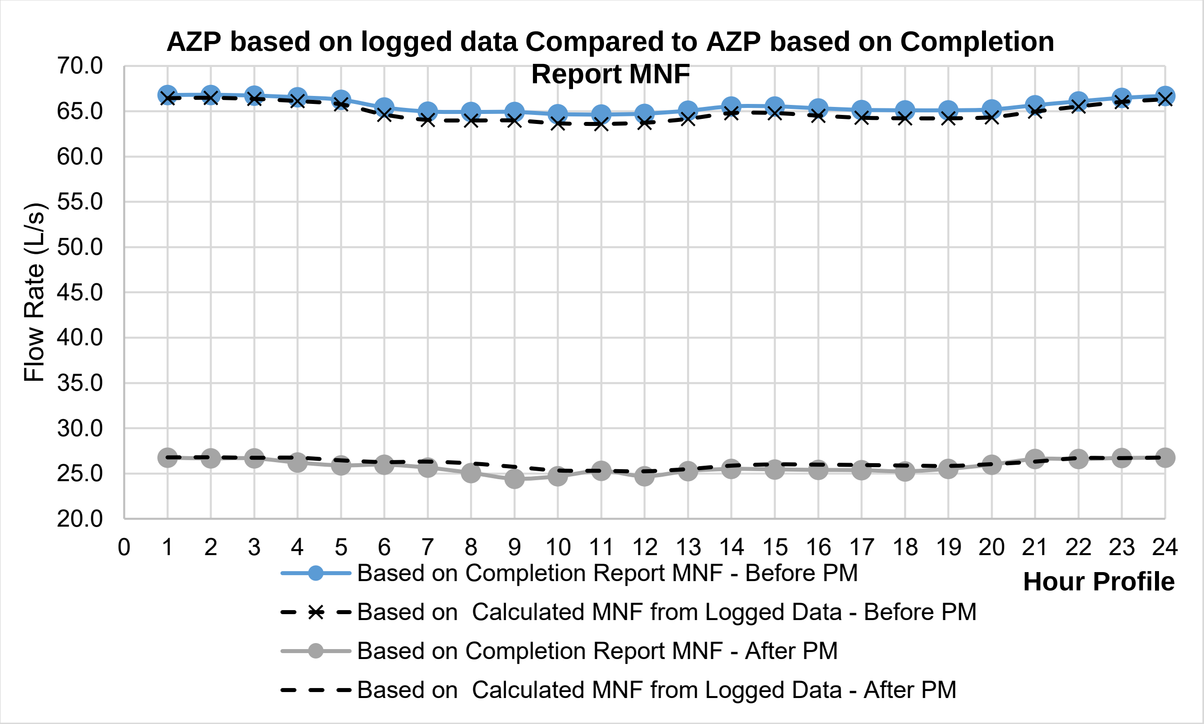


Figure 3-34: Average Zone Pressure (before and after pressure management): Completion Report Data vs Logged Data

3.6.3. Leakage models (system a year later)

The model was again simulated using two different leakage models. Each leakage model type will each have two sub-scenarios, namely, 1) the system at the completion report point in time (i.e. one week after and one week before pressure management) and 2) the system before and one year after pressure management (based on the logged data).

In total four models were developed. Two were developed using the N1 Model (based on the orifice equation) and two were developed using the FAVAD-model (based on the FAVAD equation).

Leakage and consumption was separated in these models. The leakage was calculated using the leakage equation setup within the model.

For the system, represented in the Completion Report, (reflecting data a week before and a week after pressure management), the N1 factor was calculated using the MNF and corresponding modelled and calculated AZP. The constant coefficient was then calculated.

Various leakage parameters, which serve as the model inputs were assumed and calculated.

The following assumption was made:

Discharge coefficient, Cd	0.65

The next step was to test and compare the pressure management impacts, on the two systems, for the system before pressure management and then compare the results with the system after pressure management. The aim of the models was to set the system up according to the system conditions before pressure management and then reduced the pressure to model the system after pressure management one year later. The average flows used were extracted for June/ July 2009 and June/ July 2010.

Leakage a year later will not be the same as that of the report. The data from the Completion Report (CCT, 2009) was based on minimum night flow readings one week before and one week after the pressure managed DMA was commissioned. During this time, it is likely that there would be limited interventions (such as leak repair or infrastructure upgrades) implemented which may impact influence the outcome of the reduced leakage after pressure management. In the scenario where the logged data, a year later, is compared to the same month a year before (prior to pressure management) then it may leave room for a number of interventions to have occurred (such as leak repair or valve replacements etc.).

Due to limitations of the data available, it was then proposed to use the N1 parameters calculated for the system, at the Completion Report reference data, and then adjust the leakage parameters, proportionally with the logged data. This method proved to be the most reasonable method to ensure the system is reasonably represented.

Details surrounding this calculation is available in the next Chapter.

3.6.4. Calculate The Night Day Factor

It is incorrect to assume that the minimum night flow leakage is consistent across 24 hours. This is due to the pressure-leakage relationship where higher pressures, at night, leads to higher night leakage and lower pressures, during the day, results in lower day leakage. Therefore, it would be incorrect to assume that daily leakage can be converted to hourly leakage by dividing by 24 hours/ day (and vice versa). Leak flow rates vary with average pressure. A Night Day Factor (NDF) ratio is used Lambert and WLR&A Ltd, 2017) in order to realistically reflect the leakage volume over 24 hours.

The following formula was applied to calculate the ratio of flow at each hour by raising the ratio of the pressure (at hour “n”) and average pressure at MNF by the calculated N1 for the system. This is repeated for each hour of the day generating 24 values. Where N1 = 1.33.

$$NDF\ Ratio = (P_{at\ hour\ "n"}/AZP_{mnf})^{N_1} \qquad \textbf{3-15}$$

Once the NDF Ratio was calculated for each hour, each NDF was added together in order to get an NDF of 23.45 hour/days.

Table 3-16 and **Table 3-17** represent the NDF calculated based on the NDF ratio. The NDF for the system before pressure managed, based on the Completion Report, was 23.45 hours. The NDF for the system after pressure management was 22.83 hours.

Table 3-16: AZP and NDF Before Pressure Management

Hour (“n”)	**AZP Before Pressure Management (m) (Based on Completion Report Results)**	**NDF (hours/day)**
1	66.70	1.00
2	66.79	1.00
3	**66.82**	1.00
4	66.73	1.00
5	66.54	0.99
6	66.27	0.99
7	65.41	0.97
8	64.97	0.96
9	64.92	0.96
10	64.92	0.96
11	64.68	0.96
12	64.64	0.96
13	64.73	0.96
14	65.06	0.97
15	65.54	0.97
16	65.54	0.97
17	65.33	0.99
18	65.15	0.97
19	65.11	0.97
20	65.11	0.97
21	65.20	0.97
22	65.66	0.98
23	66.09	0.99
24	66.48	0.99
Average	**65.60**	**NDF = 23.45**
Min	**64.64**	
AZPmnf	**66.82**	

Table 3-17: AZP and NDF After Pressure Management

Hour ("n")	AZP After Pressure Management (m) (Based on Completion Report Results)	NDF (hours/day)
1	26.8	1.00
2	26.8	1.00
3	26.7	0.99
4	26.7	1.00
5	26.2	0.97
6	25.9	0.96
7	26.0	0.96
8	25.6	0.94
9	25.1	0.92
10	24.4	0.89
11	24.7	0.90
12	25.3	0.93
13	24.7	0.90
14	25.3	0.93
15	25.5	0.94
16	25.5	0.94
17	25.4	0.93
18	25.4	0.93
19	25.2	0.92
20	25.5	0.94
21	26.0	0.96
22	26.6	0.99
23	26.6	0.99
24	26.7	1.00
Average	25.77	**NDF = 22.83**
Min	26.77	
AZPmnf	24.43	

3.7. WATER BALANCE AND ILI

A water balance based on the IWA table and Benchleak Model User Guide (McKenzie *et al*, 2002) was developed to represent the system before and after pressure reduction.

In order to ensure the water balance was as accurate as possible, it was important to ensure that the water balance represented a specific point in time. The data available included the following:

Water Balance Component	Source	Period Available
System Input Volume (SIV)	Logged data	June 2009 and June 2010
Billed Authorised Consumption (BAC	Billing data (sample 511 stands)	12 months before and 12 months after pressure management
UAC	Unknown	Unknown
Water Losses		
• Real Losses	Logged data (MNF)	June 2009 and June 2010
• Apparent Losses	Not available	Not available

Based on the period in which the data was most available, it was decided to set the water balance for June month. In addition, by not having information on the apparent losses, it was decided to apply the bottom up calculation of the water balance.

Once it was established that the majority of the data was reflective of June month, the water balance was developed. The units of the water balance are represented in ML/day.

3.7.1. The Water Balance Process

The process involved the following steps:

Step 1: **System Input Volume (SIV)**

This was based on the average flow rate obtained from the logged data.

Step 2: **Billed Authorised Consumption (BAC)**

This was based on the filtered domestic and non-domestic data where the unit consumption was calculated and extrapolated forward for all occupied households (±4 560) and non-vacant non-domestic users (±65). **Table 3-18** summarises the input parameters used to calculate the Billed Authorised Consumption (BAC). It further illustrates the calculated BAC

First the average usage per household and non-domestic users were calculated.

- Consumption per household = QJune/ Sample/ No. days in month
- Consumption per household (before PM) = 225.8/511
- Consumption per household (after PM) = 215.6/511

Consumption per household (before PM) = 0.442 kL/ day

Consumption per household (after PM) = 0.422 kL/ day

The average usage per non-domestic user was then calculated:

Once the usage per household was obtained, the average usage per non-domestic user was calculated

- Consumption per non-domestic user = QJune/ Sample/No days in month
- Consumption per non-domestic user (before PM) = 10.3/17
- Consumption per non-domestic user (after PM)= 12.5/17

Consumption per property (before PM) = 0.606 kL/property/day

Consumption per property (after PM) = 0.735 kL/property/day

Table 3-18: Calculated Billed Authorised Consumption

	Billed Authorised Consumption (kL/day)		**Domestic KL/day**	**No. Occupied Stands**		**Non Domestic KL/day**	**No. Occupied Stands**
Before PM	2 054.35 (2.05ML/day)	=	0.442x	4 560	+	0.605x	65
After PM	1 971.36 (1.97 ML/day)	=	0.422x	4 560	+	0.736x	65

For this study, night consumption was not distinguished separately from day-time consumption. It was assumed that very little to no consumption occurs during the minimum night period between midnight and 4am (McKenzie, 1999). Any consumption occurring at night or during the minimum night flow period would more than likely be related to pressure-independent consumption (i.e. toilet flushing). This type of consumption would not be impacted by pressure management and the volume of water used would remain the same for the period before and after pressure management thereby having no significant impact on the results (Gomes *et al*, 2011).

Step 3: **Real Losses (RL)**

This was based on the minimum night flows calculated for the system at the logged flow conditions**.** The minimum night flow (before pressure management) of 183.71m^3/hr, on converting to ML/day, was multiplied by the NDF calculated for the system based on the logged data.

MNF(ML/day) = (MNF(m^3/hr) /1000)xNDF

MNF(ML/day) = (183.71/1000) x 23.45

MNF(ML/day) = 4.308

The above steps were completed for the MNF after pressure management where the minimum night flow was 36.76m^3/hr.

MNF (ML/day) = (36.76/1000) x 22.83

MNF (ML/day) = 0.839

Step 4: **Authorised Consumption (AC)**

This was calculated as the sum of the billed authorized and unbilled authorized consumption. The unbilled authorized consumption was considered to be zero as there was no other information available to support a value to be inserted.

Step 5: **Water Losses (WL)**

This was calculated as the difference between the system input volume and authorized consumption.

Step 6: Apparent losses (AL)

This was calculated from the difference between the water losses and real losses.

Step 7: Non-Revenue Water (NRW)

Sum total of the unbilled authorized consumption and water losses

3.7.2. Water Balance

Table 3-19 represents the IWA Water Balance for the system before pressure management. **Table 3-20** represents the IWA Water Balance for the system after pressure management. The data used is based on the logged and billing data.

Table 3-19: IWA Water Balance Before Pressure Reduction

<table>
<tr><th colspan="4">Before PM (Units = ML/day)</th></tr>
<tr><td rowspan="4">SIV</td><td rowspan="2">AC</td><td>BAC</td><td>Revenue Water</td></tr>
<tr><td>2.05</td><td>2.05</td></tr>
<tr><td rowspan="2">2.05</td><td>UAC</td><td rowspan="2">NRW</td></tr>
<tr><td>-</td></tr>
<tr><td rowspan="4">6.61</td><td rowspan="2">Water Losses</td><td>AL</td><td rowspan="4">4.56</td></tr>
<tr><td>0.25</td></tr>
<tr><td rowspan="2">6.54</td><td>RL</td></tr>
<tr><td>4.31</td></tr>
</table>

Table 3-20: IWA Water Balance After Pressure Management

<table>
<tr><th colspan="4">After PM (Units = ML/day)</th></tr>
<tr><td rowspan="4">SIV</td><td rowspan="2">AC</td><td>BAC</td><td>Revenue Water</td></tr>
<tr><td>1.97</td><td>1.97</td></tr>
<tr><td rowspan="2">1.97</td><td>UAC</td><td rowspan="2">NRW</td></tr>
<tr><td>-</td></tr>
<tr><td rowspan="4">2.93</td><td rowspan="2">Water Losses</td><td>AL</td><td rowspan="4">0.96</td></tr>
<tr><td>0.12</td></tr>
<tr><td rowspan="2">0.96</td><td>RL</td></tr>
<tr><td>0.84</td></tr>
</table>

3.7.3. Infrastructure Leakage Index (ILI)

After developing the water balance for the system before and after pressure management, the Infrastructure Leakage Index was calculated and then compared.

The Infrastructure Leakage Index, a non-dimensional index, was calculated for the system before and after pressure reduction in order to assess if there had been improvements in the leakage occurring in the system. The below formula was applied and the data in the water balance tables were used.

ILI = CARL/ UARL

$$UARL = (18 \times Lm \times P) + N_s \times \left(0.8 + 25 \times \ L_p/1000 \right) \times P$$

Where:

Lm = length of mains

P = average zone pressure (m)

Ns = number of connections

Lp = average length of connections

Table 3-21 represents a summary of the input data used to calculate the Infrastructure Leakage Index (ILI) for the system before and after pressure management. It further compares the ILI results of the two ILI values. The ILI reduced by approximately half after the introduction of pressure management. In the case of the system before pressure management, the leakage is eight time higher than the unavoidable (or minimum) annual losses. In the case of the system after pressure management, the ILI reduced by approximately half which indicates that the leakage in the system is approximately four times the unavoidable annual losses.

Table 3-21: Comparison of Infrastructure Leakage Index Data Before and After Pressure Reduction

	Before	After
Pressure (m) (at MNF)	66.8	26.8
CARL(L/s)	51.03	10.21
Length mains (km)	±86	±86
Ns	±4860	±4860
*Lp (m)	15	15
UARL (L/s)	5.80	2.36
ILI	8.8	4.3

*CCT average length of connections

3.8. ELASTICITY OF DEMAND TO PRESSURE (N3)

This is a description of the methodology applied to obtain N3 and further compare them. The results, some of the methods and discussions will be presented in the next Chapter. A number of comparisons were made from the data available. There are different methods to calculate N3. Some of these methods have not been done in previous research.

Based on the data available a number of approaches to calculate N3 were applied, these include the following:

- Calculate N3 from domestic billed consumption data based on AZP simulated from the model
- Calculate N3 per month based on billed monthly consumption sample records of 511 using the AZP simulated from the model
- Calculate N3 based on the authorized consumption plus apparent losses calculated in the Water Balance.
- Collect and compare this study's results with the N3 values determined from other studies
- Calculate the N3 from the N1 Model and FAVAD hydraulic model consumption outputs. This will include:
    - N3 for the overall system
    - N3 per hour over the day

The following sections describe each approach in a bit more detail.

3.8.1. N3: Based on Average Domestic Billed Consumption Data (Domestic Users Only)

For the determination of the relationship between pressure and demand, the following steps were conducted namely,

- Plot the calculated consumer demand before pressure management (y-axis) and demand after pressure management (y-axis) against the AZP for the system based on the completion report data, on a graph using Excel.
- Insert a power regression trend line using Excel.

3.8.2. N3: Monthly Comparison

This section describes the method undertaken to calculate the N3 based on the monthly domestic billed consumption as illustrated in **Figure 4-38**.

In order to perform this calculation, **Equation 2-11** was rewritten as follows

$$N3 = \log\left({}^{Qcb}/_{Qca}\right) / \log\left({}^{P1}/_{P2}\right) \qquad \textbf{3-16}$$

Where:

Qcb = consumption before pressure management
Qca = consumption after pressure management
P1 = pressure before pressure management
P2 = pressure after pressure management

3.8.3. N3: Based on Authorised Consumption Plus Apparent Losses

It was then decided to calculate the N3 based on the Authorised Billed consumption and Apparent Losses. The reason to include apparent losses, is that apparent losses are part of consumption even though it only refers to leakage on someone's property or meter errors. The following formula was considered when deciding to include apparent losses as consumption.

SIV = *AC + AP + RL However, AC +AP = Qc **3-17**

Q_{ac+al} = SIV – RL

*AC limitation: average unit consumption projected over all occupied stands

For the determination of the relationship between pressure and demand, the following steps were conducted namely:

- Plot the calculated Qc before pressure management (y-axis) and Qc after pressure management (y-axis) against the AZP presented based on the City of Cape Town, WRP completion report data (City of Cape Town, 2009). This was illustrated in a graph in Excel.
- Insert a power regression trend line using Excel.

3.8.4. Comparison of Calculated N3 with Other Studies

All the N3 or estimated N3 values from various studies were plotted and compared with the calculated results notwithstanding that some of the N3 values from the other studies had limitations.

3.8.5. Hydraulic Model Outputs: N3

Based on the FAVAD and N1, the power regression model was applied to the consumption, which excluded leakage. It was based on the flows and pressures generated for the system before and after pressure management.

In addition, by using the values obtained per hour for consumption only, N3 per hour was calculated using **Equation 2-11**. A comparison was then made between the N3 values generated from the N1 model and that generated by the FAVAD model.

4. RESULTS AND DISCUSSION

4.1. INTRODUCTION

This chapter is aimed at presenting the main results of the analysis carried out throughout this thesis. To evaluate the impact of pressure management on end user demand the following steps were followed:

- Billed consumption data (for one year before and one year after pressure management) for the pressure managed DMA and a Control DMA was compared. Various statistical parameters were calculated.
- Secondly, the system a year before and a year after pressure management was modelled. Two types of models were used. Consumption and leakage was separated in the hydraulic models. Various leakage parameters were calculated. From this information, the leakage per node over per hour over 24-hours was calculated.
- Thirdly, the pressure-demand relationship was established by utilizing various demand inputs determined in earlier sections. This was then compared to other studies in order to validate the results attained in this thesis.

4.2. PRESSURE EFFECT ON BILLED CONSUMPTION

The aim of this section is to show the results of the pressure management activities on consumer demand. In order to validate the impact of pressure on consumer demand in the pressure managed DMA, a control DMA was selected and analyzed. From the results analysed, it was found that the overall consumption for the control area had increased over the study period which provides some confidence that there were no additional events or factors which could have influenced the behaviour of the consumers in the pressure managed DMA.

This section further compares the impact of pressure reduction on the non-domestic users. Non-domestic users were not the main focus of this study.

During the study period the following points were considered when performing the study:

- It was confirmed, that during the study period that there was no aggressive tariffing in place (Moll, personal communication, 2019)
- During the time of the study there was no indication of fire incidences as this would have been picked up in the daily flows
- The valve status and pipe sizes are in some cases unknown and unverified, respectively. This may affect the outcome in such a way that it would impact on the frictional losses and thereby impacting on the outcome of the AZP.
- The discreteness of the PRV was not verified in the field or communicated, however it was checked in the daily flow profiles.
- The system was isolated and discrete as this would have been reflected in the Completion Report results. The logged flow data did not reveal any flow anomalies which served as a good indication that the DMA was discrete.
- Large draw offs, for construction purposes, were not known to have occurred

4.2.1. AADD BEFORE AND AFTER PRESSURE MANAGEMENT: DOMESTIC USERS

From **Figure 4-35**, it is observed that the average annual daily demand (AADD) per household, had reduced after the introduction of pressure reduction to the distribution system.

The average day demand, for the Control DMA, before and after the period under investigation was 0.546kL/day/property and 0.563kL/day/property respectively. The pressure managed DMA consumption reduced, for the period under investigation, from 0.494kL/day/property to 0.473kL/day/property. This reinforces that the DMA's consumption did reduce because of the pressure management.

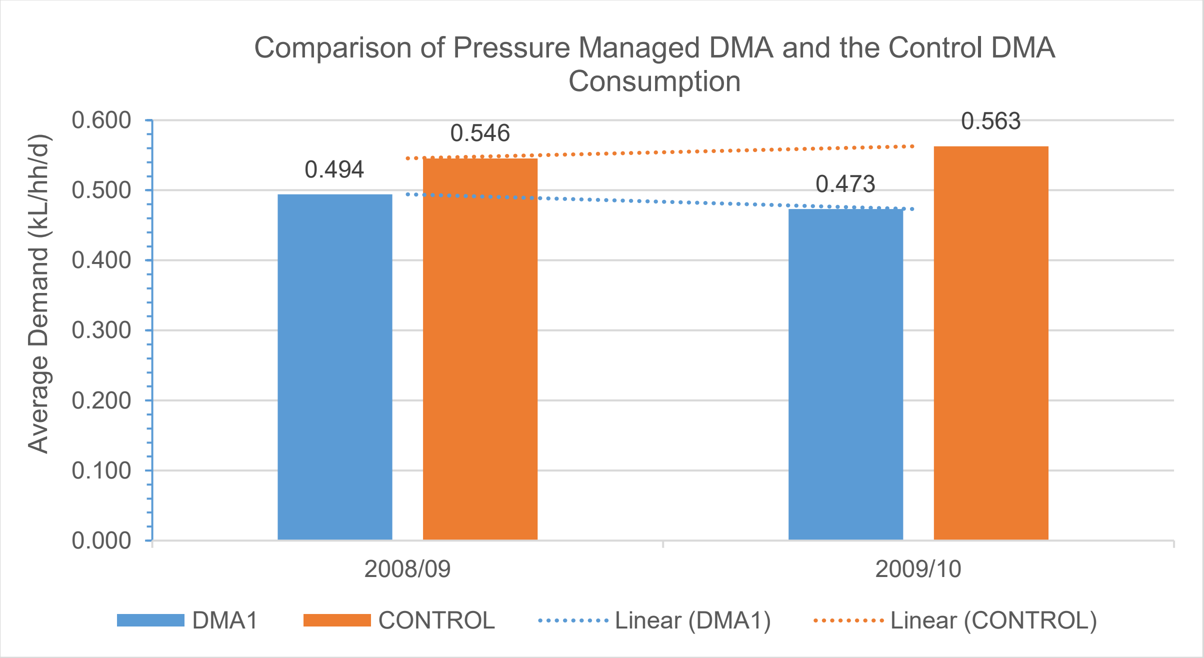


Figure 4-35: Study area comparison of AADD per household before (2008/09) and after pressure management (2009/10) with the Control AADD.

Figure 4-36, represents the frequency distribution of AADD. From this graph it is clear that a number of consumers in the category above 0.80kL/day reduced, after pressure reduction, and those in the lower categories, of less than or equal to 0.40, increased. Consumers in the category of less than 0.40 and greater or equal to 0.60 kL/day, decreased after pressure management. There is a slight increase in the consumers, within the category of greater than 0.60 and less than or equal to 0.80 kL/day. The higher demand categories above 0.40 kL/day is reduced or stays the same and the lower demand categories increased after pressure management which shows the shift to the lower demand groupings.

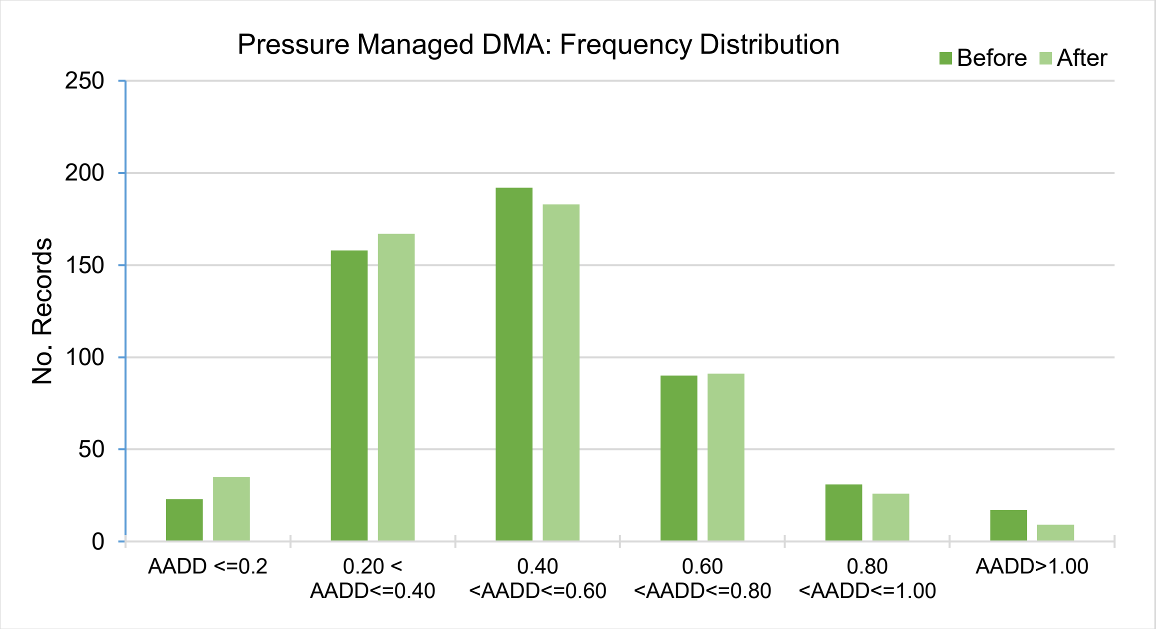


Figure 4-36 Study area: frequency distribution of average demand before and after pressure reduction

In the case of the Control DMA, from **Figure 4-37**, in contrast to the test DMA there was a shift to the higher consumption categories where the low consumption users increased displaying a shift from low to high consumption in a non-pressure managed area.

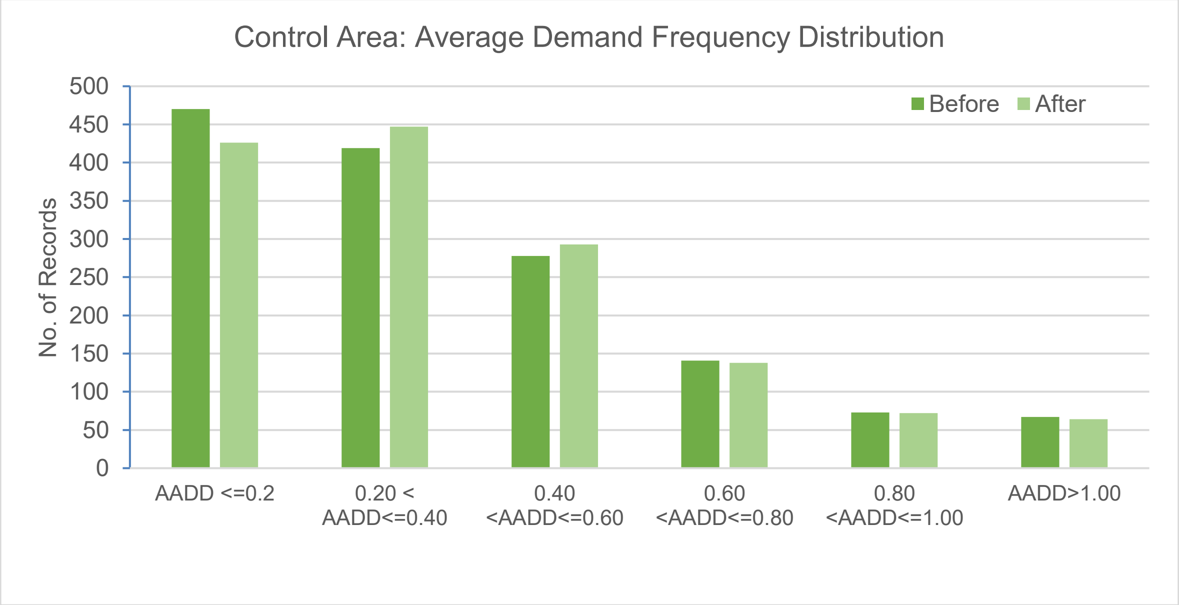


Figure 4-37: Control Area: Frequency Distribution of Average Demand before and after pressure reduction

4.2.2. Monthly Consumption Before and After Pressure Management

From **Figure 4-38**, it is clear that the monthly consumption a year later consistently decreased once pressure management was introduction.

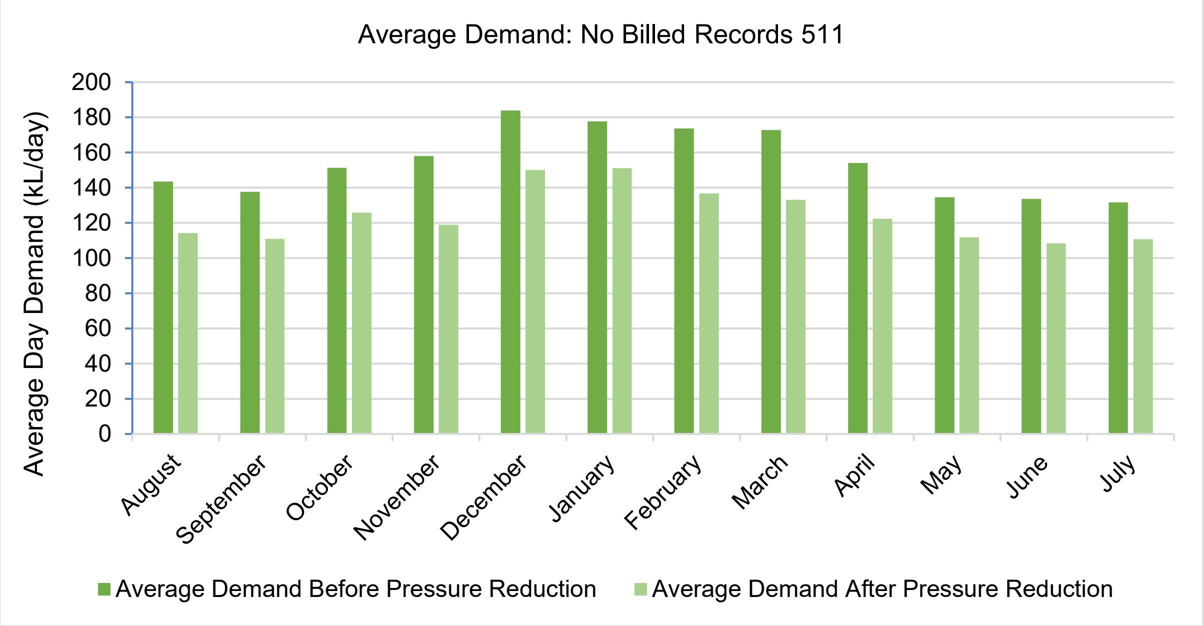


Figure 4-38: Pressure Managed DMA: Monthly Sum of Measured Billed Average Daily Demand.

As illustrated in **Figure 4-39**, in contrast to the pressure managed DMA, the consumption has increased or stayed the same for most of the months. Only two months have shown a decrease in consumption.

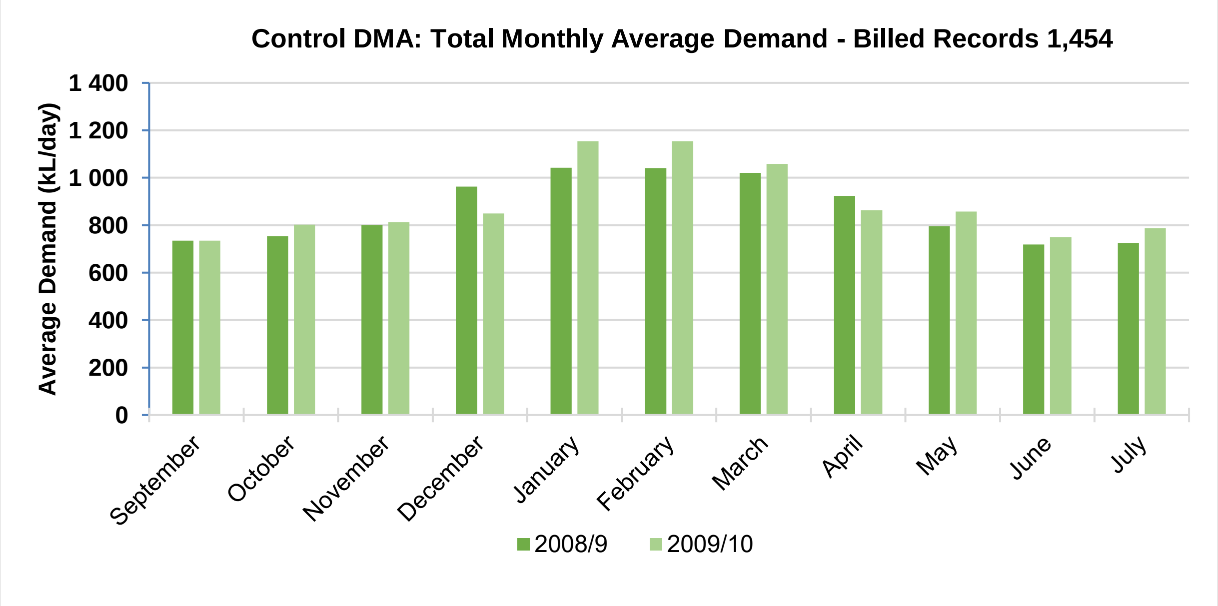


Figure 4-39: Control DMA: Total Monthly Measured Billed Average Daily Demand

4.2.3. Statistical Analysis

Pressure Managed DMA

Table 4-22 provides a summary of the statistical descriptors for the system before and after pressure management. The median of the average day demand, for before and after pressure management was 0.472 kL/day and 0.459 kL/day, respectively. This is a 2.9% decrease. The median value reduced by a higher percentage at approximately 4.5%.

Table 4-22: DMA1:Statistical Parameters, Pressure Managed DMA, before and after pressure reduction

	Average (Before)	Average (After)
Mean (kL/month)	0.498	0.476
Standard Error	0.001	0.009
Median (kL/month)	0.472	0.459
Deviation	0.223	0.211
Sample Variance	0.050	0.044
Skewness	0.943	0.717
Minimum (kL/month)	0.074	0.063
Maximum (kL/month)	1.393	1.300
Sum (kL/annum)	254.3	243.4
Count	511	511

The sample data is moderately positively skewed. This sample skewness does not apply to the entire group of consumers.

Control DMA

Table 4-23 provides a summary of the statistical descriptors for the Control DMA for the period before and after pressure management of DMA 1. The median of the average day demand, for before and after pressure management was 0.514kL/day and 0.526 kL/day, respectively. This is a 2.2% increase. The median value increased by a higher percentage at approximately 4.1%. In contrast to the pressure managed DMA, the mean and median increased over the same period.

Table 4-23: Control Area: Statistical Parameters before and after August 2009

	Before August 2009	After August 2009
Mean (kL/month)	0.587	0.612
Standard Error	0.009	0.012
Median (kL/month)	0.514	0.526
Deviation	0.335	0.471
Sample Variance	0.112	0.221
Skewness	1.784	6.771
Minimum (kL/month)	0.085	0.074
Maximum (kL/month)	2.816	8.013
Sum (kL/annum)	852.80	889.57
Count	1 454	1 454

4.2.4. AADD Before and After Pressure Management: Non-Domestic

The focus of this study was not to assess the impact of pressure reduction on the non-domestic users, however, from **Figure 4-40**, based on a year-on year comparison, it appears as though there was not much difference between the year before pressure reduction and the year after pressure reduction. The consumption reduced by 4% for Pressure Managed DMA. The Control DMA's consumption also reduced by approximately 8%. There are concerns surround the quality of the data that was available for the domestic records. This is evident in **Figure 4-42** where May 2010 consumption figures were much lower than the previous year's figures.

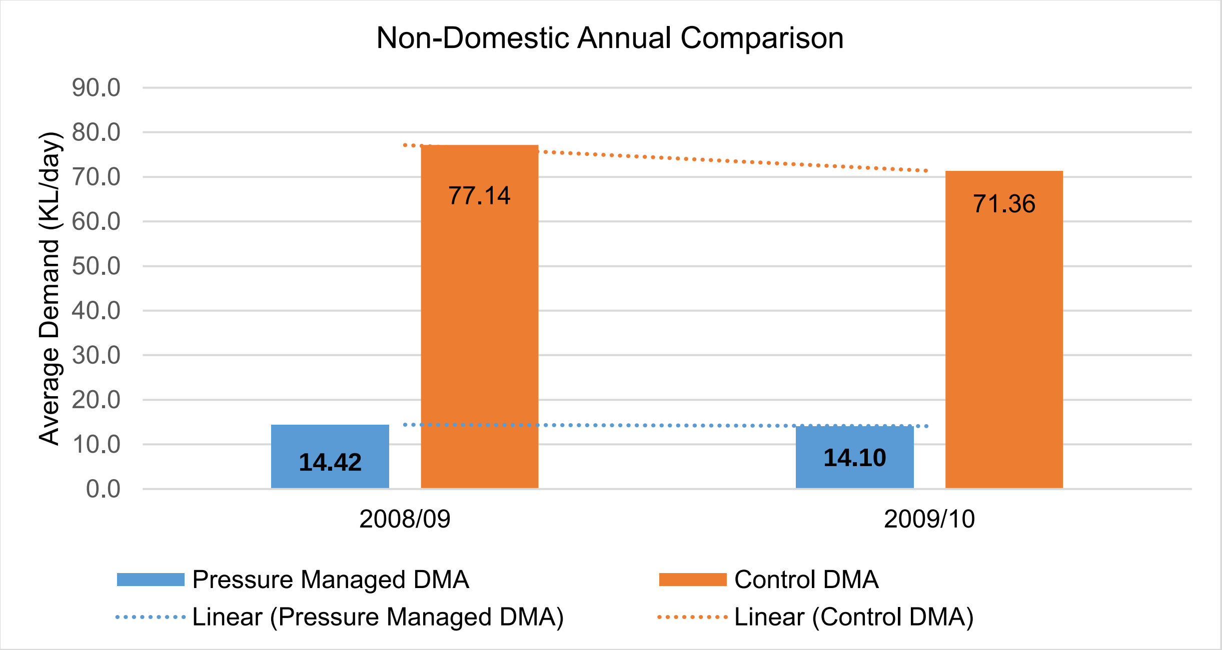


Figure 4-40: Non-domestic Consumers Annual Average Demand Comparison: Pressure Managed DMA vs Control DMA:

From **Figure 4-41**, it is clear that there is no distinct pattern between the consumption before and after pressure management. In September, October, December, March, and June the consumption after commissioning of the pressure management zone exceeded the prior year's consumption. In most cases the average demand after pressure management exceeded the demand before pressure reduction. There is no clear pattern of what the consumption does. Similarly, as illustrated in **Figure 4-42**, the Control DMA non-domestic users appear to increase in some months and decrease in other months. The billed records for May 2010 was not available for a number of the records. As discussed earlier, this could be as a result of the billing system errors or failure. Conclusive reasons for this anomaly is not available.

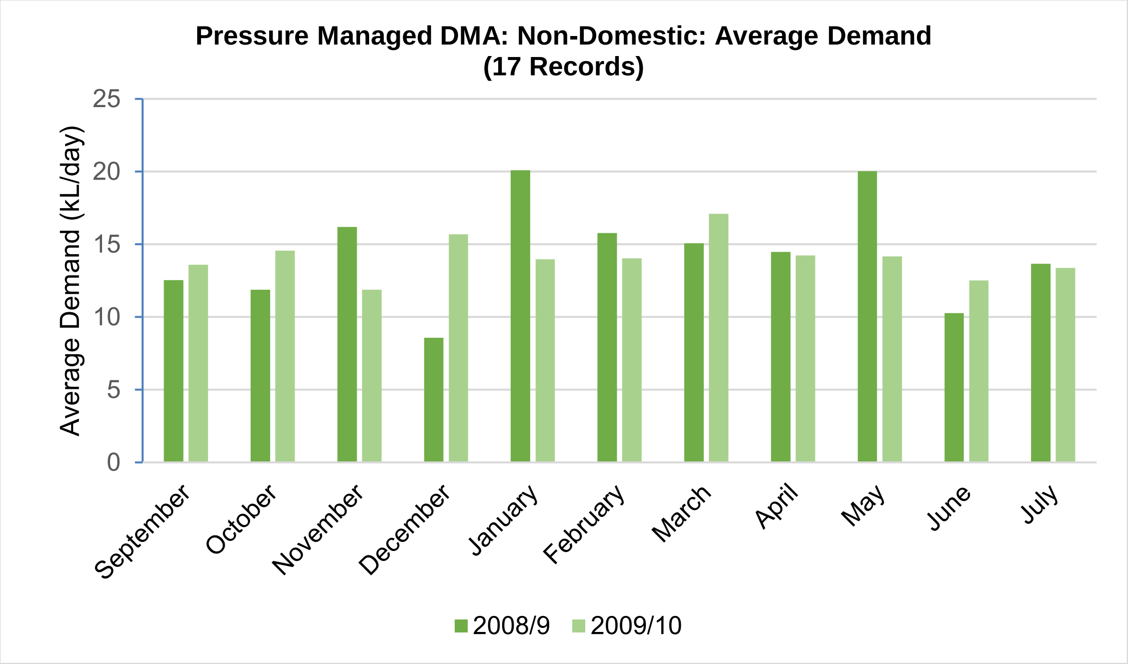


Figure 4-41: Pressure Managed DMA: Monthly comparison of non-domestic users average Demand

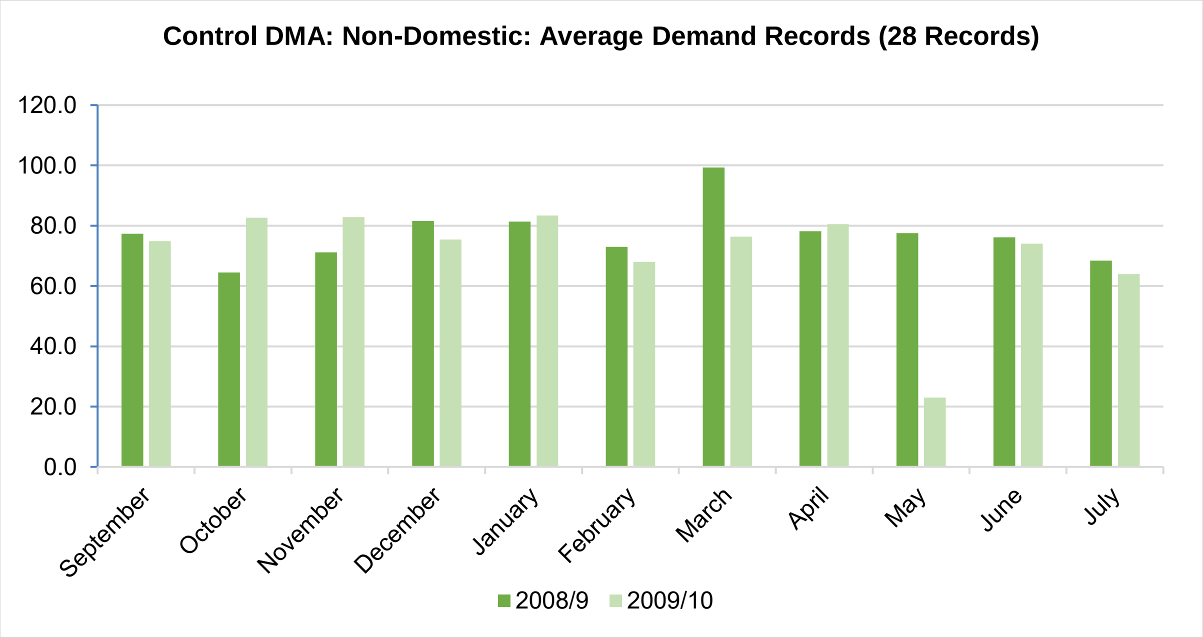


Figure 4-42: Control DMA: Monthly Comparison of non-domestic users average demand

No further analysis will be performed on the non-domestic users as this was not the focus of the study.

4.3. PRESSURE AND LEAKAGE

The aim of this section is to describe the steps undertaken to separate the leakage from the consumer demand. Various leakage parameters based on the logged data conditions (before and a year after pressure management) was calculated. The Completion Report calculated leakage parameters were used as a basis for calculation.

This information was applied two models, namely the N1 model and the FAVAD model. The leakage parameters calculated were used to calculate the leakage within the model (separate from the consumption). The system was then simulated for the system before pressure management in both models. Once the initial system was set up, the pressure setting was adjusted to represent the system after pressure management (one year later). These models were then calibrated to reflect the logged data profiles. The outputs of the two models were compared.

4.3.1. Calculate the Various Leakage Parameters: FAVAD and N1 Hydraulic Models

The system was modelled using two modelling software types. The first being the Epanet 2 Hydraulic Modelling Software (Rossman, 2000), based on the simple orifice equation, and will be known as the N1 model for this study. The second model utilized, is the Epaleaks 1 (Kabaasha, Piller and van Zyl, 2017) which is based on the modified orifice equation and will be known as the FAVAD model for this study. The following leakage parameters were determined, based on the Completion Report Data, and then adjusted to align to the Logged Data conditions:

FAVAD Model

- Initial or Fixed leakage area, A0
- Head- Area slope, m

N1 Model

- Leakage exponent remains the same, N1 = 1.33
- Constant Coefficient, C,

The next step was to adjust these parameters to represent the system conditions before and a year after pressure management.

Due to limitations of the data available, it was then proposed to use the N1 parameters calculated for the system, at the Completion Report reference data, and then adjust the leakage parameters, with the assistance of Excel Solver to the conditions as presented in **Table 4-26**.

Solver in Excel was used to find an optimal (maximum or minimum) value for a formula in one cell called the objective cell subject to constraints, or limits, on the values of other formula cells on a worksheet.

In this case the objective was to determine what factor or fraction is required to adjust leakage parameters, when applied to the Orifice Equation or modified orifice equation, to equate to the MNF (for the system before pressure management) as set out in **Table 4-26**. The MNF was set as the limit in which the Solver function was required to formulate a solution.

This method proved to be the most reasonable method to ensure the system is reasonably represented.

4.3.2. Leakage Parameters

N1 leakage parameters

Based on the Completion Report Data, the various leakage parameters, based on the MNF estimates, were calculated. **Equation 2-5** served as starting point to calculate the required leakage parameters:

$$Q = AC_d\sqrt{2gh}$$

The following input data was available, as presented in **Table 4-24:**

Table 4-24: Summary of flow and pressure values used to calculate leakage area

Before Pressure Management		After Pressure Management	
Q L/s	h (m)	Q L/s	h (m)
43.88	66.8	13.05	26.8

Equation 2-5 was rewritten in order to solve for the total system leakage area, A, as follows:

$$A = \frac{Q}{C_d\sqrt{2gh}}$$

Where Q is the minimum night flow (MNF).

This equation was applied to the system before and after pressure management as follows:

$$A_{before\ pressure\ management} = \frac{43.88\times10^{-3}}{0.65\sqrt{2x9.81x66.8}} \times 10^6$$

A= 1865.11mm^2

$$A_{after\ pressure\ management} = \frac{13.05\times10^{-3}}{0.65\sqrt{2x9.81x26.8}} \times 10^6$$

A = 875.92mm^2

Table 4-25 summarises the Model Input Parameters based on data available from the Completion Report. The total leakage area reduced from 1865.11mm^2 to 875.92mm^2.

Table 4-25 Summary of Completion report input parameters

	AZP (m)	Leakage (L/s)	Leakage (kL/h)	A (mm^2)
Point 1	66.8	43.9	158	1865.11
Point 2	26.8	13.1	47	875.92

Once the above was calculate, the N1 number was determined by applying the following equation, **Equation 2-4:**

$$\frac{Q_{Before}}{Q_{After}} = \left(\frac{h_{Before}}{h_{After}}\right)^{N1}$$

Where

$$N_1 = \frac{\log(\frac{Q_{before(mnf)}}{Q_{after(mnf)}})}{\log(\frac{h_{before(mnf)}}{h_{after(mnf)}})}$$

N1 = $\frac{\log(0.0439/0.0131)}{\log(66.48/26.8)}$

N1 = 1.33

Once the N1 value was calculated the Constant Coefficient, C, was calculated using the following formula:

$$C = \frac{Qmnf}{(AZPbefore)^{N1}}$$

$$C = \frac{0.0439}{(66.8)^{1.33}}$$

C= 1.66x10^{-04}

The initial C value of 1.66x10^{-4}, is representative of a system a week before and a week after pressure management. This value was adjusted to align to the conditions of the logged data, as represented in **Table 4-26**, using solver Excel function. “Adjusted”, in the context of this section refers to the original parameter adjusted, using Solver (Excel) to align to the logged flow and pressure values. The adjustment factor was determined as 1.1701.

Table 4-26: Logged Data by CCT

	Simulated AZP	**Measured MNF**
Before Pressure Management (June 2009)	66.48	51.03
After Pressure Management (June 2010)	26.80	10.21

N1	1.33
C (adjusted)	1.94x10^{-04}

FAVAD Leakage parameters

The following section describes the steps followed and equations used to calculate the FAVAD parameters.

The following **Equation 4-18 and Equation 4-19**, as determined by Schwaller (2012), based on **Equation 2-9,** was developed to express the Initial Area of the system (A_0) and system pressure-are slope:

$$Q_i = C_d\sqrt{2g}\left(A_{0,syst}h_i^{0.5} + m_{syst}h_i^{1.5}\right) \tag{4-18}$$

$$Q_f = C_d\sqrt{2g}\left(A_{0,syst}h_f^{0.5} + m_{syst}h_f^{1.5}\right) \tag{4-19}$$

Where

m_{syst} = pressure-area slope fitted to the system (m)

$A_{0,\ syst}$ = initial leakage area fitted to the system (m^2)

Q_i, Q_f = initial and final total leakage flow rate of the networks (m^3/s)

h_i, h_f = initial and final leakage pressure head (measured at AZP) (m)

From **Equation 4-19**, make $A_{0,\ syst}$ the subject of the formula:

$$\frac{Q_f}{C_d\sqrt{2g}} = A_{0,syst}h_f^{0.5} + m_{syst}h_f^{1.5}$$

$$A_{0,syst}h_f^{0.5} = -m_{syst}h_f^{1.5} + \frac{Q_f}{C_d\sqrt{2g}}$$

$$A_{0,syst}h_f^{0.5} = -m_{syst}\frac{h_f^{1.5}}{h_f^{0.5}} + \frac{Q_f}{C_d\sqrt{2g}h_f^{0.5}}$$

$$\therefore\ A_{0,syst} = \frac{Q_f}{C_d\sqrt{2g}h_f^{0.5}} - m_{syst}\frac{h_f^{1.5}}{h_f^{0.5}} \tag{3-20}$$

First, m_s was calculated by applying the following equation:

$$m_{syst} = \frac{1}{C_d\sqrt{2g}}\frac{h_f^{0.5}Q_i - h_i^{0.5}Q_f}{\left(h_i^{1.5}h_f^{0.5} - h_f^{1.5}h_i^{0.5}\right)} \tag{3-21}$$

Where

Q_i represents the MNF before pressure management

Q_f represents the MNF after pressure management

h_i represents the AZP before pressure management

h_f represents the AZP after pressure management

$$m_{syst} = \frac{1}{0.65\sqrt{2 \times 2.981}} \frac{26.8^{0.5}43.88 \times 10^{-3} - 66.8^{0.5}13.05 \times 10^{-3}}{(66.8^{1.5} \times 26.8^{0.5} - 26.8^{1.5} \times 66.8^{0.5})}$$

$$m_{syst} = 24.7296 \text{ mm}^2/\text{m}$$

Convert to m^2 by dividing by 10^6:

$$m_{syst} = 2.47 \times 10^{-05} \text{m}^2/\text{m}$$

The head area slope is able to inform us of the typical state and characteristics of our infrastructure. For this study, it is uncertain as to the quantity and type of leaks that are found in the system. However, a study by Dietmar; Nsanzubuhoro and van Zyl, 2020 determined typical m values for different types of leaks. They determined that systems with high head-area slopes is typical of a system where the leaks arise as a result of longitudinal cracks within the pipelines. For this system it appears as though the leak is characterized by longitudinal cracks.

After calculating the head-area slope, m$_{syst}$, the initial area, A$_{0,syst}$ was calculated by applying the **Equation 4-23,** using the data from **Table 4-25**:

$$A_{0,syst} = \frac{(13.05/1000)}{0.65 \times \sqrt{2 \times 2.981}26.8^{0.5}} - (2.47 \times 10^{-0.5}) \frac{26.8^{1.5}}{26.8^{0.5} h_f^{0.5}} \qquad \textbf{4-22}$$

$$A_{O,syst} = 213.17 \, mm^2$$

Convert to m^2 by dividing by 10^6

A0 (m^2)	2.13x10^{-04}

The initial area, A$_{0,syst}$, represents the area of the total leaks in the system when there is no pressure. The initial area calculated can be interpreted as leakage covering 14mm by 14mm space. This initial area is small, as opposed to the large head-area slope value, however under zero pressure conditions longitudinal cracks close up in the system which is why the initial area may appear small.

A typical diameter of a round role, based on the initial area of 213.12mm^2 is calculated as follows:

$$A = \pi r^2$$

Where, “A” is the area and “r” is the radius.

This equation was rewritten as follows:

$$r = \sqrt{\frac{A}{\pi}}$$

$$\therefore r = \sqrt{\frac{213.17}{\pi}}$$

$$r = 8.23$$

$$r \approx 8\,mm$$

$$\therefore Diameter\ of\ round\ role = 2\ \times 8$$

$$\therefore Diameter\ = 16mm$$

This can be interpreted as the leakage covering a 16mm diameter round role.

The initial area, $A_{O,\,Syst}$, and head-area slope, $m_{,syst}$, values calculated above, is representative of a system a week before and a week after pressure management.

This value was adjusted to align to the conditions of the logged data, denoted in **Table 4-26**, using solver Excel function. “Adjusted”, in the context of this section refers to the original parameter adjusted, using Solver (Excel) to align to the logged flow and pressure values. The adjustment factor was determined as 1.170.

DMA FAVAD parameters were also adjusted to align to the logged data reference point.

A0 (m^2)	2.50×10^{-04}
m (m^2/m)	2.90×10^{-05}

4.3.3. Alignment of the Hydraulic Models

This section describes the steps undertaken, and the results obtained, to simulate the pressure managed DMA into a hydraulic model where consumer demand is separated from the total demand (in other words, the consumer demand excludes the system leakage). The *“original”* demand pattern (as illustrated in **Figure 3-30**) includes both leakage and consumption. This demand pattern was adjusted, to exclude leakage. This was done for both the N1 Model (as referenced in Table 4-27) and FAVAD Model (as referenced Table 4-28).

The following steps were followed:

The hydraulic models were set-up to represent the system conditions based on the logged data. Two types of models were used

- N1 Model
- FAVAD Model

The next step was to calibrate the demand pattern by adjusting the “original demand pattern” to exclude leakage. This was determined for both models.

Following this step, the leak profile was calculated. This was done by separating the leakage flow rate from the actual consumption flow over 24-hour period. This step is slightly different between the two models. This is explained further down in the section.

For the system before and after pressure management, the total head in the reservoir represented 88 and 47m respectively.

The following steps describe the process undertaken.

4.3.4. N1 Model Set-up

The following activities were followed in order to separate the leakage from the total demand to determine the end user demand.

Step 1: Distribution of Discharge Coefficient, C, across each node

Excel was used to assist with distributing the adjusted C, across each node, based on the weighted average of demand. The formula applied is as follows:

C at node “n” = (Demand (LPS)/Total Demand) x Sum of C’s **4-23**

Step 2: Distribute C’s in the model

Once this was completed, open the EPAnet.inp model as a text file, paste the distributed C’s against the correct nodes under the Emitter section.

Step 3: Adjust Default Settings

In the Report Tab, select Default Settings, then Hydraulics. Adjust the Emitter Exponent to the calculated value of N1 = 1.33.

Step 4: Set the Total Head of the Reservoir

The reservoir levels, for the system before and after pressure management, was set at 88m and 47m, respectively. These values match the PRV setting pressure prior to and post commissioning of the PMZ.

Step 5: Balance the model under static conditions

In the model adjust the total duration from 24 hours to 0. This was done in order to balance the model at static conditions. Once this was done, the model was balanced.

4.3.5. FAVAD Model Set-up

In the FAVAD model, the adjusted initial Area (*A_0*) and Head-Area Slope (*m*) was utilized to calculate the FAVAD parameters required to calculate the leakage in the system.

Step 1: Distribute Initial Area and Head-Area Slope across the nodes

The Initial Area (A_0), as calculated in in the previous section was distributed across each node according the weighted average of the demand. The formula applied is as follows:

A_0 at node "n" = (Demand (LPS)/Total Demand) x Sum of A_0's

The Head-Area Slope, for every node was calculated using the initial area formula. As follows:

$$A_0 = \frac{Q_1}{C_d\sqrt{2gh_1}} - mh_1 \tag{3-24}$$

Where:

Q_1 = Initial demand (LPS)

C_d = Discharge coefficient

g = Acceleration due to gravity(m/s^2)

h_1 = Initial pressure head (m)

m = Head-area slope (m^2/m or m)

the formula was then restructured, to solve for *m*, as follows:

$$m = \frac{Q_1}{A_0 h_1\, C_d\sqrt{2gh_1}}$$

Step 2: Adjust Default Settings

The default orifice equation settings, in Epanet 2.0 is only relevant for the N1 model. For the FAVAD Model (or Epaleaks model) the default settings did not require adjusting as it was based on the modified orifice equation.

4.3.6. Calibrated Demand Patterns

The new demand profiles were generated from the Epanet Model (also known as the N1 model) and Epaleaks Model (also known as the FAVAD model). In order to calibrate the model, one needs to separate the leakage from the consumer demand. Once this is achieved, the demand pattern is adjusted (in the model), at every hour, in order to align the total demand (including leakage) to the logged profile.

The final results are presented in **Table 4-27** and **Table 4-28**, each table representing the system before and after pressure management respectively.

From **Table 4-27** slightly different demand pattern emerged in that the demand factor was zero from hour 1 through to hour 4. A number of reasons for this outcome is that the model calculated flows was too low at those hours when compared to the logged data which served as a reference point for calibrating the demand (the hourly demand factors were adjusted until the model outflows matched the logged data). This may also be linked to the possibility of the model over-estimating or under-estimating leakage at various nodes and possibly at various hours in the day.

Once this is complete extract the data for each node at each hour. This was done as follows:

N1 Model:

Use six decimal places when calculating the demands. From the Table Selection Tab, select the type of table to create. In this case, a table for the network nodes, for the system at hour zero was selected. Then select the columns to be presented based on your selection. These columns were Elevation, Demand, Head and Pressure. Demand and Pressure were the only variables used.

FAVAD Model

From the Epaleaks model, the columns selected were Elevation, Total Outflow, Cons Demand, Total Emit Flow, Head and Pressure. Consumption Demand, Total Outflow and Pressure were the only variables used for analyses.

Once this was complete, with the assistance of Excel, the AZP values were calculate for the system based on N1 and FAVAD model for the system before and after pressure management. The AZP values are represented in **Table 4-29** and **Table 4-30** for the N1 Model and **Table 4-31** and **Table 4-32** for the FAVAD Model.

A comparison of the AZP values determined from the models was illustrated. For the system before pressure management AZP values compare very well as illustrated in **Figure 4-46** and for the system after pressure management, as illustrated **Figure 4-50** the AZP.

4.3.7. Leakage Profile

N1 Model

The leakage distribution was calculated for every node at every hour over 24 hours with the assistance of the Excel spreadsheet which contained the extracted modelled flows and pressure values. In order to do this the Constant Coefficients was distributed, according to the weighted average by stands, across each node. **Equation 2-6**, the Orifice Equation, was used to calculate the leakage for every node at every hour over 24 hours. The leakage, for every node, was added per hour in order to generate the 24-hour profile.

This is presented in **Table 4-29** (system before pressure management) and **Table 4-30** (system after pressure management).

FAVAD Model

The leakage and demand were calculated separately in the model. Once the data was extracted and transferred to Excel the leakage, at every node, was added per hour in order to generate the 24-hour profile. This is presented in **Table 4-31** and **Table 4-32**.

4.3.8. Modelled end user consumption

N1 Model

From the Excel Spreadsheet developed, for generating the leakage profile, add the consumption, at every node, per hour over 24 hours. This is illustrated in **Figure 4-43**. Once this is complete subtract the calculated leakage distribution for every hour over 24 hours in order to generate the user consumption profile. This is presented in **Table 4-30** (system before pressure management) and **Table 4-31** (system after pressure management). This is further illustrated in **Figure 4-44**.

FAVAD Model

The user consumption was already generated within the model and is represented by the field titled Cons. Demand. The user consumption at each node was summed for each hour over the 24-hour period. These values are presented in **Table 4-31** and **Table 4-32**.

Table 4-27: Original Demand vs Calibrated Demand Pattern (N1 vs FAVAD Model) (Before Pressure Management)

Hour	Original Demand Pattern	N1 Calibrated Demand Pattern (excluding system MNF)	FAVAD Calibrated Demand Pattern (excluding system MNF)
1	0.712	0.134	0.135
2	0.676	0.025	0.026
3	0.667	0.000	0.000
4	0.699	0.093	0.094
5	0.760	0.228	0.279
6	0.842	0.526	0.527
7	1.058	1.185	1.186
8	1.156	1.486	1.486
9	1.165	1.513	1.514
10	1.175	1.542	1.543
11	1.221	1.685	1.685
12	1.232	1.718	1.718
13	1.210	1.652	1.652
14	1.138	1.428	1.428
15	1.031	1.101	1.101
16	1.027	1.088	1.089
17	1.082	1.256	1.257
18	1.120	1.374	1.375
19	1.132	1.413	1.413
20	1.132	1.411	1.411
21	1.106	1.332	1.332
22	0.996	0.994	0.994
23	0.887	0.663	0.664
24	0.778	0.330	0.332

Table 4-28: Original Demand vs Calibrated Demand Pattern (N1 vs FAVAD Model) (After Pressure Management)

Hour	Original Demand Pattern	N1 Calibrated Demand Pattern (excluding system MNF)	FAVAD Calibrated Demand Pattern (excluding system MNF)
1	0.712	0.000	0.000
2	0.676	0.000	0.000
3	0.667	0.000	0.000
4	0.699	0.000	0.000
5	0.760	0.625	0.602
6	0.842	0.975	0.937
7	1.058	0.885	0.851
8	1.156	1.220	1.170
9	1.165	1.720	1.649
10	1.175	2.187	2.096
11	1.221	2.223	2.130
12	1.232	2.000	1.917
13	1.210	2.000	1.917
14	1.138	1.545	1.483
15	1.031	1.362	1.307
16	1.027	1.402	1.345
17	1.082	1.445	1.386
18	1.120	1.528	1.466
19	1.132	1.578	1.513
20	1.132	1.332	1.278
21	1.106	0.885	0.851
22	0.996	0.037	0.039
23	0.887	0.037	0.039
24	0.778	0.000	0.000

Table 4-29: N1 Model Outputs Before Pressure Management

	N1 Model			
Hour	**Total Demand (L/s)**	**Leakage Only (L/s)**	**Consumption Only (L/s)**	**AZP (m)**
1	54.48	50.93	3.55	66.37
2	51.71	51.05	0.66	66.51
3	51.08	51.08	0.00	66.54
4	53.44	50.98	2.46	66.42
5	58.14	50.75	7.39	66.17
6	64.42	50.42	14.00	65.81
7	80.96	49.42	31.54	64.72
8	88.44	48.90	39.54	64.15
9	89.13	48.86	40.27	64.10
10	89.85	48.80	41.04	64.04
11	93.38	48.54	44.84	63.76
12	94.21	48.48	45.73	63.69
13	92.56	48.61	43.96	63.83
14	87.01	49.00	38.01	64.27
15	78.85	49.56	29.29	64.87
16	78.52	49.58	28.95	64.89
17	82.73	49.30	33.43	64.59
18	85.67	49.10	36.57	64.37
19	86.63	49.03	37.60	64.30
20	86.58	49.04	37.54	64.30
21	84.62	49.17	35.45	64.45
22	76.17	49.73	26.44	65.06
23	67.87	50.23	17.65	65.60
24	59.47	50.68	8.79	66.10
Average	76.50	49.63	26.86	64.95
Min	51.08	48.48	0.00	63.69
Max	94.21	51.08	45.73	66.54

Table 4-30: **N1 Model Outputs After Pressure Management**

	N1 Model			
Hour	**Total Demand (L/s)**	**Leakage Only (L/s)**	**Consumption Only (L/s)**	**AZP (m)**
1	15.51	15.51	0.00	26.72
2	15.51	15.50	0.01	26.72
3	15.51	15.51	0.00	26.72
4	15.51	15.51	0.00	26.72
5	26.26	15.34	10.91	26.48
6	32.82	15.21	17.61	26.28
7	31.23	15.24	15.98	26.33
8	37.14	15.10	22.03	26.13
9	45.92	14.86	31.06	25.77
10	54.09	14.60	39.49	25.37
11	54.72	14.57	40.15	25.34
12	50.83	14.71	36.12	25.54
13	50.83	14.71	36.12	25.54
14	42.86	14.95	27.90	25.90
15	39.63	15.04	24.59	26.03
16	40.33	15.02	25.31	26.00
17	41.09	15.00	26.09	25.97
18	42.56	14.96	27.60	25.91
19	43.43	14.93	28.50	25.87
20	39.10	15.05	24.05	26.05
21	31.23	15.24	15.98	26.33
22	16.17	15.50	0.67	26.71
23	16.17	15.50	0.67	26.71
24	15.51	15.51	0.00	26.72
Average	33.91	15.13	18.79	26.16
Min	15.51	14.57	0.00	25.34
Max	54.72	15.51	40.15	26.72

One of the benefits of using the FAVAD model is that the model calculates the end user consumption and leakage values separately. See **Table 4-31**.

Table 4-31: FAVAD Model Outputs Before Pressure Management

	FAVAD Model			
Hour	**Total Demand (L/s)**	**Leakage Only (L/s)**	**Consumption Only (L/s)**	**AZP (m)**
1	54.48	50.87	3.61	66.32
2	51.71	51.01	0.70	66.46
3	51.04	51.04	0.00	66.49
4	53.44	50.92	2.52	66.37
5	58.14	50.67	7.46	66.12
6	64.42	50.32	14.10	65.76
7	80.96	49.24	31.72	64.65
8	88.44	48.69	39.75	64.08
9	89.13	48.64	40.49	64.03
10	89.85	48.58	41.27	63.97
11	93.39	48.30	45.08	63.68
12	94.21	48.24	45.97	63.62
13	92.56	48.37	44.19	63.75
14	87.01	48.80	38.21	64.20
15	78.85	49.39	29.46	64.80
16	78.53	49.41	29.12	64.83
17	82.73	49.11	33.62	64.52
18	85.67	48.90	36.78	64.30
19	86.63	48.83	37.81	64.22
20	86.58	48.83	37.75	64.23
21	84.62	48.98	35.65	64.38
22	76.17	49.57	26.59	64.99
23	67.87	50.11	17.77	65.54
24	59.47	50.60	8.87	66.04
Average	76.50	49.48	27.02	64.89
Min	51.04	48.24	0.00	63.62
Max	94.21	51.04	45.97	66.49

Table 4-32: FAVAD Model Outputs After Pressure Management

	FAVAD Model			
Hour	**Total Demand (L/s)**	**Leakage Only (L/s)**	**Consumption Only (L/s)**	**AZP (m)**
1	15.43	15.43	0.00	26.72
2	15.43	15.43	0.00	26.72
3	15.43	15.43	0.00	26.72
4	15.43	15.43	0.00	26.72
5	26.63	15.26	11.36	26.46
6	32.81	15.14	17.67	26.27
7	31.23	15.17	16.06	26.32
8	37.12	15.04	22.08	26.12
9	45.92	14.80	31.12	25.75
10	54.09	14.54	39.55	25.36
11	54.72	14.52	40.20	25.32
12	50.83	14.65	36.18	25.52
13	50.83	14.65	36.18	25.52
14	42.88	14.89	27.99	25.89
15	39.63	14.97	24.66	26.02
16	40.33	14.96	25.37	25.99
17	41.09	14.94	26.16	25.96
18	42.56	14.90	27.67	25.90
19	43.43	14.87	28.55	25.86
20	39.10	14.99	24.11	26.04
21	31.23	15.17	16.06	26.32
22	16.15	15.42	0.73	26.71
23	16.15	15.42	0.73	26.71
24	15.43	15.43	0.00	26.72
Average	33.91	15.06	18.85	26.15
Min	15.43	14.52	0.00	25.32
Max	54.72	15.43	40.20	26.72

4.3.9. FAVAD Model vs N1 Model

From **Figure 4-43**, which demonstrate consumption and leakage only, the profiles are an accurate match. The reason for this is that the AZP does not change very much between the two models. In addition, same data is used to calibrate both models with pressures in the same ranges. Both models are similar. One will only find differences if one was extrapolating the results If you use an empirical model with the same data and within their valid ranges then it should be the outcomes should be the same. Kabaasha *et al*, 2017, found with the two models tested that average leakage at the AZP is similar however when one looks at leakage at the critical point variations can be found.

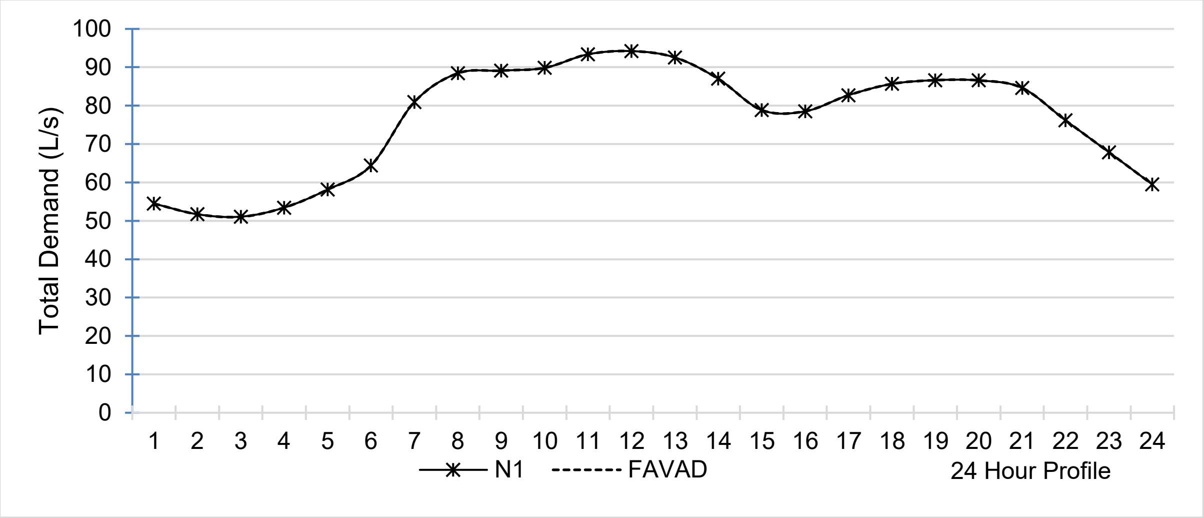


Figure 4-43: Total Demand Before Pressure Management (N1 vs FAVAD Model Output)

From **Figure 4-44,** which demonstrate consumption only, similarly with **Figure 4-43**, the profile is an accurate match.

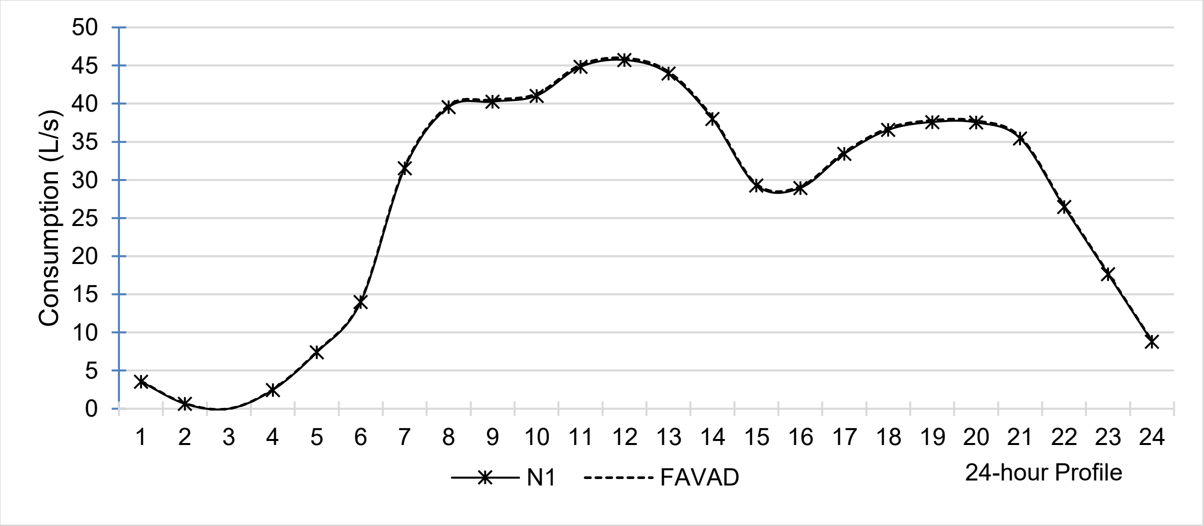


Figure 4-44: Consumption Only Before Pressure Management (N1 vs FAVAD model Outputs)

From **Figure 4-45**, when compared to the N1 model, the FAVAD model appears to generate slightly lower leakage flow rates after hour 7 until hour 22.

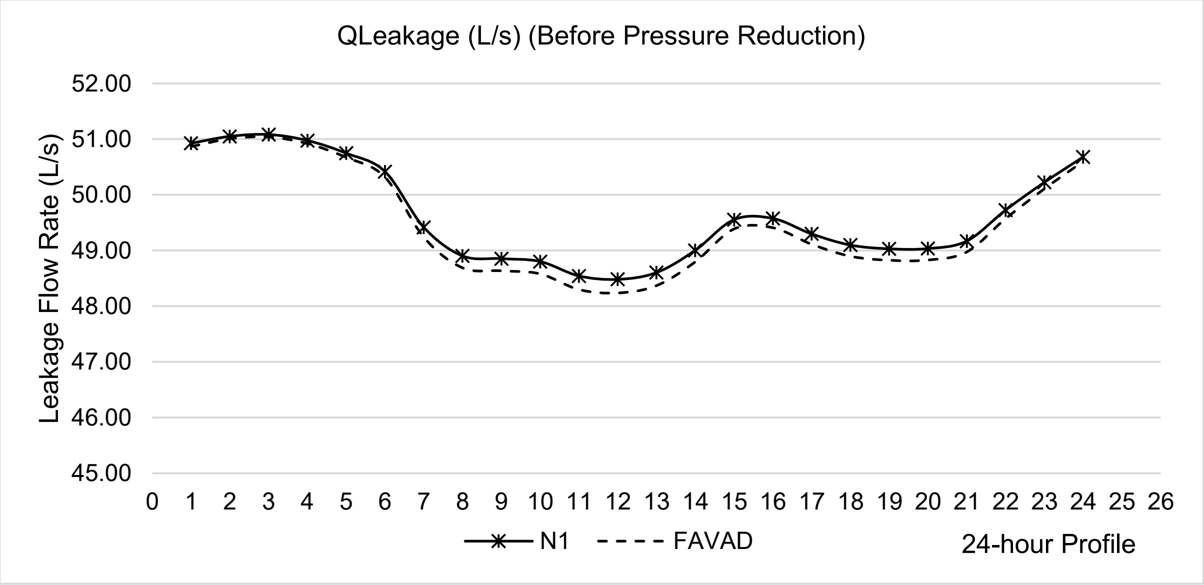


Figure 4-45: Leakage Flow Rate Before Pressure Management (N1 vs FAVAD model Outputs)

From **Figure 4-46**, the AZP for both systems are well matched.

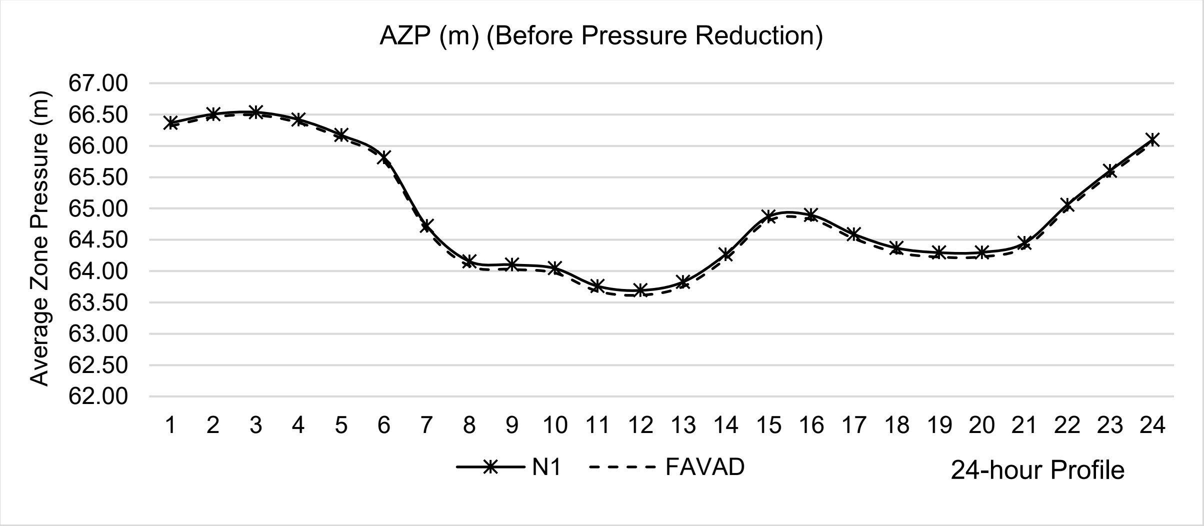


Figure 4-46: Average Zone Pressure Before Pressure Management (N1 vs FAVAD model outputs)

The system was then pressure reduced by reducing the reservoir level from 88 to 47 m.

The demand multipliers were adjusted as per the below.

Demand Multiplier	**N1**	**FAVAD**
Original (Before Pressure Management)	0.1260	0.1600
Adjusted after calibration (After Pressure Management)	0.0855	0.1178

From **Figure 4-47** and **Figure 4-48**, one can see that the N1 and FAVAD output flows are similar.

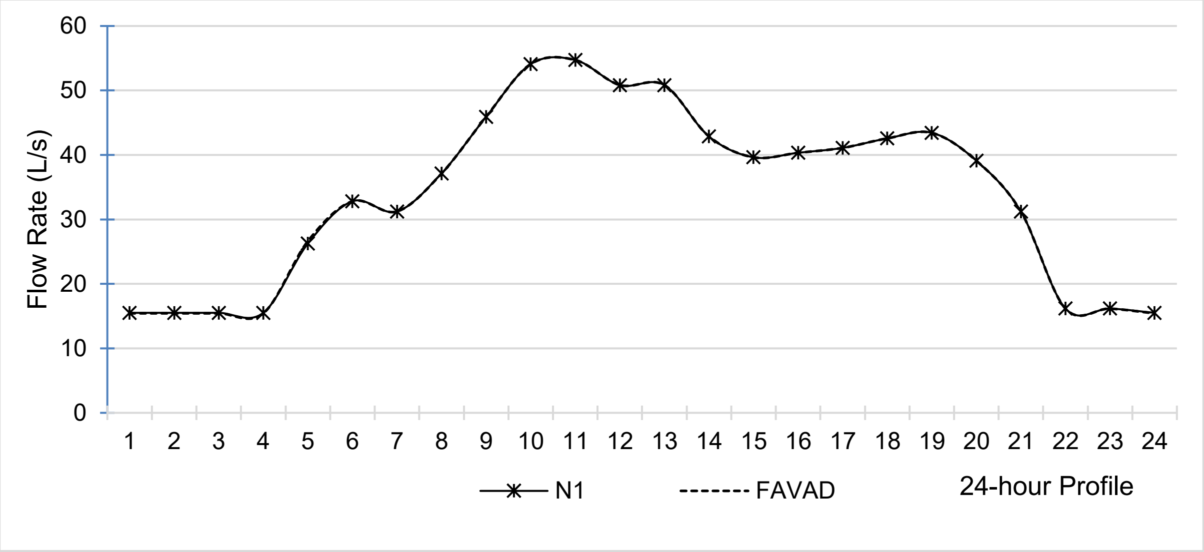


Figure 4-47: Total Demand After Pressure Management (N1 vs FAVAD Model Output)

When the leakage is removed, from **Figure 4-48**, one will notice that there appears to be no demand in the hours of 1 to 4 for both the N1 and FAVAD models. Consumption appears to draw off at about 10pm and there is a small step in consumption again at 11pm.

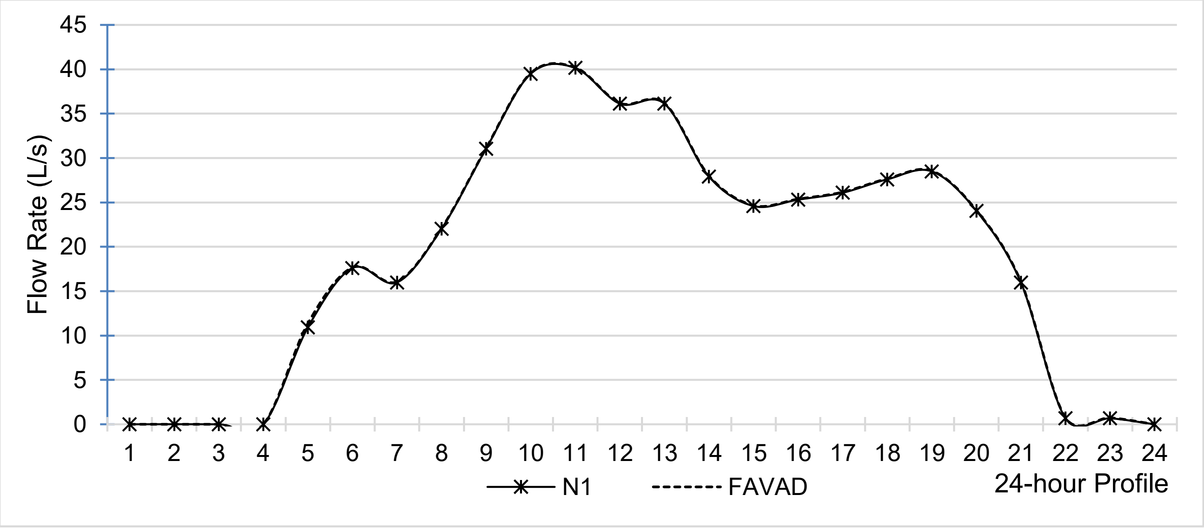


Figure 4-48: Consumption Only After Pressure Management (N1 vs FAVAD model Outputs)

From **Figure 4-49**, it is clear that N1 model reflects a slightly higher minimum night flow when compared to the FAVAD model. This is consistent throughout the entire 24hour profile. Kabaasha *et al* (2017) found that the leakage results were higher in the FAVAD model than in the N1 model. From **Figure 4-49** the converse scenario was found, however, Kabaasha *et al* (2017) also found in 1% of their 200 systems analysed, that the power equation over-estimated the leakage flow rate. It is possible for the leakage to overestimate at one node and underestimate at another node.

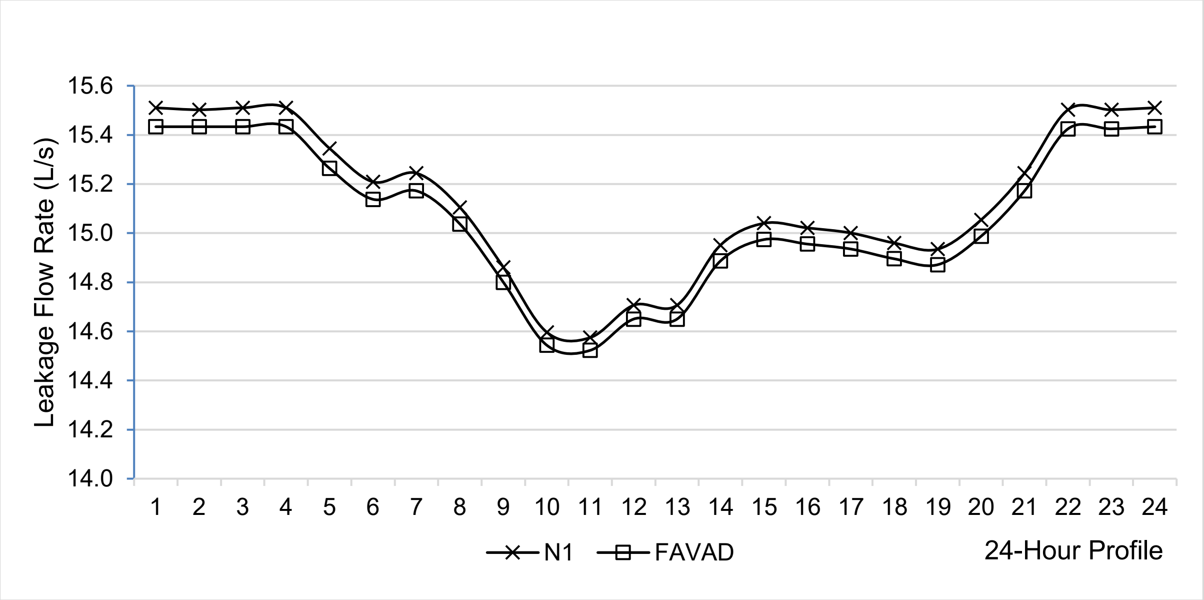


Figure 4-49: Leakage Flow Rate After Pressure Management (N1 vs FAVAD model Outputs)

From **Figure 4-50**, it is clear that the pressure profile is approximately the same.

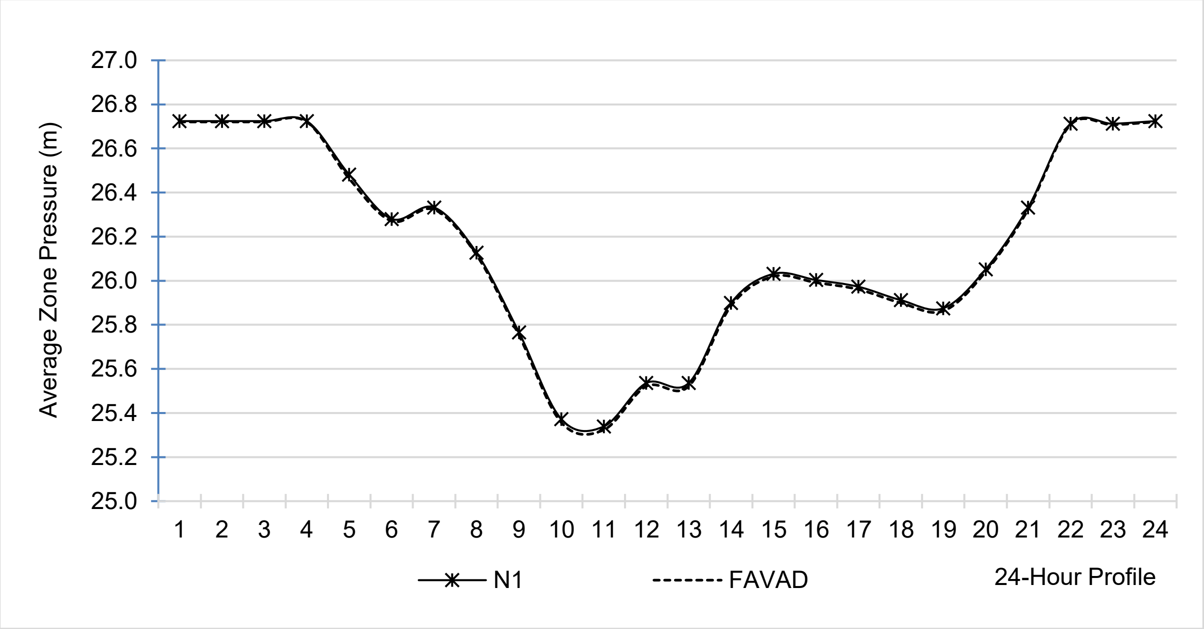


Figure 4-50: Average Zone Pressure After Pressure Management (N1 vs FAVAD model outputs)

4.4. N3 ESTIMATES

4.4.1. N3 estimations calculations from billed consumption (Pressure Managed and Control DMA)

The N3 values for Qbilled was calculated at 0.048. This value compared well with the Qmonthly N3 values. These values varied around a value of 0.05.

From **Figure 4-51**, it is clear that the N3 is approximately 0.048.

	Before	After
Average Consumption Per property per month (kL)	0.49	0.47
*System AZP (m)	64.87	26.14

*not the same as AZP at MNF conditions

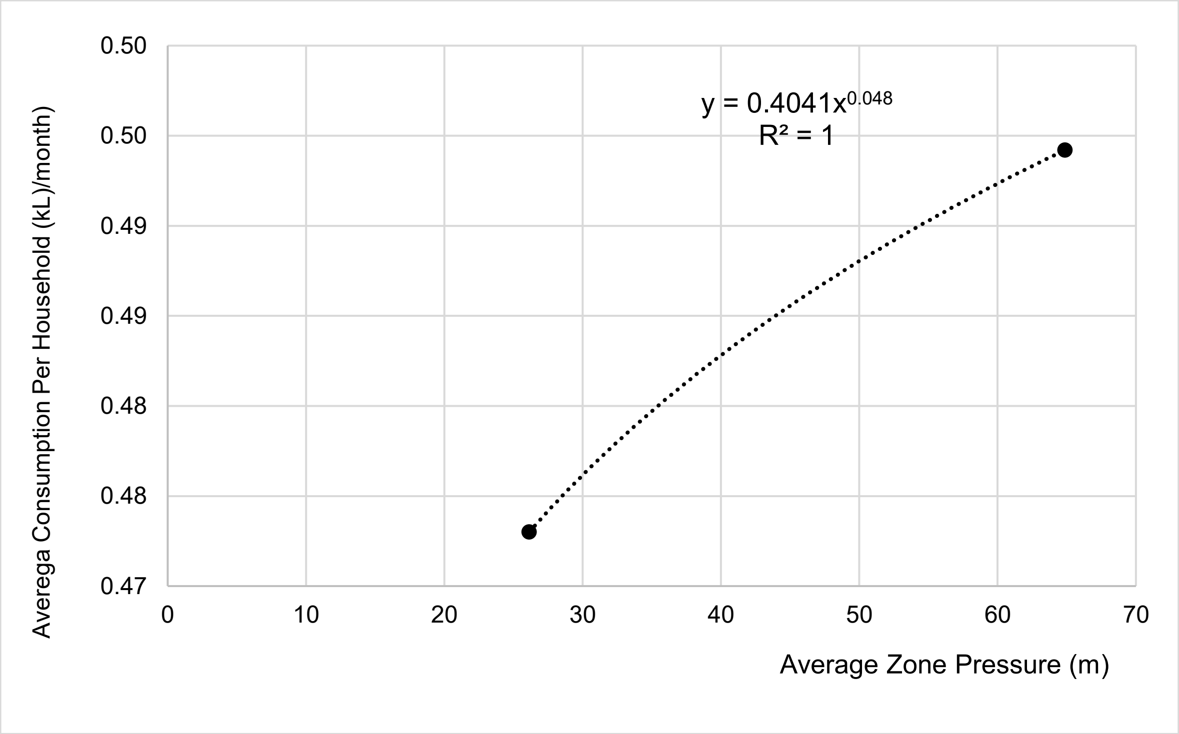


Figure 4-51: Average Property Consumption vs AZP System

4.4.2. N3 Based on Monthly Consumption

As illustrated **Figure 4-52**, the N3 value varies around the value of 0.05. This is worth highlighting as it confirms and shows that the N3 value is quite consistent. There are months which are higher and slightly lower however the trend observed indicates that the N3 value is consistent with the center line.

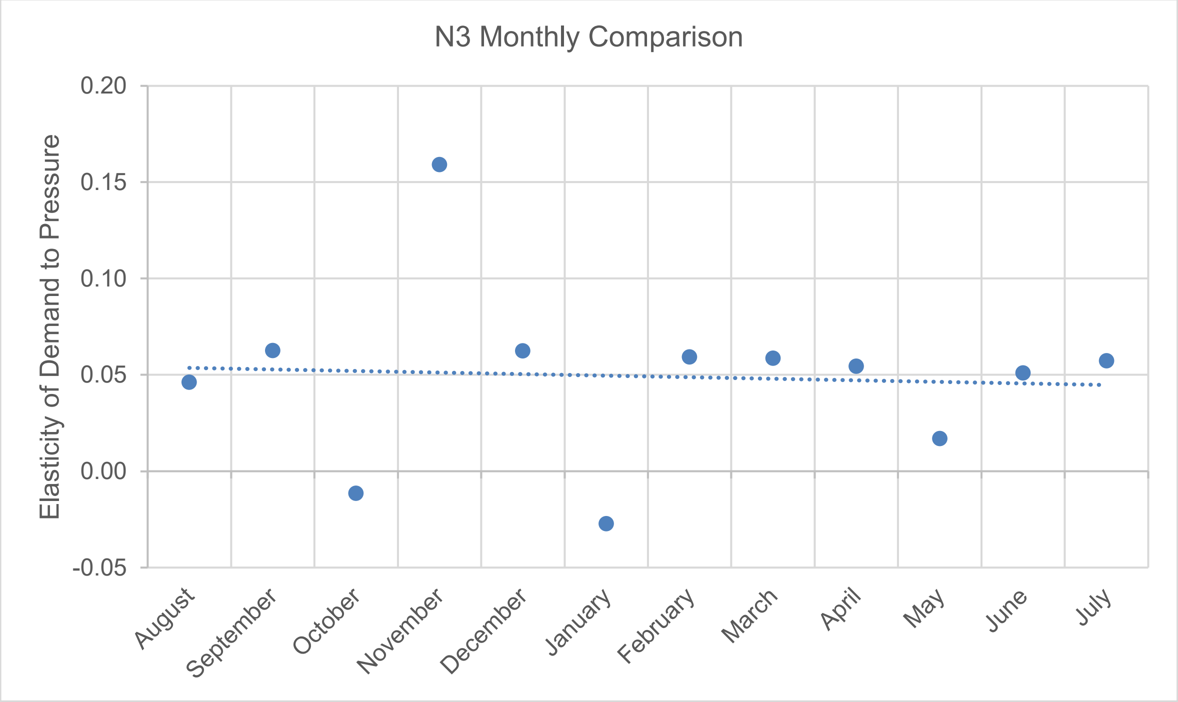


Figure 4-52: Monthly comparison of N3

4.4.3. N3 including apparent losses from water balances

As illustrated **Figure 4-53** N3 value was approximately 0.11. This value was derived by using the authorized billed consumption plus the apparent losses which are losses related to meter inaccuracies, data transfer issues and illegal connections. The latter still forms part of consumption. These apparent losses were obtained from the Water Balance calculations for the system before and after pressure management.

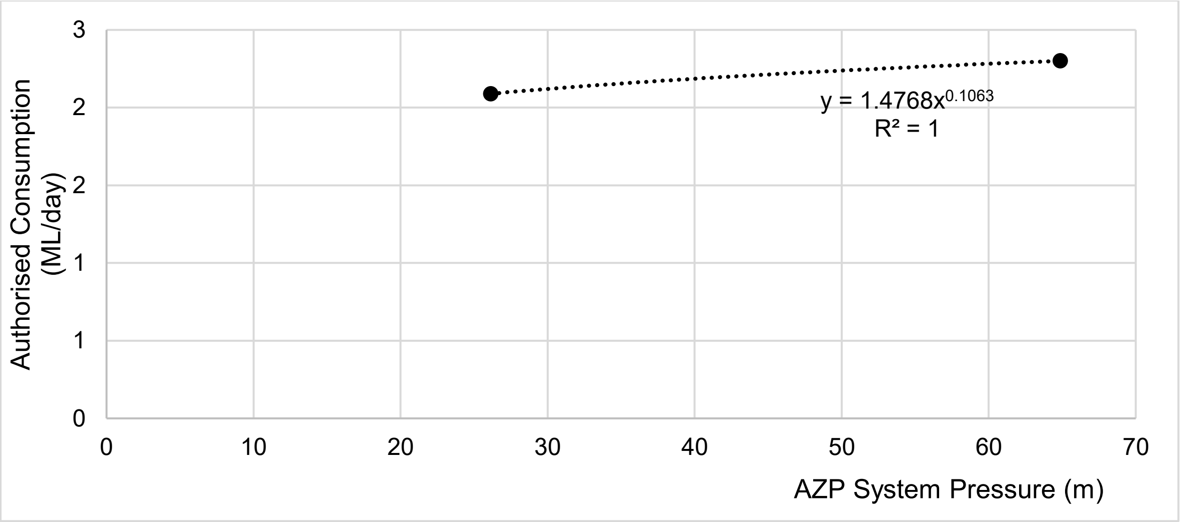


Figure 4-53: Based on June/ July system conditions only

4.4.4. N3 Estimates Considering Leakage

In this section the demand elasticity was determined based on the consumption outputs of the Orifice Equation (N1 Model) and Modified Orifice Equation (FAVAD Mode).

The following N3 estimates were derived and compared.

The FAVAD and N1 hydraulic model related consumption outputs enabled the calculation of the N3 value for the system and on an hourly basis.

The data used is presented below:

	Before Pressure Reduction		**After Pressure Reduction**	
	P_1	Q_{c1}	P_2	Q_{c2}
N1 Model	64.95	26.86	26.17	18.65
FAVAD Model	64.89	27.07	26.15	18.85

Where

P_1 = pressure before pressure reduction (m)

P_2 = pressure after pressure reduction (m)

Q_{c1} = consumption only (less system leakage) (L/s)

Q_{c2} = consumption only (less system leakage) (L/s)

Figure 4-54, present the results of the demand elasticity to pressure as 0.40 and 0.39 for the N1 model and FAVAD model respectively.

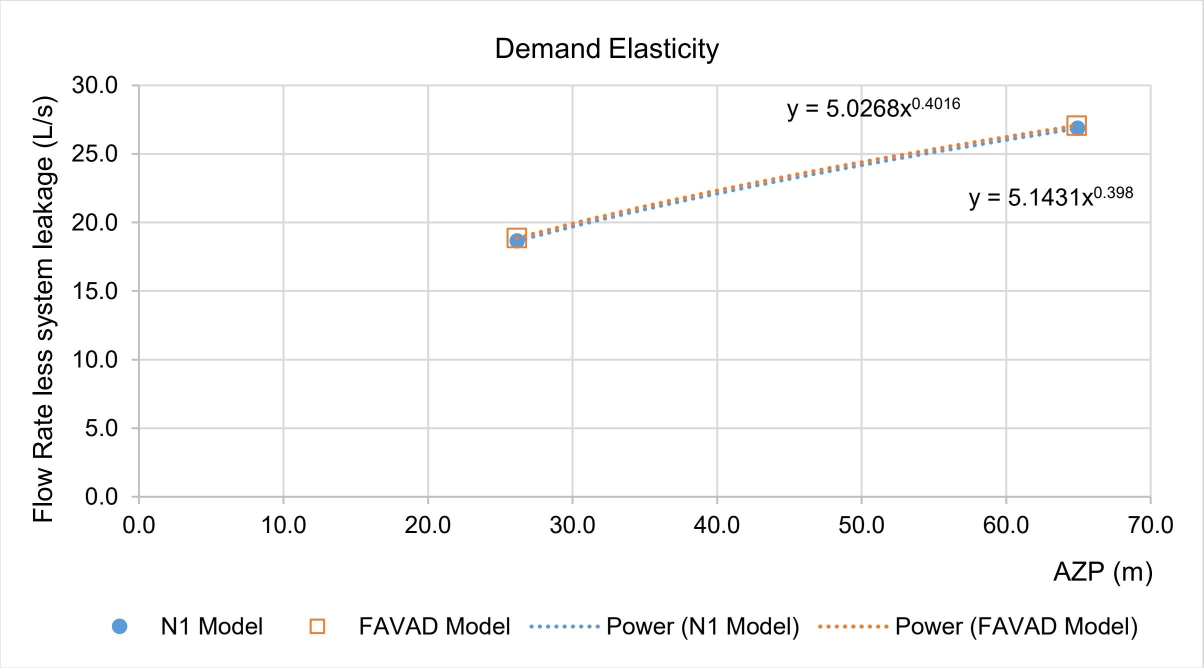


Figure 4-54: Demand vs Pressure Relationship: N1 vs FAVAD Model

For the N1 model the leakage profile is subtracted from the total demand profile in order to obtain the profile representing consumption only for the entire system. For the FAVAD model, the leakage and consumption are calculated separately. One of the major inputs for the latter model is the leakage area and its distribution across the system in order to equate to the sum of leaks.

The latter is an important aspect to consider, when assessing these results, due to the fact that leakage at a single point in time compared to year ago, in reality, is unlikely to remain the same.

Another aspect to consider regarding the N3 value of approximately 0.40 is that this data is based on the logged system data for the entire system (including non-domestic users).

4.4.5. N3 Distribution Per Hour

From **Table 4-33** and illustrated **Figure 4-55**, from period hour 1 to hour 6, the results were either inconclusive or negative. At period 7, 11 and between 12 and 19, the N3 values were similar. Between 8am and 10am the results generated, from the Orifice equation model (Epanet), was slightly higher than that of the FAVAD model (Epaleaks). The latter can be similarly seen between period 12 and 15. Overall, during the day the N3 values appear to be similar, however it appears to be lower in cases where leakage is possibly included.

It is important to note that this study is mining the data deeper than it is possibly safe to do so. There is a high likelihood that there is going to be uncertainty in the data. The N3 analysis on an hourly basis was interesting to see in order to observe the trend however it is not reasonable to take this too seriously without considering additional tests in order to verify these results. This type of analysis has not been done in any other studies.

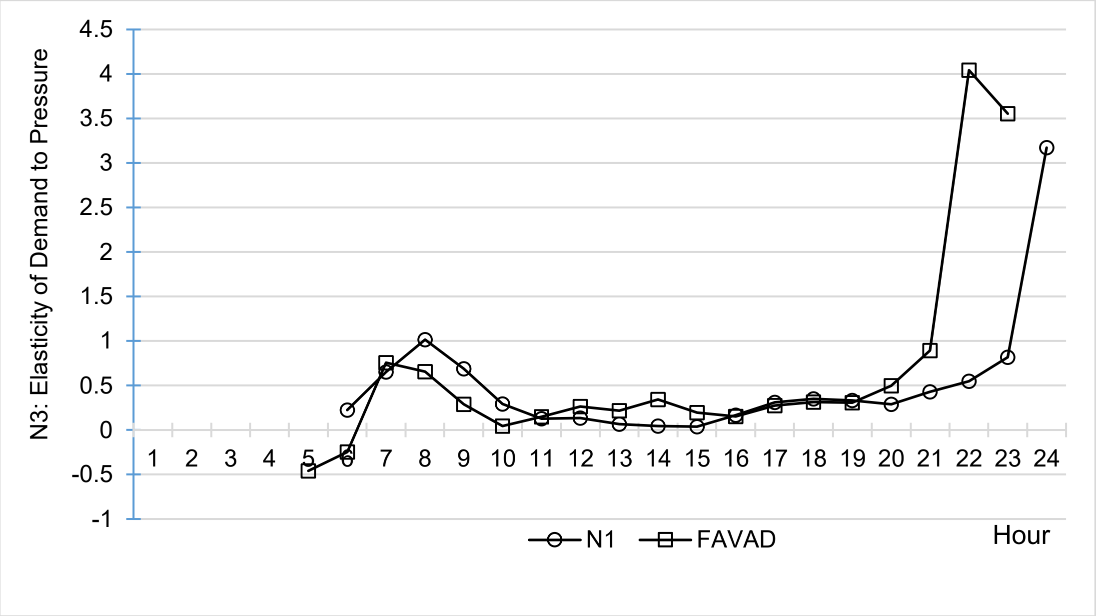


Figure 4-55: N3 Distribution per hour based on the outcomes of the N1 and FAVAD Model

Table 4-33: Summary of N3 Values Calculated for every hour over 25 hours.

Hour	N1 Model	FAVAD Model
1	#N/A	#N/A
2	#N/A	#N/A
3	#N/A	#N/A
4	#N/A	#N/A
5	#N/A	-0.46
6	0.22	-0.25
7	0.65	0.76
8	1.02	0.66
9	0.69	0.29
10	0.29	0.05
11	0.13	0.15
12	0.13	0.26
13	0.07	0.22
14	0.04	0.34
15	0.04	0.19
16	0.17	0.15
17	0.31	0.28
18	0.35	0.31
19	0.33	0.31
20	0.29	0.50
21	0.43	0.89
22	0.55	4.04
23	0.82	3.55
24	3.17	#N/A

4.4.6. Discussion of N3 results and comparison to other studies

The overall relationship between the changes in pressure and changes in demand appear to be mostly positive and appear to be similar to what had previously been determined in practice.

It was expected that the demand and pressure elasticity for the consumption (billed) and that determined based on the model outputs would be similar. Further discussion on the results and comparison to other findings are discussed in the next section.

Table 4-34: Summary of calculated elasticity of demand to pressure

Parameter	N3	Source	Limitation
$Q_{\text{billed (overall system)}}$	0.05	Billed Consumption	±10% sample analysed (rigorous filtering process)
Q_{monthly}	≈0.05	Billed Consumption	±10% sample analysed (rigorous filtering process)
$Q_{\text{ac+al}}$	0.11	Water Balance	Apparent losses are estimated
$Q_{\text{N1 (overall system)}}$	0.40	Hydraulic Model	Consumption includes non-domestic and domestic consumption for the entire system.
$Q_{\text{FAVAD (overall system)}}$	0.38	Hydraulic Model	Consumption includes non-domestic and domestic consumption for the entire system.
$Q_{\text{hour (N1)}}$ hour 7 to 21	Range ≈0.05 to ≈0.30	Hydraulic Model	Consumption includes non-domestic and domestic consumption for the entire system.
$Q_{\text{hour (FAVAD)}}$	≈0.05 to ≈0.30	Hydraulic Model	Consumption includes non-domestic and domestic consumption for the entire system.

Where:

Q_{billed} = N3 calculated using the Billed Consumption Data

Q_{ac+ap} = N3 calculated using the apparent losses and authorized consumption

Q_{N1} = N3 calculated based on the demand outputs from the N1 model

Q_{FAVAD} =N3 calculated based on the demand outputs from the FAVAD model

Q_{hour} = N3 calculated at every hour for 24 hours

The N3 value for Q_{billed} and monthly consumption compared well in that they fell within the same range of 0.05 to 0.06. This value was lower than what was expected. This could be due to the rigorous filtering process. It could be possible that some of the high leakage properties may have been excluded from the filter.

The N3 values, for the monthly comparison, varied well around the value of 0.05. This data was based on the billed consumption data. It matched reasonable well with the results obtained for the average billed consumption. Approximately 10% of the total records were used for this analysis.

For the N1 and FAVAD model an N3 of ≈0.40 and ≈0.39, was obtained. Both models resulted in very similar N3 values being calculated. The N3 values are much higher than the previously calculated results ranging between 0.03 and 0.05. Possible reasons for this difference large difference is that the model outputs were based on the logged data for the entire pressure managed DMA. This logged flow data includes non-domestic users as well as households with high leakage. Higher pressure-dependent demand items result in higher N3 values. The differences lie in the source of the data used.

The billed consumption data, in contrast to the logged data, went through a rigorous filtering process, resulting in a total household sample of 10% of the total records, it is possible that most of the households with high leakage was removed. However, in the logged data these high leakage households would have reflected in the flow data.

Due to the different sources of data (the filtered billed consumption records and the logged system data), which play a strong role in influencing the N3 value, it is believed that the both calculated N3 values are true. However, in the case of the N3 values calculated from consumption inclusive of apparent losses, it is expected that this may not be true due to all the estimates applied in determining the apparent losses.

4.4.7. Discussion of N3 results and comparison to other studies

As illustrated in **Figure 4-56**, there is a huge range of N3's that have been determined through various studies.

A study by Girard and Stewart (2007) revealed results of a consumer survey which indicated that pressure management had the greatest impact on garden irrigation and shower during the period of 3pm and 8pm.

Gebhardt (1975) investigated the impact of pressure, within the reticulation system, on water wastage related to excessive water usage and water loss such as leakage. One of his objectives was to determine the extent to which pressure contributed to overall water wastage (or excessive household usage). Within the one test area, described as a mixed use well-developed area, he determined that an approximate 64% reduction in pressure resulted in approximately 30% reduction in water usage with N3 = 0.54. He went further to test the effect of manipulated pressure changes on system consumption. Seven tests were performed. Three categories of user's consumptions were analysed. The results were plotted on a graph and the power regression model revealed that the N3 for the flats, schools and shopping centre were 0.26, 0.87 and 0.62 respectively. In the case of the shopping centre and the schools, due to the high N3 values, it is expected that there is a high possibility of water wastage or leakage.

Fantozzie and Lambert (2010) study indicated typical demand elasticity exponents for indoor consumption of 0.04. Houses serviced with roof tanks were zero. Typical outdoor exponents (sprinklers and hosepipes) yielded a value of 0.5. However, households which contain flexible seepage hoses with multiple holes yielded exponents as high as 0.75. Lambert, personal communication, 2017, stated that consumption exponents of 0.5 for indoor household consumption generally related to high levels of leakage. This goes to say, that indoor household consumptions generating exponents of 0.5 and greater have high leakage levels.

Although non-domestic consumption was not the focus of this study, Tuhovcak, Suchaek and Rucka (2018), assessed the impact of pressure on the consumption at an office building. He determined a value of 0.15.

The elasticity of demand to pressure was approximately 0.05 for DMA 1 (High to medium) and DMA 3 (Low income) and in the range of approximately 0.25 for DMA 2 (Medium Income).

The study concluded that the relationship was not consistent between various periods and in some cases remained the same. Meyer, 2018, indicated in his unpublished thesis, that the power regression model suggested an elasticity of demand to pressure in the range of ≈0.15 to ≈0.30 where on-site leakage was included, and in the range of ≈0.05 to ≈0.25 where on-site leakage was excluded.

In addition, in the case of DMA 3 and DMA 2 (Mayor, 2018), N3 values were determined under three conditions, 1) on the system level (inclusive of all consumers), 2) on a sample of consumers without high household leakage and 3) on the sample of consumers which excluded high and medium leakage. The N3 values ranged from 0.25 to 0.29 and then 0.19 to 0.04.

This proves that the N3 value may differ based on the number of consumers in the test. However, the varying number does not prove it will vary if the consumers in the sample vary. The N3 results for this study, ranging between ≈0.4 to ≈0.05 compare reasonably well with results obtained from other studies.

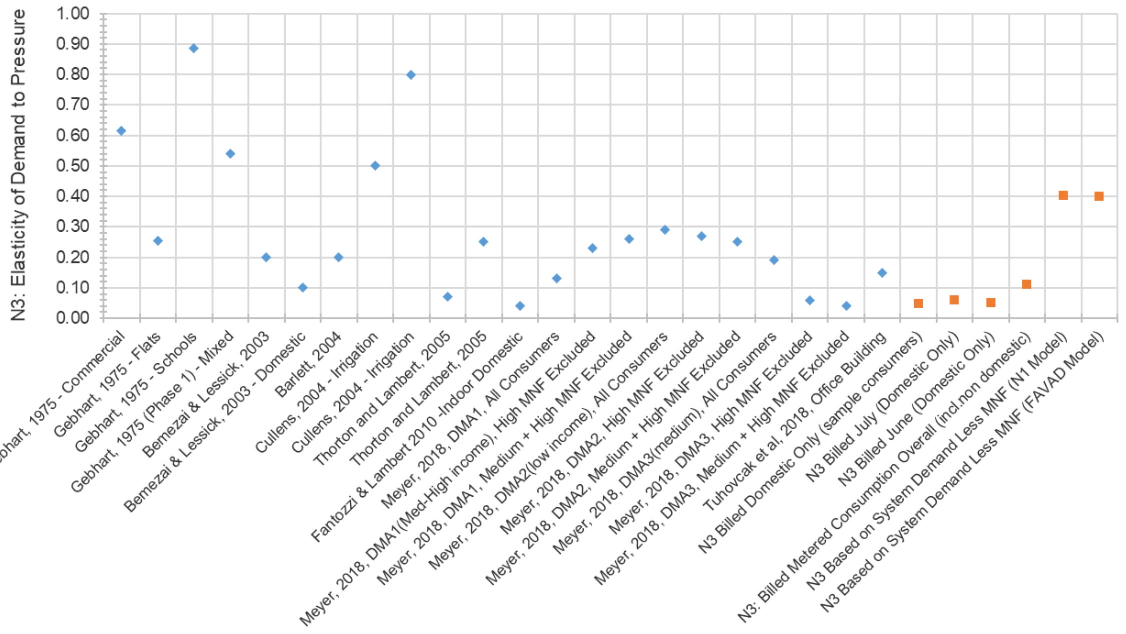


Figure 4-56: Comparison of various N3 values extracted from literature with those determined by this study (square blocks)

5. CONCLUSIONS AND RECOMMENDATIONS

5.1. SUMMARY OF FINDINGS

The aim of this study was to investigate the impact of system pressure on water demand (elasticity of demand to pressure) on a select pressure managed zone in the City of Cape Town (CCT) and a control zone. This investigation aimed to analyse the logged system flow and pressure before and after pressure management. In addition to analysing the field data, this study further aimed to simulate the system conditions before and after pressure management through the use of hydraulic modelling to investigate the impact of diurnal pressure variations on the N3 factor.

The first part of the thesis was aimed at identifying a suitable Pressure Managed DMA and Control DMA. This section then further confirmed, by comparing the Pressure Managed DMA Billed Consumption with the Control DMA (before and after pressure reduction), that the pressure reduction in the pressure managed DMA was in fact as a result of pressure reduction and not any other intervention. The concept of using a Control DMA to evaluate the pressure is not commonly observed. Meyer (2018) is the only reference known to have used a control.

The second part of this study was aimed at modelling the system conditions, by using two different models, namely the N1 Model (based on the Orifice Equation) and the FAVAD Model (based on the Modified Orifice Equation). These models separated the MNF leakage from consumption and enabled the calculation of the AZP under different conditions. These models produced very similar outcomes. There was a minor difference in the leakage distribution over 24-hours.

5.2. CONCLUSION

The main conclusion of this study is that pressure reduction, in a water distribution system, does impact on the domestic end user demand. This information is significant for municipalities in that reduced consumption will result in reduced revenue. In assessing the cost-benefit of pressure management, Finance Managers can now consider the impact of pressure management on revenue.

The billed consumption for the pressure managed DMA clearly shows that the consumption reduced once pressure management was introduced. The control DMA confirmed that reduction was as a result of pressure and not any other intervention.

The FAVAD and N1 model outputs both produced similar consumption and AZP profiles. The difference lies in the leakage profile generated over 24 hours. The N1 modelled leakage profile was slightly higher during hour 7 to 22 for the system prior to the commissioning of pressure reduction. For the system after pressure reduction, the N1 modelled leakage is slightly higher throughout the 24-hour period. The modelled leakage profile was then separated from the total demand profile in order to establish the relationship between pressure and demand.

The power regression model suggests an N3 of approximately 0.05 to 0.06 for the system based on a sample of filtered billed consumption data. However, in the case of the entire system end use consumption (based on the logged data extracted from the model) the N3 value was approximately 0.4. N3 was then determined per hour. The N3 values ranged between 0.05 and 0.30 between hours 9 and 20.

The N3 values compared reasonably well with other studies especially in the case where the pressure demand elasticity tests were conducted on medium income households and in cases where it was known that the households have high leakage. These studies indicated that the demand elasticity for indoor usage may range from 0.04 to 0.29 up to approximately 0.5.

Some limitations to the study include the fact that only about 10% of the billed data was suitable for the analyses. In addition, the household night leakage, was not quantified or described in the Completion Report or through any other data source. This may impact on the value of N3 as the leakage within the household may be seen as demand. Information regarding system changes was not available, this includes leak repairs or pipe replacements.

5.3. RECOMMENDATIONS FOR FUTURE WORK

It is recommended that multiple pressure managed zones be analysed and assessed through a similar method. This is to enable some repeatability to be established in the results obtained. This will better draw in greater confidence of the final results.

It is recommended that further research be applied in a DMA where one can change the pressure on a weekly basis to have several points representative of different weeks in the year in order to get more detail from the analysis. By doing so one will be able to collect more reliable data on the behaviour of the demand in the system.

It is recommended that research be done where smart metering is used in order that all the household consumptions can be accurately collected at a single point in time and will enable one to monitor the change in consumption on a much larger scale.

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