The effect of controlled pressure adjustment on consumer water demand in an urban water distribution system

by

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DECLARATION

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ABSTRACT

Pressure management is commonly employed as part of water conservation and water demand management strategies in water distribution systems (WDS). Most of the earlier work on this subject focussed on the reduction of water leakage and of burst pipes as a result of pressure reduction, and few studies have been undertaken to investigate the pressure-demand relationship.

In this regard, a series of pressure adjustments in three operational district metered areas (DMAs) were successfully planned and conducted to assess the impact of pressure change on the total water demand in each DMA as well as on the water demand of 76 consumers. All three research sites reported a positive relationship between pressure change and consumer demand, where reduced pressure resulted in reduced demand. The impact of pressure on demand varied from one research site to the next.

Two significant factors were identified which could influence elasticity of demand to pressure, namely: the presence of on-site leakage and the presence of household plumbing pressure reducing valves (PRVs). For the sites investigated, on-site leakage was one of the main factors behind the pressure-demand relationship and where on-site leakage was excluded the impact of pressure changes on demand was generally found to decrease. 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.

The impact of pressure changes on consumer demand may be perceived to be relatively low, but could be partially explained by the presence of household plumbing PRVs. If the pressure to a building is regulated by a household plumbing PRV (often installed on the supply to a hot water geyser) then changes in the WDS pressure are not expected to influence supply pressure at individual end-uses downstream of such a plumbing PRV, unless the WDS pressure is reduced below the setting of the plumbing PRV. The elasticity of demand to pressure (excluding on-site leakage) was in the range of ≈0.05 for DMAs with a high likelihood of household plumbing PRVs and in the range of ≈0.25 for the DMA where fewer properties were expected to have such PRVs. The finding has significant implications for pressure management programmes, suggesting that consumer demand in suburban areas (excluding on-site leakage) may in some cases not reduce notably with relatively large changes in pressure, probably due to the presence of household plumbing PRVs which would have controlled pressure to some end-use points in the home in the first place.

The field exercise confirmed that individual consumer demand would not necessarily decrease with reduced pressure, and that the impact of non-technical aspects could surpass pressure-induced change for an individual consumer. A basic but useful approach was proposed to estimate the demand component in the DMA from the flow recording data. The study also highlighted the practical lower limit of pressure reduction in the DMAs investigated, which may be of use for water utilities when planning pressure reduction programmes.

OPSOMMING

Waterdrukbestuur word algemeen gebruik as deel van bestuurstrategië vir waterbesparing en wateraanvraag in waterverspreidingstelsels. Die meeste vroeër werk oor hierdie onderwerp het gefokus op die vermindering van waterlekkasies en van gebarste pype deur drukvermindering, en min studies is al gedoen om die verhouding tussen waterdruk en wateraanvraag te ondersoek.

In hierdie verband is 'n reeks drukaanpassings in drie operasionele toetsareas suksesvol beplan en uitgevoer om die impak van drukverandering op die totale wateraanvraag in elke toetsarea asook by 76 verbruikers te evalueer. Die resultate by al drie toetsareas wys 'n positiewe verwantskap tussen drukverandering en wateraanvraag, waar verminderde druk lei tot 'n verminderde wateraanvraag. Die impak van druk op aanvraag het gewissel van een area na die ander.

Twee belangrike faktore is geïdentifiseer wat elastisiteit van wateraanvraag deur druk kan beïnvloed, naamlik: die voorkoms van lekkasies op erwe en die teenwoordigheid van huishoudelike drukverminderingskleppe. Lekkasies op erwe het geblyk een van die hooffaktore te wees wat die druk-aanvraag verhouding kan beïnvloed, en waar lekkasies weggelaat is, het die impak van druk op aanvraag gedaal. Die elastisiteit van wateraanvraag deur druk was ≈0.15 tot ≈0.30 waar lekkasies op erwe ingesluit is, en ≈0.05 tot ≈0.25 waar sulke lekkasies uitgesluit is.

Die impak van drukveranderinge op aanvraag was relatief laag, maar kan gedeeltelik verklaar word deur die teenwoordigheid van huishoudelike drukverminderingskleppe. As die druk by 'n gebou gereguleer word deur 'n huishoudelike drukverminderingsklep (tipies geïnstalleer by 'n warmwater-geiser) behoort drukverandering in die waternetwerk nie die druk stroomaf van daardie drukverminderingskleppe te beïnvloed nie, tensy die waternetwerkdruk onder die stelling van die drukverminderingsklep daal. Die elastisiteit van wateraanvraag deur druk (uitgesluit lekkasie op erwe) was ongeveer ≈0.05 vir areas met 'n hoë waarskynlikheid van huishoudelike drukverminderingskleppe en ≈0.25 vir areas waar minder sulke drukverminderingskleppe verwag sou word. Die bevinding het belangrike implikasies vir munisipale waterdrukbestuur; dit dui daarop dat verbruikersaanvraag in stedelike gebiede (uitgesluit lekkasie op erwe) in sommige gevalle nie merkbaar gaan verminder met relatief groot veranderinge in druk nie, waarskynlik as gevolg van die teenwoordigheid van huishoudelike drukverminderingskleppe wat in elk geval die druk by sekere watergebruikspunte op die erf beheer.

Die studie het bevestig dat individuele wateraanvraag nie noodwendig sal afneem met verminderde druk nie, en dat die impak van nie-tegniese aspekte die impak van drukverandering by 'n individuele verbruiker kan oortref. 'n Basiese maar nuttige benadering is voorgestel om die wateraanvraag-komponent vir ‘n toetsarea uit gemete vloeidata te bepaal. Die studie het ook gewys dat daar ’n praktiese limiet is vir drukvermindering in die areas wat ondersoek is, wat in ag geneem kan word deur munisipaliteite in die beplanning van drukbestuurprogramme.

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LIST OF SYMBOLS

°C	degrees Celsius
A_0	initial leak area at zero pressure
C	constant coefficient
C_d	discharge coefficient
d	day
g	acceleration due to gravity
h	pressure head (metres head)
h_0	initial average pressure head
h_1	new average pressure head
kL	kilolitre
kL/d	kilolitre per day
kPa	kilopascal
L	litres
L/d	litres per day
L_0	initial leak flow rate
L_1	new leak flow rate
Lm	length of mains
Lp	length of underground pipe from street edge to customer meter
m	metres
m_a	pressure-area slope
mm	millimetres
N1	power law leakage exponent
N3	power law demand exponent
Nc	number of service connections

Q	flow rate
Q_0	initial leak flow rate
Q_1	new leak flow rate
$Q_{consumer}$	consumer flow rate
Q_{dem}	consumer water demand
Q_{dem-c1}	average demand for all individual consumers in used dataset
Q_{dem-c2}	average demand for individual consumers in used dataset, excluding consumers with high MNF
Q_{dem-c3}	average demand for individual consumers in used dataset, excluding consumers with medium or high MNF
Q_{DMA}	DMA inlet flow rate
R^2	coefficient of determination
β	elasticity of demand to pressure

ACRONYMS AND ABBREVIATIONS

AADD	average annual daily demand (kL/d)
BABE	Burst and Background Estimate
CARL	current annual real losses
CP	critical point
CSIR	Council for Scientific and Industrial Research
DMA	district metered area
DWAF	Department of Water Affairs and Forestation (currently DWS)
DWS	Department of Water and Sanitation (formerly DWAF and DWA)
FAVAD	Fixed and Variable Area Discharge
GL	ground level
GSM	global system for mobile communications
ILI	Infrastructure Leakage Index
IMQS	Infrastructure Management Query System
IWA	International Water Association
MNF	minimum night flow
PRV	pressure reducing valve
SANS	South African National Standards
SIV	system input volume
UARL	unavoidable annual real losses
WC	water conservation
WDM	water demand management
WDS	water distribution system
WLSG	Water Loss Specialist Group (of the IWA)
WRC	Water Research Commission

1 INTRODUCTION

1.1 BACKGROUND

Residential water demand in a water distribution system (WDS) can be influenced by a number of factors. According to Jacobs and Haarhoff (2007) the top influencing parameters for indoor use are stand size, stand value, people per household, toilet flush frequency, on-site leak volume, shower event volume and toilet flush volume. For outdoor use Jacobs and Haarhoff (2007) found that the top parameters to influence demand were an irrigation factor for lawns and garden beds (ratio of actual irrigation to theoretical irrigation requirements), pan evaporation and surface area of the lawns. Jacobs and Haarhoff (2007) did not incorporate pressure as an independent variable.

A number of studies and reports have highlighted the benefits of pressure management in a WDS (Wegelin and McKenzie 2002, Waldron 2005, Girard and Stewart 2007, Gomes et al. 2011, Ghorbanian et al. 2017). These benefits include: reduced water leakage, extended life of water infrastructure, improved level of customer service, reduced pipe bursts, cost savings and reduced pressure dependent demand. The impact of pressure on consumer demand is one of the benefits of pressure management that has been researched the least.

As noted, studies have been undertaken to investigate the effect of external factors on consumer water demand as well as on the benefits of pressure management. Of these studies few to date have focussed specifically on the relationship between pressure and consumer water demand and none investigated the role of on-site leakage in the pressure-demand relationship (leakage beyond the consumer meter).

1.2 TERMINOLOGY

Terminology relevant to this thesis is listed below with the stated meaning.

1.2.1 Average Annual Daily Demand (AADD)

AADD is widely used in the Southern African water fraternity (CSIR 2005; Makwiza and Jacobs 2016) and is an indication of the average daily water use by a consumer. An explanation of how to determine the AADD is provided by Strijdom et al. (in press).

1.2.2 Consumer Water Demand

For the purposes of this thesis consumer water demand is regarded as comprising actual consumer usage as well as any leakage on the consumer's property, thus downstream of the consumer meter.

1.2.3 Consumer Water Consumption

Consumer water consumption is the water flow rate that is utilised by consumers, which excludes leakage downstream of the consumer meter.

1.2.4 Critical Point (CP)

The critical point (CP) is the node in a DMA where pressure is expected to be at a minimum. The CP is typically used to report residual pressure, with particular interest in the CP pressure head during peak demand.

1.2.5 Data Recording or Data Logging

Data recording or data logging refers to the procedure of recording data at regular intervals using mechanical recorders or electronic devices, referred to as data recorders or data loggers (Meyer and Seago - in press). Flow recording is undertaken by connecting a data recorder with flow pulsar to a water meter and pressure recording is undertaken by connecting a data recorder with pressure transducer to a suitable access point (fire hydrant, tap or pressure connection).

1.2.6 District Metered Area (DMA)

The term district metered area (DMA) was adopted from the UK water industry and refers to a discrete portion of the WDS with a defined and permanent boundary, for which all the inlet and outlet water pipes are metered (Farley 2001). An alternative description for a DMA could be a water management zone.

1.2.7 DMA Discreteness

A DMA is considered to be discrete if no open cross-boundary connections with adjacent DMAs exist.

1.2.8 Elasticity

Dibb et al. (2001) defined elasticity as a measure of the sensitivity of one (dependent) variable to changes in another (independent) variable. As an example, the elasticity of water demand to water pressure refers to the sensitivity of demand to changes in pressure (referred to by Van Zyl and Clayton 2007).

1.2.9 End-use

Jacobs (2004) defined end-use as a device or fixture where water is released from the pressurised water supply system to atmosphere.

1.2.10 Minimum Night Flow (MNF)

Minimum night flow (MNF) refers to the minimum flow for a DMA or a consumer and is normally measured between midnight and 04h00, when most consumers will be asleep, and can therefore be used as an indicator of leakage (McKenzie 1999).

1.2.11 Pressure Reducing Valve (PRV)

A pressure reducing valve (PRV) is a device used to lower water pressure to a set pressure.

1.2.12 Pressure Control Valve

According to SANS 10252-1 (2012), a pressure control valve is a PRV that incorporates an expansion control function.

1.2.13 Pressure Management

Pressure management refers to the procedure of reducing and regulating water pressure in a WDS.

1.2.14 Water Conservation and Water Demand Management (WC and WDM)

The Water Services Sector Strategy (DWAF 2004) defines Water Conservation (WC) and Water Demand Management (WDM) as follows:

- WC is the minimisation of water loss and the protection of water resources and the efficient use of water.
- WDM is the adaption and employment of a strategy to influence water demand in order to ensure sustainability of water supply sources and services.

1.3 METHODOLOGY

A quantitative research method was selected to test the impact of controlled pressure adjustments on consumer water demand. Full-scale field experiments were designed and implemented that involved recording flow and pressure data while controlled pressure step changes were implemented. For the field experiments three operational DMAs were identified based on selection criteria. The three DMAs were located in the City of Tshwane (formerly Pretoria). Data recording equipment was installed to record flow and pressure data for the three test DMAs as well as for 76 individual consumers in the same DMAs. Pressure step changes were implemented in each DMA and the recorded data was analysed by establishing the pressure-demand relationship for each test DMA, as well as for individual consumers.

1.4 PROBLEM STATEMENT

Pressure management, commonly employed as part of WC and WDM strategies, holds advantages such as reduced pipe burst frequency and reduced system input volume. Most of the earlier work on the topic focussed on the pressure-leakage relationship, infrastructure failure and system-wide use, where minimum night flows are typically assessed to determine the reduction in water leakage and losses. Few studies have been undertaken to investigate the pressure-demand relationship and even fewer studies have focussed on the pressure-demand relationship where leakage beyond the consumer meter was separately investigated or excluded.

1.5 AIMS AND OBJECTIVES

The aim of this study was to determine the effect of controlled pressure adjustments on consumer water demand (elasticity of demand to pressure). The following research objectives were set for this study:

- Conduct field experiments in three operational DMAs and determine the pressure-demand relationship.
- Test the practical limits of pressure reduction in the three selected DMAs.
- Develop an approach to estimate the demand component in the DMA with recorded flow data.

1.6 DELINEATION AND LIMITATIONS

A number of factors have been shown to influence residential consumer water demand in a WDS. In this study the focus is on the impact of pressure changes on residential consumer water demand, and the effect of other factors are beyond the scope of this research. The impact of changes in pressure on indoor versus outdoor end-uses was not investigated. The impact of pressure changes on non-residential consumers was excluded.

1.7 OVERVIEW OF CHAPTERS

This thesis comprises five chapters. Chapter 1 provides an introduction. Chapter 2 contains a literature review on the pressure-demand relationship and on related WC and WDM concepts. Chapter 3 provides an overview of the case studies that were undertaken. Chapter 4 describes the data analysis and discussion of results, and Chapter 5 presents concluding remarks.

2 LITERATURE REVIEW

2.1 FACTORS INFLUENCING RESIDENTIAL HOUSEHOLD WATER DEMAND

2.1.1 General

Factors affecting residential consumer water demand have been researched extensively (Aitken et al. 1994, Roberts 2005, Husselmann and Van Zyl 2006, Jacobs and Haarhoff 2007, Willis et al. 2009, Willis et al. 2013, Rathnayaka et al. 2014, Sebri 2014, Rathnayaka et al. 2015). Husselmann and Van Zyl (2006) investigated the effect of stand size and income on residential water demand for consumers in the Tshwane and Ekurhuleni metropolitan areas. The study investigated the independent effects of both stand size and stand value on water demand. The study found that water demand increases with increasing stand size and increasing stand value.

Jacobs and Haarhoff (2007) prioritised the numerous parameters influencing household water use at the end-use level, for typical South African consumers. People per household, toilet flush frequency, on-site leak volume, shower event volume and toilet flush volume were identified as the top five parameters influencing indoor water use. For outdoor use the top parameters found to influence demand was an irrigation factor for lawns and garden beds (ratio of actual irrigation to theoretical irrigation requirements), pan evaporation and surface area of the lawns.

Rathnayaka et al. (2015) studied the seasonal demand dynamics of residential water end-uses in Melbourne, Australia. Analysis on shower water use suggested that it is driven by weather and by behavioural factors.

2.1.2 Potential Factors Impacting on Short-Term Variation in Individual Consumer Water Demand

Most of the factors which can influence individual consumer water demand are not expected to vary significantly in the short-term (i.e. within days or weeks). A few of these factors which may however change in the short-term are summarised below.

2.1.2.1 On-Site Water Leakage

Data analysed in this thesis (Figure 13) showed that on-site leakages at consumers may increase or decrease within a short space of time and can therefore result in a short-term change in consumer demand. According to Jacobs and Haarhoff (2007) the third most significant parameter influencing indoor household water use is on-site leak volume (beyond the consumer meter).

2.1.2.2 Unpredictable Human Behaviour

Torriti (2014) reviewed time use models of residential electricity demand. It was found that unpredictable loads describe the major part of electricity consumption within a dwelling. Although the focus of that study was on electricity consumption, there may be similarities between energy- and water demand. Willis et al. (2009) reported that water demand can vary significantly between individual households and noticeably between socio-economic regions. Husselmann and Van Zyl (2006) commented on the unpredictability of water demand behaviour. Rathnayaka et al. (2015) commented that shower use is driven by behavioural factors in addition to weather. These comments show that water use can be influenced by unpredictable human behaviour, which can consequently result in short-term variation in consumer water demand.

2.1.2.3 Changes in Weather Parameters

Weather parameters can change quickly and can also impact on short-term changes in residential household water demand. Maidment and Miaou (1986) commented that the reaction of water use to rainfall depends firstly on the occurrence of rainfall and then on the magnitude thereof. The water use was studied in nine cities in three states in the USA. It was reported that the occurrence of rainfall of more than 1.3 mm/d caused a drop in the seasonal component of demand one day later, and the impact varied from one location to the next. It was also stated that there was a non-linear response of water use to air temperature changes, with no response for daily maximum air temperatures between 4° and 21°C, and an increase in water use with warmer temperatures.

Gato et al. (2007) found that residential water use was not affected by temperature changes at 15.3°C or below and rainfall of 4.8 mm or higher, based on a case study in Victoria, Australia. Sarker et al. (2013) determined the thresholds at which water demand is independent of temperature and rainfall. Data from Melbourne, Australia was analysed. The temperature threshold was found to be 15.5°C and the rainfall threshold as 4.1 mm. It was noted that at temperatures higher than 15.5°C, daily water use increases with temperature increases but below this threshold, daily water use seemed to be independent of temperature. It was noted that daily water use increases as the rainfall decreases, but above the threshold of 4.1 mm, any additional rainfall does not contribute to daily water use reduction.

2.1.2.4 Changes in Water Pressure

Van Zyl et al. (2003) commented that the impact of pressure on demand was likely to be small but noticeable, where reduced pressure should result in reduced consumer demand (excluding on-site leakages beyond the consumer meter).

Water pressure in a residential DMA will normally maintain a fairly consistent weekly profile if no changes in the DMA occur. If the DMA is however supplied through a pump or PRV it is possible for the pressures to change through adjustment or through malfunctioning of the equipment, and the change could be rapid. Additional information on the pressure-demand relationship is provided in Section 2.9.1.

2.2 IWA WATER BALANCE AND RELATED TERMINOLOGY

2.2.1 IWA Standard Water Balance

The Water Loss Specialist Group (WLSG) of the International Water Association (IWA) has developed a number of concepts to assist water utilities to manage their water losses. One of the key developments was the IWA volumetric water balance, which provides a breakdown of the system input volume into different components of consumption and water losses. The standard IWA water balance was modified by Seago and McKenzie (2007) for South African conditions, as shown in Figure 1. The preparation of a water balance is normally seen as one of the first tasks of any WC and WDM programme as it highlights the magnitude of Non-Revenue Water (NRW) and potential gaps and shortcomings in the water balance components. Terminology related to the IWA water balance (adapted from Seago and McKenzie 2007) is summarised below:

- System input volume (SIV) refers to the total volume of potable water supply into a WDS.
- Authorised consumption refers to the volume of authorised metered and authorised un-metered consumption for customers.
- Water loss consists of physical and commercial losses and is equal to the SIV less authorised consumption.
- Commercial loss (or apparent loss) refers to unauthorised consumption, meter errors and billing inaccuracies.
- Physical loss (or real loss) refers to the physical water loss from a WDS up to the customer meter and is equal to the total water loss less commercial loss. The physical loss can include overflow from storage reservoirs, leakage from water pipes and leakage upstream of the consumer supply connection.
- Non-Revenue Water (NRW) refers to the volume of water supplied by the utility for which no income is derived.

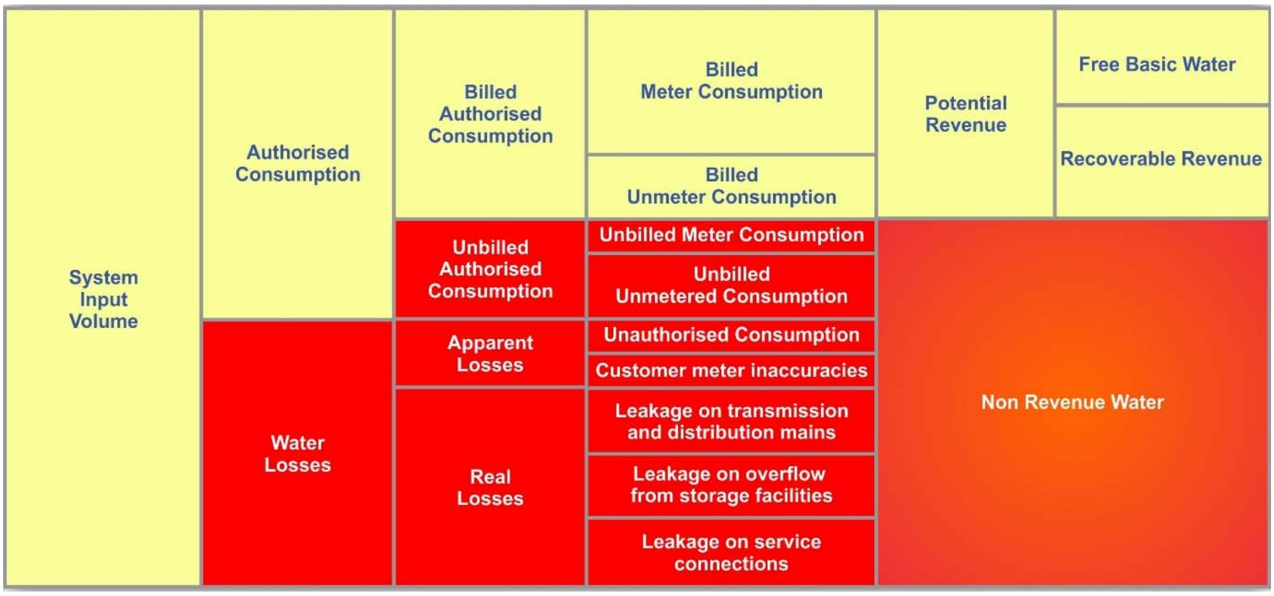

Figure 1: Modified IWA water balance for South Africa (Seago and McKenzie 2007)

2.2.2 District Metered Areas

The term district metered area (DMA) refers to a discrete portion of the water network with a defined and permanent boundary, for which all the inlet and outlet water pipes are metered (Farley 2001). The basic motivation behind implementing DMAs is to sectorise a potentially large WDS into smaller components (DMAs) where the water supply and water losses can be measured and managed separately in each DMA. An example of a typical DMA layout is provided in Figure 2. By analysing the losses and other leakage indicators in each DMA the water utility will be guided where WC and WDM efforts should be focussed. The requirement to sectorise WDSs and to measure the water supply and losses in each sector is also stipulated in Clause 11 of the *Regulations Relating to Compulsory National Standards and Measures to Conserve Water* (DWAF 2001).

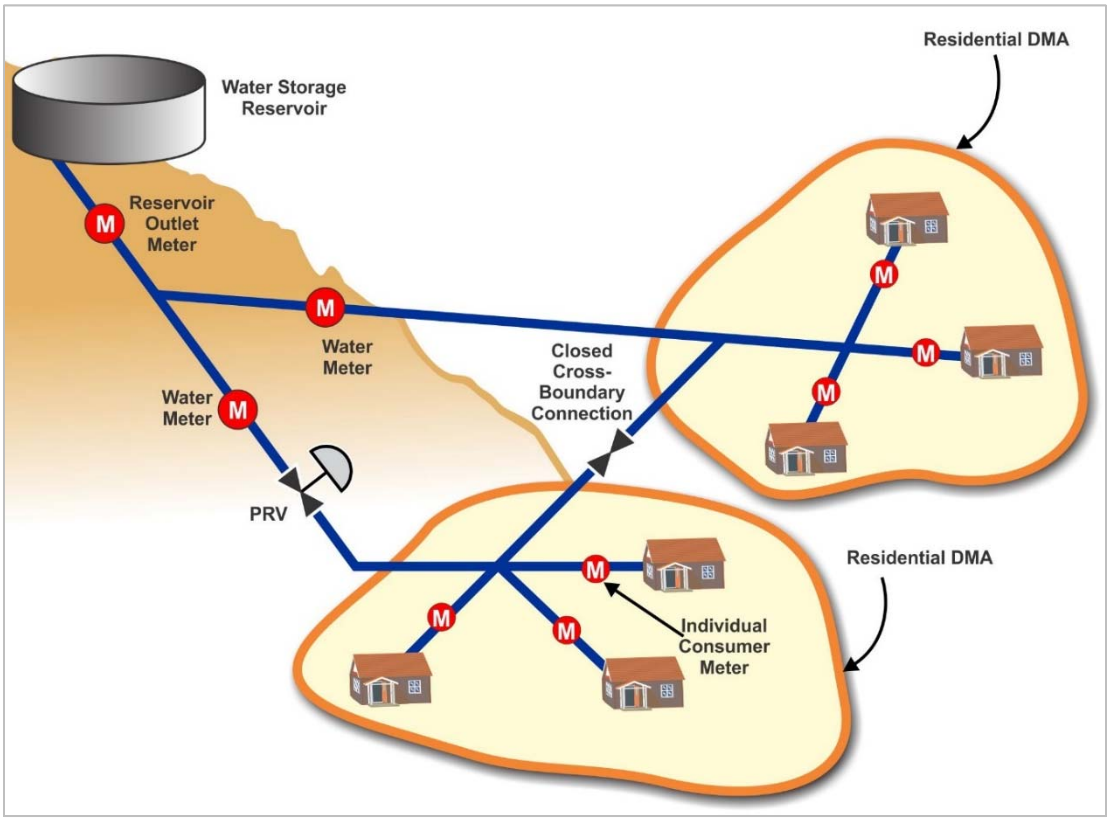

Figure 2: Example of a typical DMA layout

2.2.3 Minimum Night Flow (MNF)

According to McKenzie (1999) the minimum night flow (MNF) to a DMA is normally measured sometime between midnight and 04h00, when most consumers would be asleep, and can therefore be used as an indicator of leakage. McKenzie (1999) provided a detailed method to analyse minimum night flows which is based on the Burst and Background Estimate (BABE) procedure developed by the UK water industry (WRc, Report E). In this approach the MNF is considered to consist of three main components, namely: 1) legitimate night use, 2) background losses, and 3) unexplained leakage or burst leakage. The legitimate night use and background losses are calculated based on the standard BABE procedures and subtracted from the measured MNF, which then provides the unexplained or burst leakage component. The higher the unexplained or burst leakage component in a DMA the larger is the potential leakage problem.

McKenzie (2013) also provided a basic method for MNF analysis to determine whether the leakage in a DMA is significant or not. The method presented by McKenzie (2013) involves calculating the ratio of MNF to average flow, and where this ratio is above 20% there may be a leakage problem. Based on flow data obtained in this study, Figure 3 was prepared to show an example of MNF for a DMA and for an individual residential consumer in the same DMA. The graph shown in Figure 3 represents a time series flow profile of 96 h at intervals of 15 minutes.

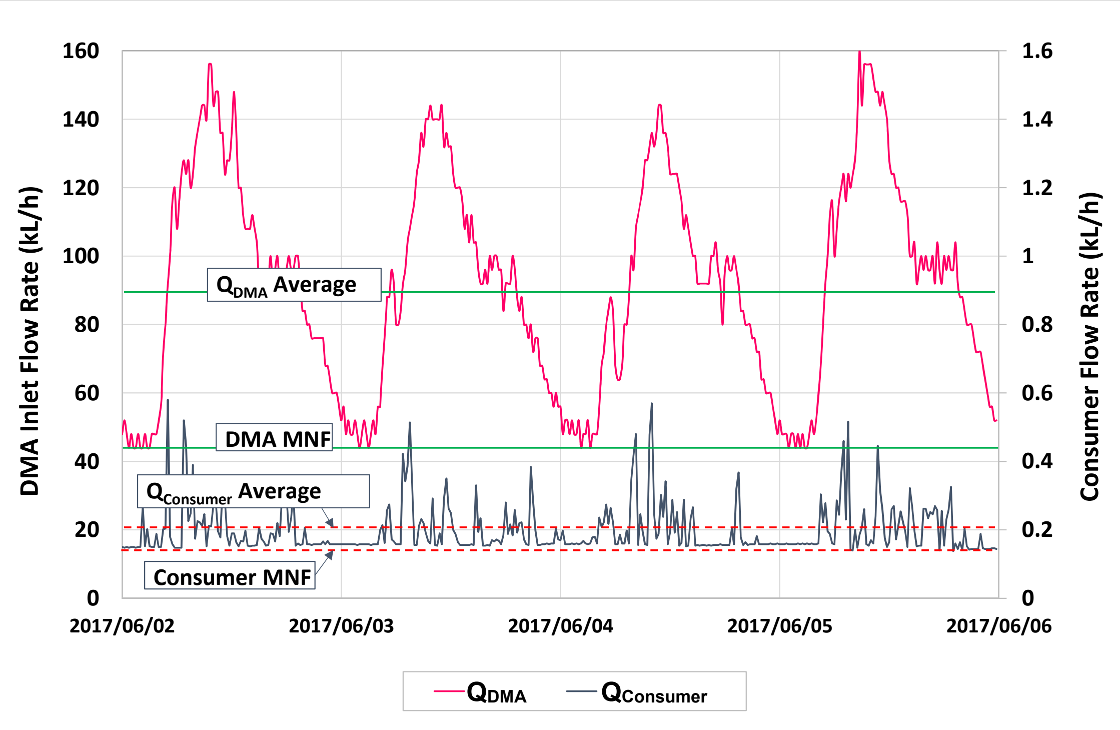

Figure 3: Time series flow profiles for a DMA and consumer in the same DMA

2.2.4 Physical Water Loss Reduction

A summary of some of the key concepts relating to analysis and reduction of physical water loss (developed by the IWA WLSP) is shown in this section.

2.2.4.1 Unavoidable Annual Real Loss (UARL)

According to Lambert et al. (1999) the Unavoidable Annual Real Loss (UARL) concerns the level of physical leakage (real losses) that cannot be avoided. Every water supply system will have some form of leakage and the UARL represents the lowest theoretical leakage for a particular system. The UARL equation is shown in (1).

$$UARL = (18\ Lm + 0.80\ Nc + 25\ Lp)\ h \qquad (1)$$

Where:

UARL = Unavoidable annual real losses (L/d);

Lm = Length of mains (km);

Nc = Number of service connections;

h = Average pressure head at average point (m);

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

According to McKenzie and Lambert (2002) the Lp component in (1) is only used in cases where the customer meter is further than 10 m away from the water main. In South Africa the customer meter is typically located at the property boundary and therefore the Lp component falls away. The UARL equation can then be simplified as:

$$UARL = (18\ Lm + 0.80\ Nc)\ h \quad (2)$$

2.2.4.2 Current Annual Real Losses

According to McKenzie and Lambert (2002) current annual real loss (CARL) refers to the real loss (physical leakage) for the period under consideration. CARL can be calculated from the following water balance components, as shown in Figure 1.

$$CARL = SIV - \text{Authorised Consumption} - \text{Commercial Losses} \quad (3)$$

2.2.4.3 Infrastructure Leakage Index

Lambert et al. (1999) defined the Infrastructure Leakage Index (ILI) as the ratio of CARL to UARL, shown in (4). The ILI is a dimensionless performance indicator for physical losses in a WDS. The theoretical lower limit of the ILI is one, and the higher the ILI the higher the expected physical losses. Using data from 2012, McKenzie et al. (2012) indicated that the ILI in South Africa ranged from 2 to 20 with an average of 6.8.

$$ILI = \frac{CARL}{UARL} \quad (4)$$

2.2.4.4 Key Leakage Management Activities

The IWA WLSP (Brothers 2003) identified four key leakage management activities to reduce physical water loss in a WDS. These initiatives are: 1) pressure management, 2) active leak control, 3) speed and quality of repairs, and 4) asset management and renewal of infrastructure (Figure 4). The pressure management initiative shown in Figure 4 has a double arrow because leakage can either increase or decrease depending on whether pressure is increased or reduced. Brothers (2003) recommends that a water utility should analyse the cost benefit for each of the four interventions to determine where the maximum benefit can be achieved.

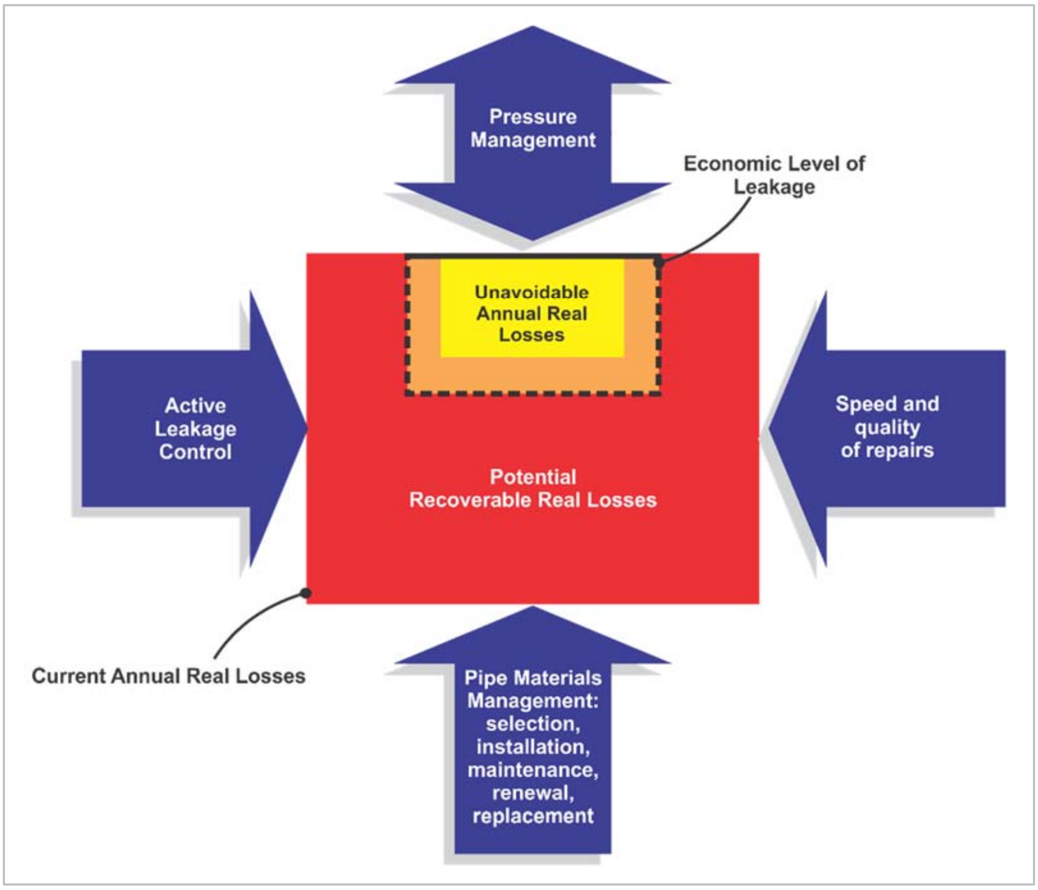

Figure 4: IWA WLSG leakage management activities (adapted from Brothers 2003)

2.3 PRESSURE-LEAKAGE AND PRESSURE-DEMAND RELATIONSHIPS

2.3.1 Theoretical Pressure-Leakage Relationship

The pressure-leakage relationship has been studied extensively over many years. A few of the prominent papers and publications on this topic are summarised in this section. Ledochowski (1956) presented one of the first papers on the pressure-leakage relationship in a WDS. He used (5) to express leakage flow rate through an orifice.

$$Q = C_d \, h^{N1} \tag{5}$$

Where:

Q = flow rate (m^3/s);

C_d = discharge coefficient (dimensionless);

h = pressure head (m);

N1 = leakage exponent (dimensionless).

May (1994) proposed the well-known Fixed and Variable Area Discharges (FAVAD) equation, which is often referred to by water loss practitioners. Cassa et al. (2010) proposed an equation for modelling the effect of pressure on an individual leak (6) which is similar to the FAVAD equation. May (1994) suggested that some leaks have fixed areas (exponent of 0.5) and others have variable areas (exponent of 1.5), while (6) assumes that all leaks have certain areas that vary linearly with pressure, and that it is only the extent of the variations that differs.

$$Q = C_d \sqrt{2g}\,(A_0\, h^{0.5} + m_a\, h^{1.5}) \qquad (6)$$

Where:

Q = flow rate (m^3/s);

h = pressure head (m);

A_0 = initial leak area at zero pressure (m^2);

m_a = the pressure-area slope (m);

C_d = discharge coefficient (dimensionless);

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

The UK water industry (Lambert 2002) adopted a generalised version of the FAVAD equation, which is popular with water loss practitioners for predicting the likely effect on leakage from changes in pressure, shown in (7).

$$Q_0 / Q_1 = (h_0 / h_1)^{N1} \qquad (7)$$

Where:

Q_0 = Initial leak flow rate (m^3/s);

Q_1 = New leak flow rate (m^3/s);

h_0 = Initial average pressure head (m);

h_1 = New average pressure head (m);

N1 = Leakage exponent (dimensionless).

Van Zyl et al. (2017) highlighted that the power equation (7) is an empirical equation and should only be used within its calibration pressure range. It was stated that C_d and N1 are not constant for any given system as they vary with pressure, and that substantial errors are possible if the power equation is extrapolated beyond the calibration pressure range or at high exponent values. Van Zyl et al. (2017) recommended to use the modified orifice equation (6) to describe the pressure-leakage relationship through leak openings.

Farley and Trow (2003) mentioned that the leakage exponent (N1) values determined from field studies can be significantly larger than 0.5 and typically vary between 0.5 and 2.79, with a mean value of 1.15. Wegelin (2015) calculated the N1 values for 23 DMAs in South Africa. The N1 for small DMAs (<1000 properties) was found to be closer to 1.0 while the N1 values for larger DMAs was closer to 0.5. Greyvenstein and Van Zyl (2007) performed a number of experimental studies on damaged pipes which were taken from the field in Johannesburg and on new pipes with artificially induced failures. The following N1 values were found:

- Asbestos-cement pipe with longitudinal crack: 0.78 – 1.04
- Steel and uPVC Pipe with round hole: 0.52
- uPVC pipe with longitudinal crack: 1.50 – 1.85
- uPVC pipe with circumferential crack: 0.40 – 0.52

2.3.2 Theoretical Pressure-Demand Relationship

A few studies have been dedicated to the pressure-demand relationship, some of which are summarised in this section. Van Zyl et al. (2003) reported on a water demand model which incorporated water price, household income, stand size and pressure as parameters. The impact of pressure on demand was noted to be small but noticeable. The theoretically estimated pressure-demand relationship was presented in graphs that showed that a 50% reduction in pressure could result in a reduction of consumer demand of between 10% and 16% for suburbs, and between 7% and 13% for townships (excluding the effect of pressure on on-site losses).

Van Zyl and Clayton (2007) commented that water demand cannot be classified as leakage, but it is often impossible to separate legitimate water demand from leakage measurements in the field. The effect of pressure on demand (Q_{dem}) was expressed as (8).

$$Q_{dem} = C\, h^{\beta} \qquad (8)$$

Where:

Q_{dem} = consumer water demand (m^3/s);

C = constant coefficient (dimensionless);

h = pressure head (m);

β = elasticity of demand to pressure (dimensionless).

Van Zyl and Clayton (2007) noted that there is a clear resemblance between equations for leakage and those for demand elasticity. It was mentioned that elasticity includes the effects of human behaviour, such as reacting to an increased pressure by opening taps less to obtain the same flow rate. It was noted that a higher exponent can be expected for outdoor use, although this exponent is unlikely to exceed 0.5. Koeller and Lalonde (2010) indicated that (7) can also be used to express the relationship between pressure head and consumption, but a different exponent N3 was used. It was concluded that for indoor use N3 tends towards zero and for outdoor use N3 is generally in the range 0.5 - 0.75.

2.4 PRESSURE STANDARDS IN WATER DISTRIBUTION SYSTEMS

Ghorbanian et al. (2016) summarised the minimum water pressure requirements for nine countries (Table 1). The minimum pressure requirement (excluding fire flow conditions) varies significantly from one country to the next, with 10 m in United Kingdom and Wales to 35 m in parts of Canada.

Table 1: Minimum pressure standards (adapted from Ghorbanian et al. 2016)

Region	Minimum Pressure Standard (m)	
	During fire flow	**During normal demand / maximum hourly demand / all conditions**
Canada		
British Columbia	14	28
Alberta	15	35
Saskatchewan	14	35
Halifax	15	28
Manitoba	14	28
USA		
Louisiana	-	10.5
Connecticut, Oklahoma, Delaware	14	17.5
Michigan	-	24.5
UK and Wales	-	10
Brazil	-	15
Australia	20	-
New Zealand	10	-
South Africa	-	24
Netherlands	-	20
Hong Kong	-	20

In South Africa the *Regulations Relating to Compulsory National Standards and Measures to Conserve Water* (DWAF 2001) stipulate that WDSs must be designed and maintained to operate below a maximum pressure of 90 m. The CSIR (2005) recommends a minimum pressure during peak demand of 24 m for residential areas in South Africa.

Strijdom et al. (in press) analysed hydraulic models for 71 South African towns and found that approximately 16.5% of modelled nodes experienced pressure heads below the design criterion of 24 m. It was also noted that a minimum pressure of 10 m is required to ensure effective operation of some household appliances and that the minimum pressure for South African systems could possibly be reduced in future once the benefits and implications of operating at lower pressures are better understood.

2.5 FLOW AND PRESSURE DATA RECORDING

According to Meyer and Seago (in press), data recording or data logging refers to the procedure of recording data at regular intervals using mechanical recorders or electronic devices, referred to as data recorders or data loggers. Flow recording is undertaken by connecting a data recorder with flow pulsar to a water meter, and pressure recording is undertaken by connecting a data recorder with pressure transducer to a suitable access point (fire hydrant, tap or pressure connection). Data on the recorders can be attained either through manual downloading or through remote transfer if the recorder is equipped with a global system for mobile communications (GSM) modem.

According to Westman (1990), digital flow data can be obtained by means of time-based or event-based methods. In both cases the connection between the water meter and the data recorder is similar but the method used to store the data varies. Time-based data recording works on the principle of counting the number of pulses in a fixed pre-determined interval, and since the value of a pulse is known (e.g. 1 kL/pulse), the total volume that has passed through the meter during each interval can be calculated. For event-based flow recording, the data recorder is triggered by the flow of water through the meter and the time between pulses is recorded. The flow rate can then be determined since the value of the triggering pulse is known. Both time- and event-based methods have advantages and disadvantages and in different situations one type may be preferred over the other. Time-based flow recording can typically be used where general flow profiles are required; and event-based flow recording can be used where specific events (such as peaks in the flow profile) are to be investigated.

2.6 PRESSURE MANAGEMENT

Pressure management is the procedure of lowering water pressure in a WDS to minimum acceptable levels that are in line with national and municipal guidelines. Typical pressure management methods and benefits are discussed in this section.

2.6.1 Pressure Management Methods

According to McKenzie (2014) water pressure in a distribution network can be reduced through a number of methods, each with its own advantages and disadvantages, as summarised below.

2.6.1.1 Fixed outlet pressure control

Fixed outlet control is the most common form of pressure control in a WDS and normally involves the use of a pressure reducing valve (PRV) to reduce pressures to a fixed level. The most common type of PRV in WDSs in South Africa is a diaphragm actuated hydraulic control valve. This type of PRV is normally fitted with a hydraulic control circuit which includes a spring-tensioned pressure reducing pilot valve. The PRV downstream pressure is altered by turning the adjusting nut on the pilot valve. The PRV set pressure is attained when the downstream pressure of the PRV creates an opening force inside the pilot valve that is equal to the closing force created by the tensioned pilot spring. The advantage of fixed outlet control is that the PRV downstream pressure is fixed and unaffected by changes in the flow rate and upstream pressure. Another benefit is that the upstream water pressure is used as an energy source to open and close the PRV and no other external energy source is required.

2.6.1.2 Advanced Pressure Control (Smart Pressure Control)

WDSs are normally designed for peak flows and PRVs are typically set to ensure sufficient pressure at the critical point (CP), during peak flow conditions. During off-peak periods pressures tend to increase, which means there is often scope for further pressure reduction during certain hours. In this regard, advanced pressure control options can be considered to regulate the pressure based on criteria such as the flow rate or time. These types of control methods involve the addition of an electronic or hydraulic device to the standard hydraulic control circuit of the PRV. The main benefit of such control methods compared to fixed outlet control is that, in certain cases, additional water savings can be achieved by further lowering of off-peak pressures. A disadvantage of such methods is that it adds complexity and cost to the pressure management solution; therefore such control methods should only be considered where the benefits outweigh the additional capital and maintenance expenditure.

A summary of some of the advanced pressure control options is shown below:

- Electronic time-modulated pressure control. This device regulates the PRV downstream pressure according to pre-set times and is typically used to reduce off-peak pressures. Certain models can vary the pressure only between two set pressures and other more expensive models can vary the pressure in multiple steps. The time-modulated option is normally the cheapest form of advanced pressure control and is also the easiest to install and operate. A potential disadvantage of time-modulated control is that it does not react to changes in flow, which could be problematic when the flow rate varies significantly during the day or from one day to the next or when higher pressure is required during fire-flow conditions.

- Electronic flow-modulated pressure control. This device regulates the PRV downstream pressure between a minimum and maximum limit according to changes in flow rate. A water meter is therefore required near the PRV that can be linked to the device. Flow-modulated control normally provides larger water savings than time-modulated control but the flow-modulated option is typically more expensive and more complex to install and operate than time-modulated control.

- Hydraulic flow-modulated pressure control. This type of system works in a similar manner to the electronic flow-modulated option but is hydraulically actuated. The benefit of such a device is that it requires no external power, but a potential limitation is that it provides less functionality than electronic devices and can sometimes be more difficult to commission.

- Electronic remote-node pressure control. In this method the PRV downstream pressure is regulated according to information received from a GSM pressure data recorder at the CP. Certain devices react continuously to live data from the CP while other models obtain the daily data from the CP, which is then used to automatically develop and update an optimal pressure profile for different times of the day and week. This method of control can normally yield the highest savings of any type of pressure control but it is also the most expensive and often more complicated to program and operate.

A number of software packages have been developed to analyse the potential water savings from implementing different forms of pressure management. Most of these packages use (7) as a basis to calculate the reduced leakage from pressure management. Examples of software packages include Presmac (McKenzie 2001), and Prescalc (Thornton and Lambert 2005).

2.6.2 Pressure Management Benefits

Pressure management has been documented to be fundamental in WC and WDM strategies (Gebhardt 1975; Bamezai and Lessick 2003; Girard and Stewart 2007). A number of studies and reports have highlighted the benefits of pressure management, a summary of which is provided below:

Reduced leakage
Numerous case studies confirmed that reduced pressure would result in reduced water leakage (Gebhardt 1975, McKenzie et al. 2004, Mckenzie and Wegelin 2005, Girard and Stewart 2007, Ghorbanian et al. 2017).

Reduced burst pipes
Studies by Lambert (2001), Gomes et al. (2011) and Martínez-Codina et al. (2015) confirmed that reduced pressure would result in reduced burst pipes.

Extended asset life
With reduced burst pipes the WDS is likely to last longer. Lambert and Thornton (2012) presented a method to estimate the extended life of a pipe through pressure management.

Improved level of customer service
With reduced burst pipes customers experience fewer water supply interruptions and there is less chance of water contamination during the pipe repair process. Pressure management may sometimes be perceived as an inconvenience for customers but interestingly, in a trial pressure management study by Girard and Stewart (2007) it was found that 82% did not notice a change to their water services.

Cost and Energy savings
Reduced pressure can result in reduced treatment and pumping costs. This was highlighted by Mckenzie et al. (2004) and Mckenzie & Wegelin (2005), which showed that pressure management can result in reduced pumping costs, reduced sewerage treatment costs, as well as the associated reduction in emissions. In some cases it has also been shown that pressure management resulted in the postponement of upgrading water/wastewater treatment plants (Mckenzie et al. 2004). Ghorbanian et al. (2017) commented that reduced energy consumption was estimated for two pressure management case studies. It was found that a 30% reduction in delivery pressure would decrease energy consumption by about 5.5% to 13%, and emissions by about 5.5% to 13%.

Reduced pressure dependent demand
The impact of pressure on demand is one of the benefits of pressure management that has been researched the least. Some of the studies that have been undertaken are discussed in Section 2.9.

2.7 PRESSURE DEPENDENT VERSUS PRESSURE INDEPENDENT END-USE

Certain leaks and water end-use components are influenced by pressure and are deemed pressure dependent, while other leaks and water end-use components are not influenced by pressure and are deemed pressure independent (McKenzie 2001). Consider for example two consumers using the same volume of water for personal cleansing, but one consumer uses a shower (demand would be pressure dependent) while the other likes to bath (demand would be pressure independent). Also, the leakage at one consumer may be caused by a malfunctioning toilet flush valve (pressure independent) while the leakage at a different consumer may be due to a leaking toilet inlet mechanism (pressure dependent). A summary of typical pressure dependent and pressure independent leaks and water end-uses is set out in Table 2.

Table 2: Pressure dependent versus pressure independent end-uses

	Pressure dependent	Pressure independent
High Water Usage	Garden irrigation, shower, toilet/urinal flushing mechanism (without cistern).	Filling of toilet cistern, running of bath water, kitchen appliances such as electric washing machine and dishwasher.
Low Water Usage	Water usage directly from taps.	Filling of container, bucket, or kettle.
Water Leaks	Leaks on pipes and fittings.	Leaks on toilet cistern flush valve.

Household plumbing systems at many suburban homes in South Africa are equipped with PRVs, which are often installed on the inlet pipes to hot water geysers. In terms of SANS 10252-1 (2012) *Water supply installations for buildings*: “If necessary, a pressure control valve shall be installed to reduce the incoming water pressure either to the working pressure of a water heater incorporated in the installation or to the maximum permissible pressure allowed in the installation. The pressure control valve shall be situated at a convenient position in the incoming cold water supply pipeline.” According to SANS 10252-1 (2012) a pressure control valve is a PRV that incorporates an expansion control function, where the expansion is caused by hot water. In some older suburbs, only the hot water household plumbing systems are pressure controlled, and in many newer areas both the hot and cold-water systems are pressure controlled. If the WDS pressure is reduced it is expected to affect only those household end-uses that are not on pressure controlled pipes, unless the network pressure is reduced below the household plumbing PRV setting.

2.8 ON-SITE LEAKAGE AT RESIDENTIAL PROPERTIES

A number of international studies have highlighted the extent of on-site leakage at consumer properties. The leakage as a percentage of total demand was in the range of 1 to 5.7% for Australia and New Zealand (Willis et al. 2009, Heinrich 2007, Roberts 2005) and in the range of 2.3 to 10.3% for USA and Canada (DeOreo et al. 1996, Mayer 1999, DeOreo 2001).

South African studies have shown that on-site leakage is typically higher than in developed countries. Lobanga et al. (2009) investigated the extent of non-compliant plumbing components used in South Africa and found that compliance is approximately 50%. It was mentioned that the level of non-compliance seemed to be particularly large in low-cost housing developments. McKenzie et al. (2002) reported on significant water savings achieved by repairing on-site leakage in low-income housing areas in the Rand Water area of supply. A study by Lugoma et al. (2012) found that on-site leakage for a sample of 182 properties in Johannesburg was 25% of the monthly household water demand, with an average leakage rate of 12 kL/month per residential property. Ncube and Taigbenu (2016) examined the water demand profiles and extent of on-site leakage in Johannesburg. A total of 408 properties comprising of residential, multi residential, business and public benefit properties were randomly selected and the flows recorded. A 63% occurrence of leakage was found within the sampled properties, with a weighted average contribution of 9 – 11% of night losses to the total water demand for multi-residential and residential properties respectively. These studies highlight that on-site leakage in many areas in South Africa constitutes a significant portion of residential water demand.

2.9 THE IMPACT OF PRESSURE ON CONSUMER WATER DEMAND

2.9.1 Pressure-Demand Relationship

Some of the available studies on the pressure-demand relationship is set out below:

Cullen (2004) tested the pressure-discharge relationship for six types of irrigation devices at different operating pressures and found that the discharge reduced with reduced pressure, and that flexible devices were more sensitive to pressure changes than rigid devices. The N1 pressure exponent in the pressure-discharge relationship (7) was found to be near 0.5 for rigid devices and near 0.75 for flexible devices.

Gebhardt (1975) investigated the relationship between pressure and total water demand (which included leakage) for various DMAs and large consumers in Johannesburg. He analysed the relationship using (5), developed by Ledochowski (1956). Since (5) was used to assess the data with a leakage exponent of 0.5 it was stated that a rise of 60% in pressure causes a 30% increase in demand in a residential township.

Bamezai & Lessick (2003) demonstrated that reduced water pressure can reduce residential demand, especially at properties where garden irrigation is common. In one test area a 17.6% reduction in pressure resulted in a decrease of 1.9% in the total domestic demand (equivalent to elasticity of demand to pressure of 0.11), and a decrease of 4.1% was reported for properties with larger gardens (equivalent to elasticity of demand to pressure of 0.24). In another test area the reduction in demand was negligible for a 6% reduction in pressure. The study did not investigate whether some of the consumers concerned had on-site leakage (beyond the consumer meter).

Bartlett (2004) investigated the water consumption patterns at student accommodation on the campus of University of Johannesburg and found that the indoor water demand reduced with reduced pressure. Based on a portion of the data analysed, the indoor demand elasticity to pressure was found to be approximately 0.2. This result was however not obtained for all the data analysed and for some of the data a meaningful demand elasticity for pressure could not be obtained.

The above-mentioned studies confirm that reduced system pressure should, amongst other effects, result in reduced consumer demand. None of the earlier studies, however, included flow recording for individual households while pressure adjustments were implemented and none investigated the role of on-site leakage in the pressure-demand relationship.

3 CASE STUDIES

3.1 DESCRIPTION OF THE STUDY SITE

The data analysed in this study was collected through three full-scale field experiments, conducted in three DMAs which form part of an operational WDS. All three DMAs were located in the City of Tshwane (formerly Pretoria), the administrative capital of South Africa. Tshwane is located in the Gauteng province in a summer rainfall region with relatively high summer temperatures and moderately cold, dry winters.

3.2 IMPLEMENTATION PROCEDURE

Step 1: Planning of field experiments.

Field experiments were planned to obtain pressure and flow data from an operational WDS while planned pressure step changes were being implemented. The field experiments were planned to include multiple pressure step changes and to gather data not only at the DMA level but also at individual consumers. The objective of the study was discussed with officials of the City of Tshwane, who gave permission that the tests could be undertaken in Tshwane. It was agreed that the pressure in the selected DMAs could be increased to the maximum available PRV setting (at which a constant PRV downstream pressure could be maintained) during the start of the test and then, through planned pressure step changes, gradually lowered by approximately 10 m with each step adjustment.

Step 2: Selection of case study areas.

Three DMAs in three different residential areas were identified, based on selection criteria referred to in Section 3.3. The three DMAs included a medium to high, medium and low-income area.

Step 3: Installation of pressure and flow recording equipment.

Pressure recording equipment was installed at the PRV and critical point of each DMA, and flow recording equipment was installed at the DMA inlet meter and at a sample of domestic consumer meters in each DMA. The data was recorded simultaneously at individual consumers and the DMA as a whole while the pressure in each DMA was being reduced.

Step 4: Pressure step changes.

Pressure step changes were implemented at the first study site, then repeated at the second and third study sites. The timing of the pressure step changes had to be scheduled, with consideration for minimum allowable pressures and possible consumer inconvenience during the experiments.

Step 5: Data analysis.

Finally, the recorded data was analysed. The results for individual consumers were compared with the results for the DMA to establish whether individual consumers and the DMA responded in a similar manner to the step pressure changes.

3.3 DMA SELECTION CRITERIA

The following criteria were used to select the DMAs for the field experiments:

- The DMAs had to be largely residential and supplied through a single metered connection fitted with a pressure reducing valve (PRV). DMAs with multiple supplies were avoided due to additional complexities involved to adjust and monitor the pressures at different supply points to a DMA.
- The pressurised potable supply to the consumers had to be uninterrupted, with no scheduled maintenance, and no intermittent supply problems. If the potable supply was intermittent it would have impacted on the recorded pressures and flows.
- Some of consumer meters in the DMA had to be equipped with a pulse output for flow recording and the meters had to be less than 10 years old (which were considered sufficiently accurate for flow measurement).
- The difference between the potential maximum and minimum PRV downstream pressure in the DMA had to differ by 30 m or more, which would allow for multiple pressure step changes between the maximum and minimum limits.
- The DMAs had to be confirmed as discrete (discussed in Section 3.4).
- The PRVs had to be operational and the outlet pressure had to be relatively constant (±2 m pressure variance on the PRV downstream pressure was considered acceptable). If the PRV had not been functioning properly it would not have been possible to implement the pressure step changes accurately.
- The pressure head loss in the DMA between the inlet and the CP had to be relatively low (less than 10 m head loss was considered acceptable). If the head loss and pressure fluctuation in a DMA was high it would have added additional complications since the time of day that certain demands occur would then have had to be taken into account.

Three DMAs meeting the above criteria were identified and are summarised in Table 3.

Table 3: Characteristics of selected DMAs (adapted from Meyer at al. submitted)

Description	DMA1	DMA2	DMA3
Average income of consumers	Medium to high	Low	Medium
Total plots/stands	1201	4683	923
Occupied plots/stands	1087	4558	866
Residential plots/stands according to municipal zoning code (expressed as a number and percentage of the occupied plots)	1025 (94%)	4547 (98%)	827 (95%)
Total length of water pipes in DMA (km)	±24	±45	±18
PRV elevation (m above sea level)	1460	1275	1475
Critical Point (CP) elevation (m above sea level).	1462	1280	1480
Lowest geographical point elevation (m above sea level)	1424	1218	1440

3.4 VERIFICATION OF DMA DISCRETENESS

It was important to confirm, prior to the field experiments, that the DMAs selected for field measurements were discrete. Any open cross-boundary connection would have potentially impacted on the recorded pressures and flows. In this regard, a number of checks were performed in each DMA.

3.4.1 DMA1

Two DMAs are located adjacent to DMA 1, one to the north and one to the south. Pressures were checked at several locations on both sides of the northern and southern boundaries of DMA1 and it was confirmed that the water pressures in DMA1 did not correspond to the pressures in the adjacent DMAs. The pressures on the DMA1 side of the boundary were generally 20 m to 30 m lower than the pressures in the adjacent DMAs. Furthermore, the operational personnel from the City of Tshwane in the past observed that the pressure in the northern DMA dropped to zero during planned maintenance, while the water pipes inside DMA1 remained pressurised.

3.4.2 DMA2

Two DMAs are located adjacent to DMA2, one to the west and one to the south. Pressures were checked on both sides of the western and southern boundaries of DMA2 and it was confirmed that the pressure in DMA2 did not correspond to the pressures in the adjacent DMAs. The pressures on the DMA2 side of the southern boundary were generally 15 m lower than the pressures in the southern DMA, and the pressures on the DMA2 side of the western boundary were generally 25 m higher than the pressures in the western DMA. The pressure checks revealed that the DMA boundary on site appeared to be slightly different to the DMA boundary shown on the drawings.

In order to verify that the correct DMA boundary was used for the study it was agreed with the City of Tshwane to undertake a pressure drop test. The pressure drop test involves temporarily closing the inlet to the DMA while continuously checking the pressures at various locations inside and outside the DMA. The drop test was planned and executed through liaison with the City of Tshwane. During the drop test pressure inside the DMA dropped significantly while the pressure in the western and southern DMAs remained unchanged, which confirmed that DMA2 was discrete.

3.4.3 DMA3

DMA3 is surrounded by one other DMA. Pressures were checked on all sides of the DMA3 boundary and it was confirmed that the pressures inside DMA3 did not correspond to the pressures in the adjacent DMA. The pressures on the DMA3 side of the southern boundary were generally 30 m lower than the pressures in the adjacent DMA.

The findings confirmed that all three DMAs were discrete, thus suitable for pressure adjustment and further research.

3.5 DATA RECORDING PLANNING

Flow recording was undertaken by connecting data recorders to consumer water meters and DMA inlet meters. Pressure recording was undertaken by connecting a pressure transducer and data recorder to a suitable access point (fire hydrant, tap or pressure connection). A summary of the network nodes identified for data recording is shown in Table 4. The equipment had to be installed and secured out of sight in the light of infrastructure vandalism and theft problems prevalent in South Africa (Zindoga et al. 2010).

Table 4: Summary of network nodes identified for data recording

Description	DMA1	DMA2	DMA 3
Bulk meter at DMA Inlet	200mm diameter Sensus WPD Meter	200mm diameter Sensus WPD Meter	250mm diameter Sensus WPD Main Meter (Isolated) 150mm diameter Sensus WPD by-pass Meter (Active)
PRV downstream pressure	200mm diameter Singer PRV	150mm diameter Bermad PRV	250mm diameter Bermad Main PRV (Isolated) 150mm diameter Bermad by-pass PRV (Active)
Pressure at CP	Pressure tapping on water main	Pressure tapping on water main	Pressure tapping on water main
Flow at a sample of consumers	16 x 220c Sensus domestic meters	28 x 220c Sensus domestic meters	32 x 220c Sensus domestic meters

The Technolog Cello4 (GSM type) data recorder was used to record pressure at the PRVs and critical points as well as the flow rate at DMA inlet meters. The data recorders at PRVs and bulk meters were placed inside subsurface chambers that housed the PRVs, and the recorders at the critical points were installed inside custom built chambers where a pressure tapping on the mains was provided by the City of Tshwane. The live recording data from the GSM data recorders was placed on a web-based monitoring system while the tests were being performed. This enabled the author and the municipality to monitor the flows and pressures continuously.

For flow recording at consumers the Technolog Metrolog (non-GSM type) data recorder was used. The data recorders at consumer meters were installed inside existing above-ground meter boxes and placed below the meters to decrease the possibility of theft. The data on the non-GSM recorders was downloaded to a computer after the exercise for subsequent analysis.

Flow data recorders were programmed for time-based recording using 15-minute intervals. For this study the average flow over selected periods was used, therefore it was considered appropriate to use time-based recording. The volumetric recording sensitivity was 0.5 L and 1000 L (1 kL) per pulse for the consumer meters and DMA bulk meters respectively.

3.6 SELECTION OF PROPERTIES AND INSTALLATION OF EQUIPMENT

The sample size for consumer flow recording was dictated by the availability of data recorders at the time of each field exercise. A total of 16 data recorders were used for consumer flow recording in DMA1, 28 for DMA2 and 32 for DMA3. One data recorder was installed per consumer connection and data was recorded at 15-minute intervals. In total, the pressure and flow data from 76 different homes in three different DMAs were analysed as part of this study, with measurements for 11 weeks in DMA1, 14 weeks in DMA2 and 13 weeks in DMA3. Despite the relatively large data set gathered as part of the field experiment, it was recognised that the consumer coverage was relatively poor, with data for 1.6%, 0.6% and 3.9% of all consumers in DMA1, DMA2 and DMA3 respectively being recorded. A larger sample size would have been preferable to ensure that results would be representative of the larger population.

A detailed map was created for each DMA that showed the contours and historical average annual daily demand (AADD) for each stand. Consumers were then selected to ensure a relatively even distribution between three demand categories (AADD based) and three pressure categories (contour based), as summarised in Table 5. The consumer meters concerned required a pulse output facility to connect to a data recorder, and therefore only certain types of water meters could be selected for flow recording. Since DMA2 is a low-income area, the individual consumer demand was generally lower than in DMA1 and DMA3 and, therefore, a higher proportion of the consumers in DMA2 were in the AADD ≤ 0.5 kL/d category. The contour and AADD information was obtained by interrogating the Infrastructure Management Query System (IMQS) that is used by the City of Tshwane to spatially display water network and water demand data.

The recording of flow data at individual consumers was a time-consuming process that involved the programming, installation, removing and downloading of recorders at 76 homes in the three DMAs. Since the recorders were placed below the consumer meters (i.e. inside the existing meter boxes) it meant that each consumer meter had to be carefully removed and re-installed with the installation and again with the removal of each data recorder. Numerous site visits had to be undertaken to install and remove the equipment and additional ad-hoc checks were performed during each recording exercise to ensure that the equipment was functioning properly.

During the installation of the equipment the number of selected consumers that appeared to have witnessed the installation of the data recorders was none, 4 and 3 for DMA1, DMA2 and DMA3 respectively. Consumers in the study sample were purposefully not informed about the field experiments and the research study in order to minimise consumer bias.

Table 5: Selection of consumers for flow recording

DMA	Ground level (GL) in m above sea level	No. of consumers with AADD (kL/d) in range		
		AADD ≤ 0.5	0.5 < AADD < 1.0	AADD ≥ 1.0
DMA 1 (16 data recorders)	GL ≤ 1440 m	1	3	2
	1440 m < GL < 1450 m	3	0	4
	GL ≥ 1450 m	1	1	1
DMA 2 (28 data recorders)	GL ≤ 1250 m	7	1	1
	1250m < GL < 1270 m	9	4	0
	GL ≥ 1470 m	5	0	1
DMA 3 (32 data recorders)	GL ≤ 1455 m	1	4	8
	1455m < GL < 1465 m	1	3	3
	GL ≥ 1465 m	4	4	4

3.7 CONTROLLED PRESSURE ADJUSTMENTS

The duration and intensity of each test had to be (i) long enough and notable enough to draw research conclusions and (ii) short enough not to upset the consumers who were subjected to undesirable reduced pressures, while unaware of the research conducted. At the same time pressure violations in terms of the criteria for minimum pressure at each consumer connection had to be prevented. Based on the findings presented in Section 2.4, a minimum system pressure head of 10m was targeted in each area.

3.7.1 DMA1

In DMA1 the field exercise was undertaken from 6 May 2016 to 23 July 2016. The pressure adjustments were implemented manually at predetermined times by adjusting the pilot valve on the PRV. The increments of pressure reduction ranged from 4 m to 13 m per step with the aim of achieving an adjustment of approximately 10 m per step. Five pressure adjustments were made, approximately one adjustment every 14 days (Periods 1 to 5).

The minimum peak-hour pressure at the CP was 52m in Period 1 (during the maximum pressure step) and ultimately reduced to 18m in Period 5 (during the minimum pressure step). When the CP pressure reached 18m, a number of low pressure complaints were reported via the municipality's normal consumer help line. The PRV setting at ~20m was maintained for the two-week period, but the intended further reduction to 10m was not completed in DMA1. The field experiment was terminated after Period 5.

3.7.2 DMA2

The field experiment in DMA2 was undertaken from 27 October 2016 to 31 January 2017. The PRV at DMA2 was equipped with a GSM enabled electronic control device. The required pressure adjustments were introduced remotely with the use of the electronic controller. The increments of pressure reduction ranged from 3 m to 10 m per step. Six pressure adjustments were made, approximately one adjustment every 14 days (Periods 1 to 6). The minimum peak-hour pressure at the CP was 40m in Period 1 (maximum pressure step) and 10m in Period 6 (minimum pressure step).

The municipality received four complaints of no-water during the test, but no complaints of low pressure were reported. According to data supplied by the municipality two of the no-water complaints were related to blockages at consumer meters and the other two were noted to be non-pressure related according to municipal staff.

3.7.3 DMA3

The field experiment in DMA3 was undertaken from 10 May 2017 to 6 August 2017. The PRV at DMA 3 was also equipped with a GSM enabled electronic control device which enabled remote pressure adjustments of the PRV. The increments of pressure reduction ranged from 4 m to 12 m per step. Six pressure adjustments were made, approximately one adjustment every 14 days (Periods 1 to 6). The minimum peak-hour pressure at the CP was 55m in Period 1 (maximum pressure step) and 14m in Period 6 (minimum pressure step).

When the CP pressure reached 14m, a low-pressure complaint was reported to the City of Tshwane. The complaint came from a multi-storey apartment building where no residual water pressure remained at the top floor of the building. After 6 days from the start of Period 6, at a PRV setting of ~21m, the City of Tshwane operational staff manually increased the setting of the PRV and the field experiment was terminated.

3.8 DMA PRESSURE AND FLOW DATA

The daily average pressures and daily average DMA flows were calculated from the 15-minute data and plotted in Figure 5 to Figure 7 for the three test DMAs respectively. The pressures shown include the PRV downstream and CP pressures and the flows include the daily average DMA inlet flow rates (Q_{DMA}) and the DMA minimum night flows (MNF). The small dots show the average daily pressure at the CP, which is slightly higher than the minimum pressure recorded during peak hour flow. The grey shaded areas on the figures represent the recording periods. The water supply to DMA1 was unexpectedly interrupted (19-20 May 2016) and the water network was re-charged on 21 May 2016. In this regard, the pressure and flow data over these three days were removed from the analysis and do not appear in Figure 5. The recording periods in DMA1 were selected to exclude 19 to 21 May 2016. The interruption and exclusion of data during this period was not considered to impact the results of the field experiment in DMA1, especially since the interruption occurred immediately prior to a step change in pressure.

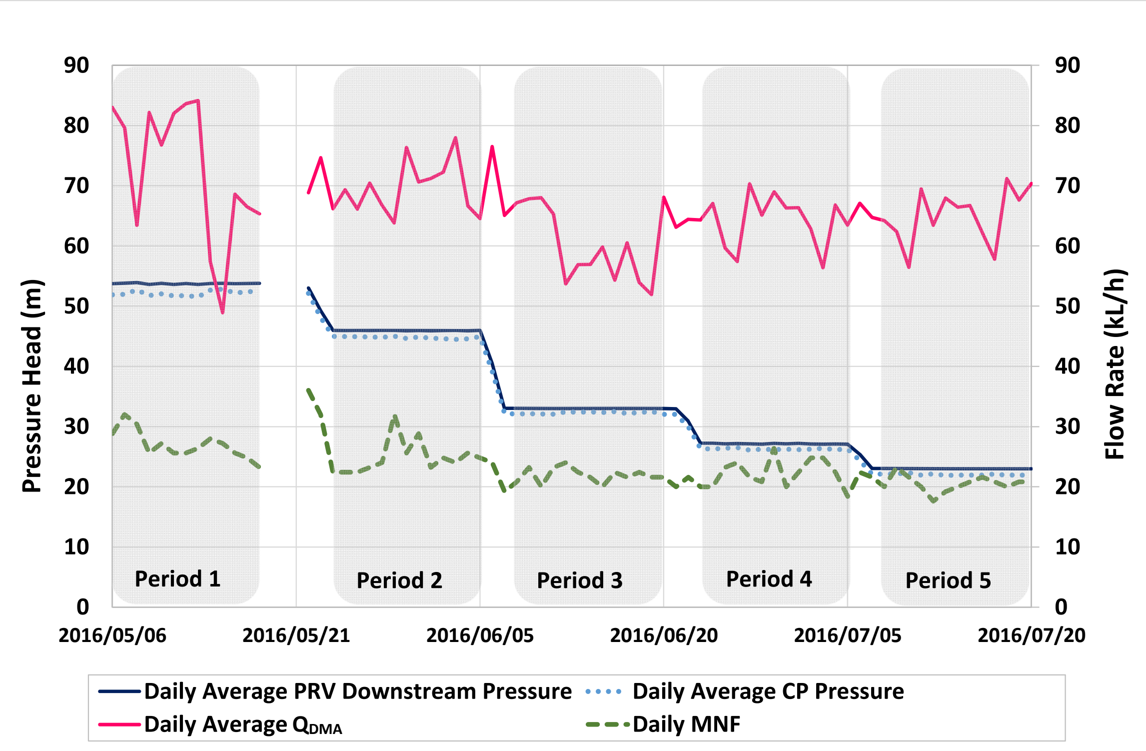

Figure 5: DMA1 time series pressure and flow profile (adapted from Meyer et al. submitted)

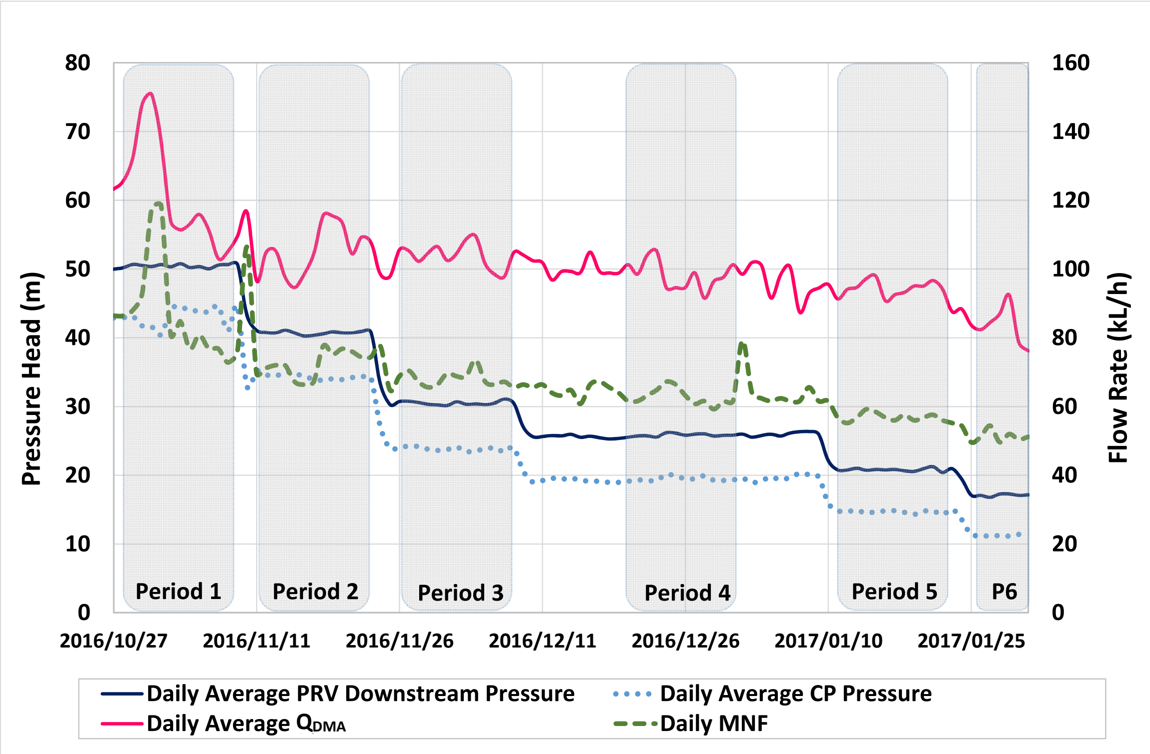

Figure 6: DMA2 time series pressure and flow profile (adapted from Meyer et al. submitted)

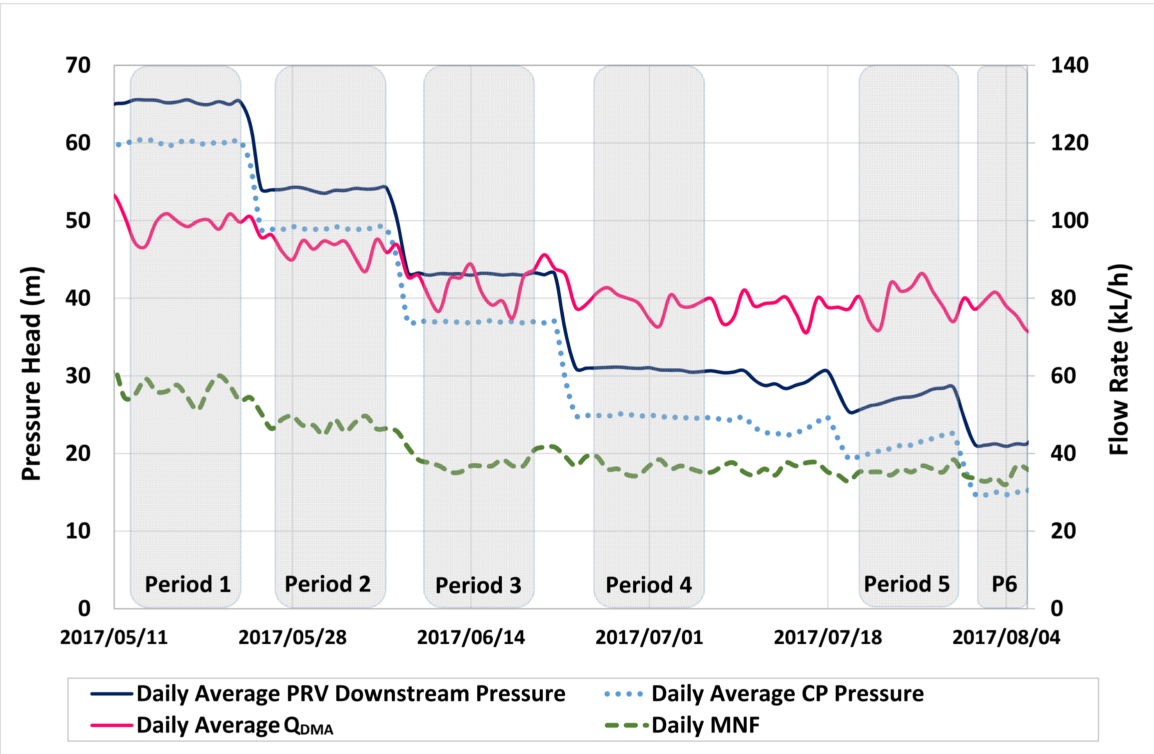

Figure 7: DMA3 time series pressure and flow profile

Figures 5 to 7 show that for all three test DMAs the PRV downstream pressure and critical point pressure reduced, with each test period. In DMA2 and DMA3 the Q_{DMA} and MNF reduced with reduced pressure in each period. In DMA1 the Q_{DMA} reduced from Period 1 to 3, after which Q_{DMA} increased slightly from Period 3 to 5. This was likely caused by increased garden irrigation, which is common for high income areas in the latter part of the dry season. The MNF in DMA1 reduced with reduced pressure. The Q_{DMA} in DMA1 showed unforeseen reduction for a few days in Period 1 and again in Period 3 and this coincides with a similar reduction in Q_{DMA} for a control area where the pressure was kept constant (Section 4.2). This suggests that weather related parameters such as rainfall and temperature could have impacted on the recorded flow in DMA1.

In Figure 8 to Figure 10 the average Q_{DMA} and MNF were calculated for each period and plotted against the corresponding average pressure head in the DMA, for the same period. The MNF represents the combined physical leakage at a WDS and consumer level, as well as a small component of legitimate night usage at consumers (McKenzie 1999). A basic but useful approach is proposed to estimate the demand component (Q_{dem}) in each period, as shown in (9).

$$Q_{dem} = (\text{Average } Q_{DMA} - \text{Average MNF}) + \text{Legitimate Night Usage} \tag{9}$$

Parameter Q_{dem} represents the actual demand for the DMA in a specific time period which excludes physical leakage in the WDS and at consumers. The legitimate night usage in a residential DMA can be calculated but is expected to be small and mainly due to toilet use (McKenzie 1999), which is also pressure independent (refer to Table 2). The legitimate night usage component in the residential DMAs should therefore remain constant under pressure changes and should not contribute to any variance in Q_{dem}. In this regard, the Q_{dem} calculation for a residential DMA was simplified to exclude legitimate night usage, as shown in (10). Q_{dem} values were plotted in Figure 8 to Figure 10.

$$Q_{dem} = \text{Average } Q_{DMA} - \text{Average MNF} \tag{10}$$

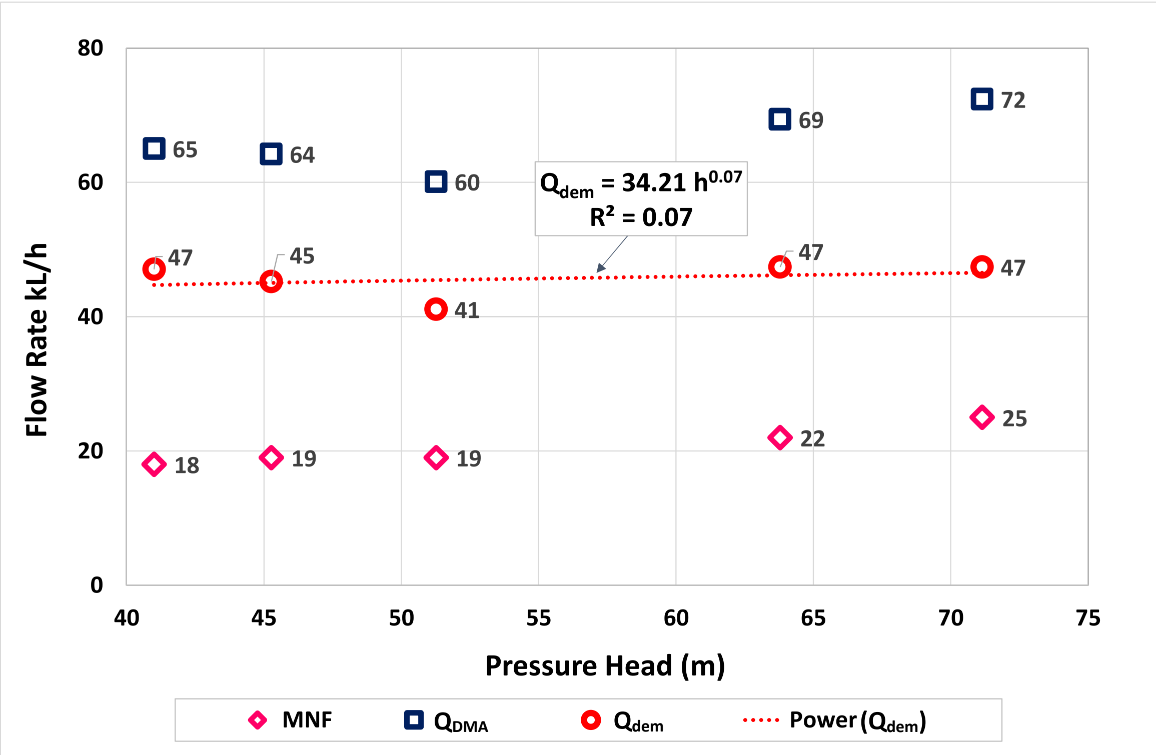

Figure 8 : DMA1 Q_{DMA}, MNF and Q_{dem} versus pressure head

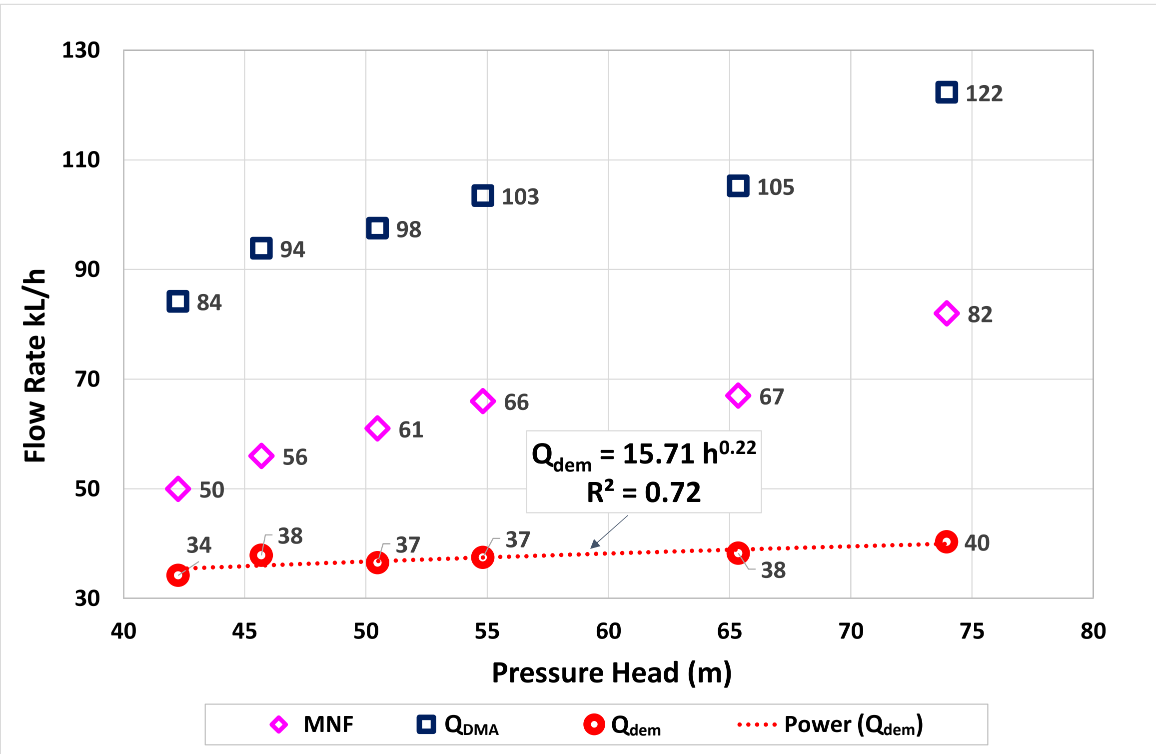

Figure 9: DMA2 Q_{DMA}, MNF and Q_{dem} versus pressure head

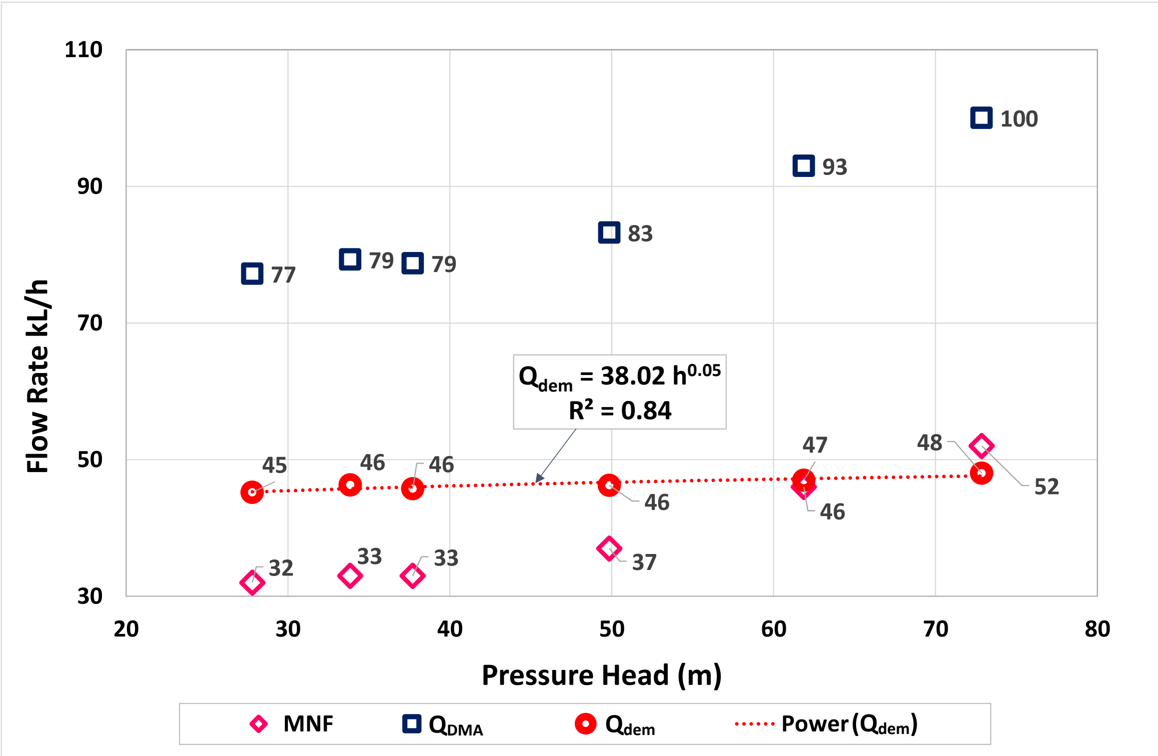

Figure 10: DMA3 Q_{DMA}, MNF and Q_{dem} versus pressure head

Figures 8 to 10 show that Q_{DMA}, MNF and Q_{dem} generally reduced with reduced pressure. The impact of pressure changes on Q_{dem} does however seem to be small. Trend lines based on power regression equations were fitted to the Q_{dem} values on Figure 8 to Figure 10**.** The trend lines indicate the approximate pressure-demand relationship for the particular cases in question and do not take into account the potential role of other external factors on consumer demand. A summary of the trend lines is shown in Table 6. The coefficient of determination (R^2) was significantly lower for the trend line in DMA1 (0.07) than for DMA2 (0.72) and DMA3 (0.84).

Table 6: Summary of trend lines shown on Figure 8 to Figure 10

DMA	Equation	R^2	β
DMA1	$Q_{dem}= 43.2\ h^{0.07}$ (11)	0.07	0.07
DMA2	$Q_{dem}= 15.7\ h^{0.22}$ (12)	0.72	0.22
DMA3	$Q_{dem}= 38.0\ h^{0.05}$ (13)	0.84	0.05

3.9 CONSUMER FLOW DATA

3.9.1 Consumer Data Filtering

3.9.1.1 Pre-Analysis Data Filtering

In DMA3 the datasets for four consumers were excluded from the analysis. Three of the four consumer flow datasets had large gaps which occurred when problems were experienced with downloading of the flow recorders. Due to the large gaps it would not have been possible to calculate representative average flows for each period and in this regard the three datasets were excluded. The fourth consumer had an un-metered connection, which was noticed when the recording device was removed. The consumer did not use the metered connection on a daily basis and it was considered appropriate to exclude the data from this consumer in the analysis. Out of a total 76 consumer flow records 72 were further analysed.

3.9.1.2 Consumer Minimum Night Flow (MNF) Analysis

A significant MNF was recorded at a number of the consumers. It is not unusual for properties to experience genuine night usage of around 2 L/h in a specific hour (Farley 2001), and in some cases the MNF could increase even higher for short periods as a result of garden irrigation with automatic sprinklers. However, if the MNF remains high for long periods it will normally be an indication of leakage. For the purposes of this study the consumer MNF was defined as the steady minimum flow for a property over a period of five consecutive days or more. The method for estimating the consumer MNF involved calculating the average flow for each consumer between 1:00 and 2:00 for each 24 h interval, and filtering the data to determine if the MNF (as per Table 7 categories) was experienced for five consecutive days or more.

Table 7: Consumers per MNF category (adapted from Meyer et al. submitted)

DMA	**Consumers per MNF category (L/h)**			**Total**
	None or Low MNF ≤ 5	**Medium** 5 < MNF < 15	**High** MNF ≥ 15	
DMA 1	8	5	3	**16**
DMA 2	20	5	3	**28**
DMA 3	19	4	5	**28**
Total	**47**	**14**	**11**	**72**

3.9.1.3 Post MNF Analysis Data Filtering

The consumer MNF evaluation and filtering was conducted after obtaining initial results, so that the impact on the results for each potential exclusion could be carefully considered. The flow data for the 11 consumers with a high MNF (≥ 15 L/h in Table 7) was further examined to decide whether the data for these consumers should be included or excluded in the consumer demand analysis. The criteria selected for excluding a consumer was based on the MNF increasing consistently over the study period, which suggested that the MNF was caused by pressure independent factors (most likely leakage). In summary:

- For three consumers (one in DMA1 and two in DMA2) the MNF increased consistently during the study period while the pressure was reduced, and it was subsequently decided to exclude the data for the three consumers from the analysis. The MNF at the three consumers increased by a factor of 1.5, 4 and 5 from the start to end of the recording period. An example showing increase in MNF for one of these consumers in DMA2 is shown in Figure 11. The hourly average flow rate for a consumer ($Q_{consumer}$) and the PRV downstream pressure for the DMA are shown.
- Eight consumers with a high MNF that were not filtered out experienced a high MNF either for certain weeks or throughout the logging period, but the MNF did not increase consistently over time and therefore the data for these consumers was included in the analysis. Sudden changes in MNF at some consumers, which did not correspond to changes in pressure, highlighted the potential impact of leakages in altering the consumer demand in the short-term. Examples showing a stable consumer MNF and fluctuating consumer MNF are shown in Figure 12 and Figure 13 respectively.

The data for three consumers with increasing MNF were excluded and the 69 remaining consumer flow records (15 in DMA1, 26 in DMA2 and 28 in DMA3) were analysed in the remainder of the study.

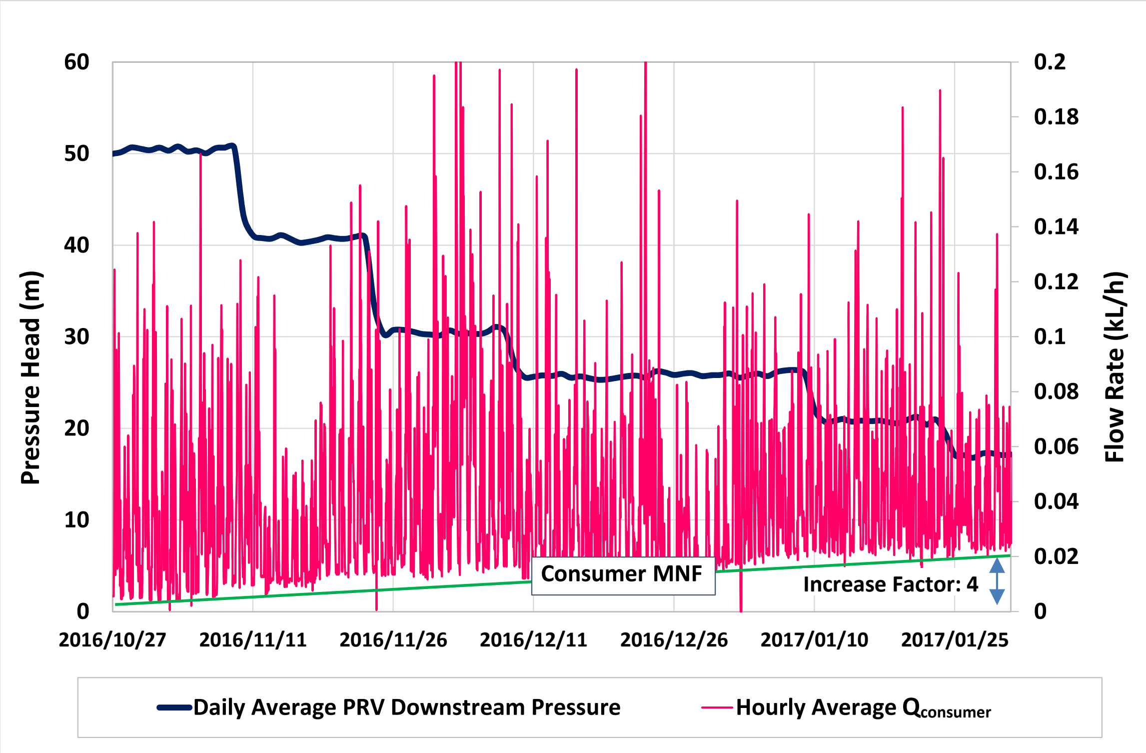

Figure 11: Consumer MNF in DMA2, showing increased MNF with decreased pressure

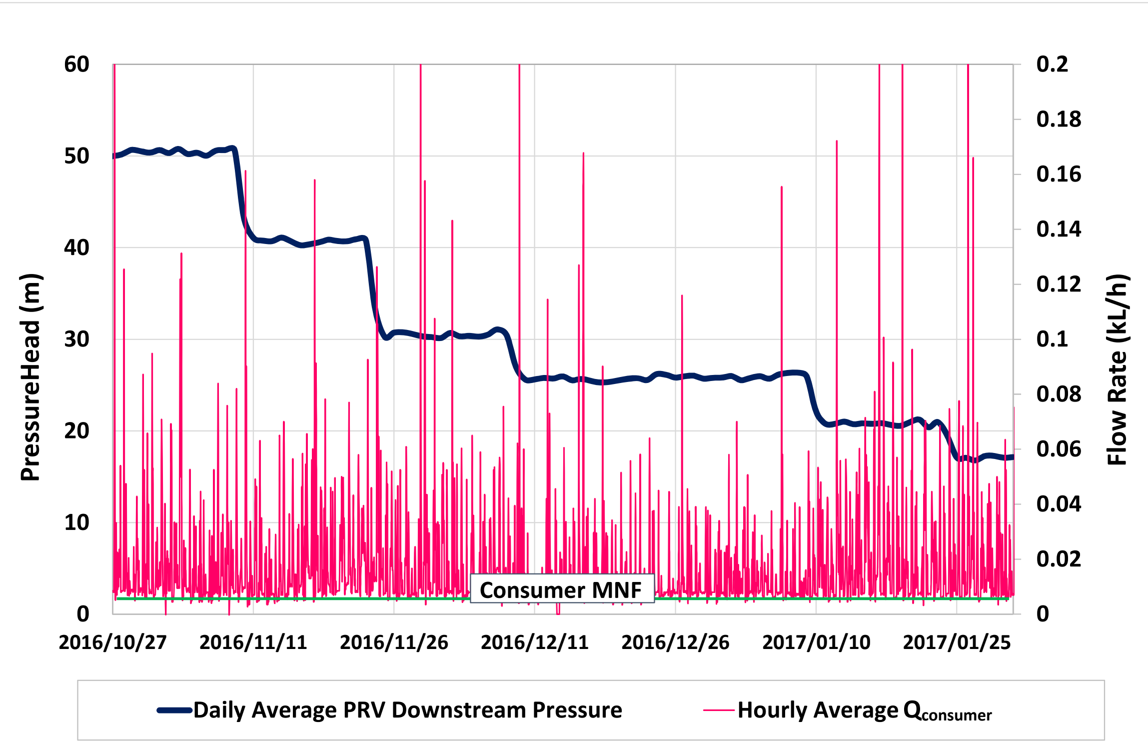

Figure 12: Consumer MNF in DMA2, showing stable MNF with decreased pressure

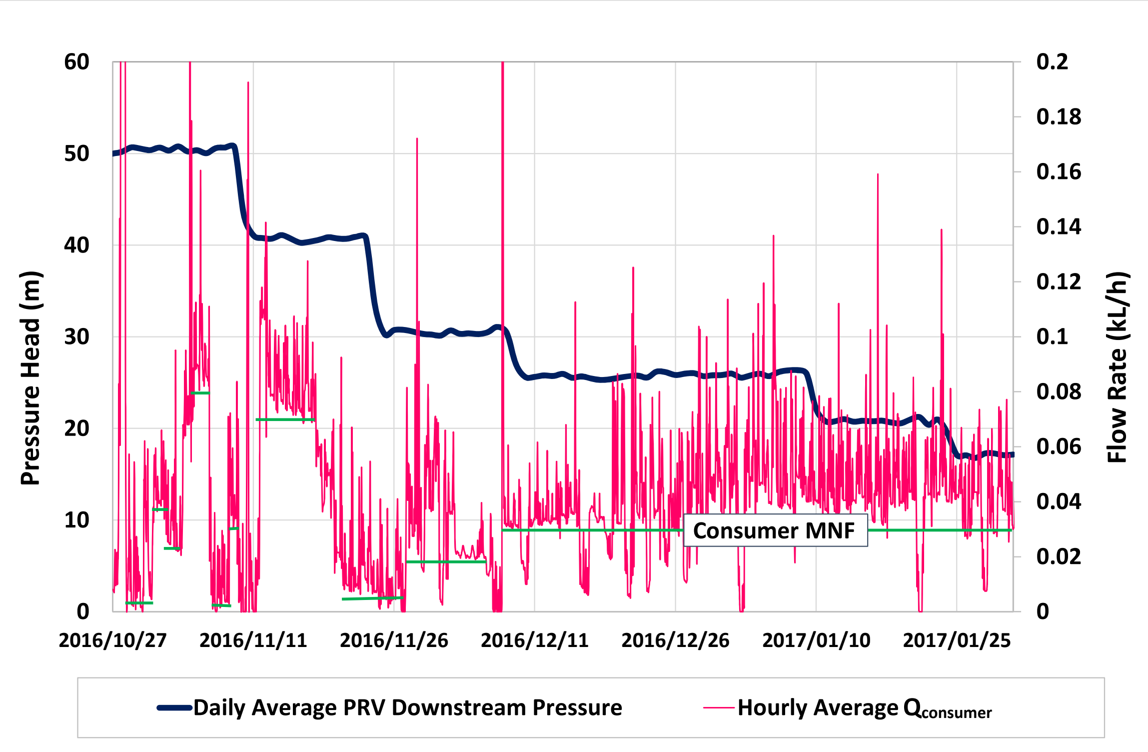

Figure 13: Consumer MNF in DMA2, showing fluctuating MNF with decreased pressure

3.9.2 Individual Consumer Flow Data

A number of different methods were evaluated to best display the recorded flow data for individual consumers. The method selected involved plotting the change in water demand versus the change in pressure during each period, for each consumer separately. The results for the three DMAs are shown in Figure 14 to Figure 16. The average values in each period, were also calculated and plotted, indicated by the larger red circles in each figure.

An explanation of the data series in Figure 14 to Figure 16 is provided below:

- Individual consumer demand (Q): Using the average individual consumer demand from Period 1 as the base, the percentage change in average individual consumer demand (ΔQ) was calculated for each of Period 2 to Period 5 in DMA1, and Period 2 to Period 6 in DMA2 and DMA3. Parameter ΔQ was plotted against the percentage change in pressure at each individual consumer. The pressure at each consumer was determined using the recorded pressure data from the CP and the ground elevations of the various consumers.
- Average consumer demand (Average Q): Using the average demand (of the recorded consumers) from Period 1 as the base, the percentage change in average consumer demand was calculated for each period. The Average ΔQ was plotted against the average pressure head in the DMA.

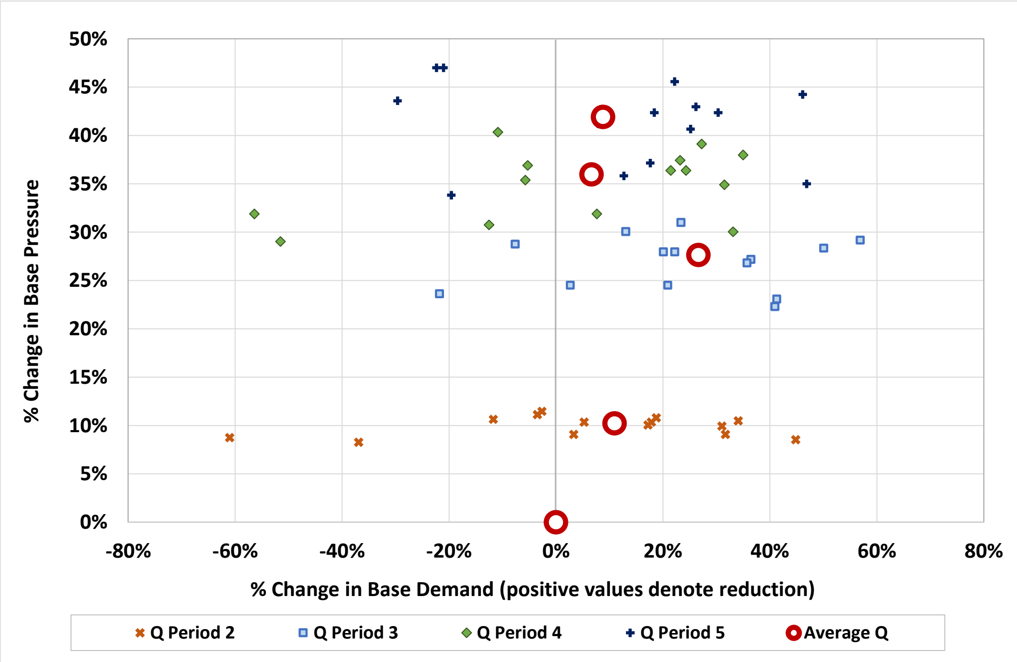

Figure 14: DMA1 Change in pressure versus change in consumer demand (adapted from Meyer et al. submitted)

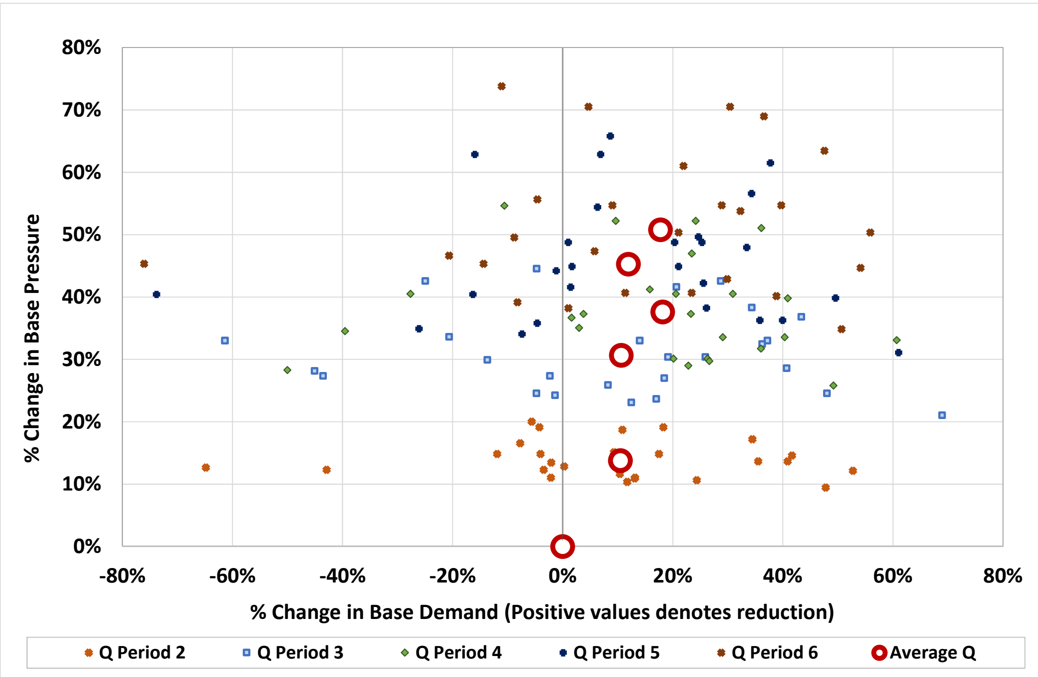

Figure 15: DMA2 Change in pressure versus change in consumer demand (adapted from Meyer et al. submitted)

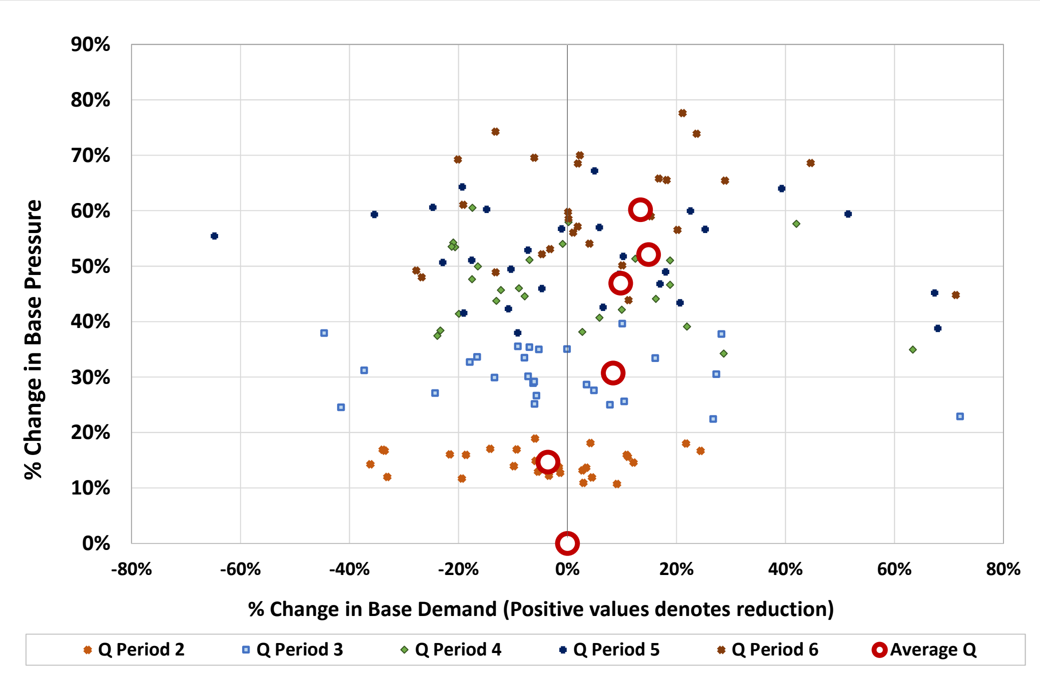

Figure 16: DMA3 Change in pressure versus change in consumer demand

The average values in Figure 14 to Figure 16 generally show reduced consumer demand (Q) with reduced pressure. A wide ∆Q-range is however apparent for individual consumers, with all three figures including values recorded in the -80% to +80% range on the x-axis. In DMA1 the maximum ∆Q in the used data set was -176% and in DMA3 it was -110%. All values for DMA2 plotted in -80% to +80% range on the x-axis. It was considered appropriate to list the outliers in DMA1 and DMA3 instead of increasing the x-axis bounds to show those values:

- In DMA1 two consumers reported values outside the 80% bounds in the ∆Q-range. Consumer 1 reported three values outside the bounds (-124%, -86% and -137%) and for consumer 2 one value exceeded the axis-limits (-176%).
- In DMA3 two consumers reported values outside the 80% bounds in the ∆Q-range. Consumer 1 reported two values outside the bounds (-87% and -110%) and for consumer 2 one value exceeded the axis-limits (-88%).

Despite careful investigation, no grounds could be found to exclude these four consumers from the dataset and all four were included in the analysis. In order to evaluate the role of potential on-site leakage in the pressure-demand relationship, the data was re-filtered to exclude the data for consumers with medium or high MNF, as per Table 7. The number of consumer datasets which were excluded during the re-filtering were 8, 8 and 9 for DMA1, DMA2 and DMA3 respectively. Using the re-filtered data, additional graphs were prepared as shown in Figure 17 to Figure 19.

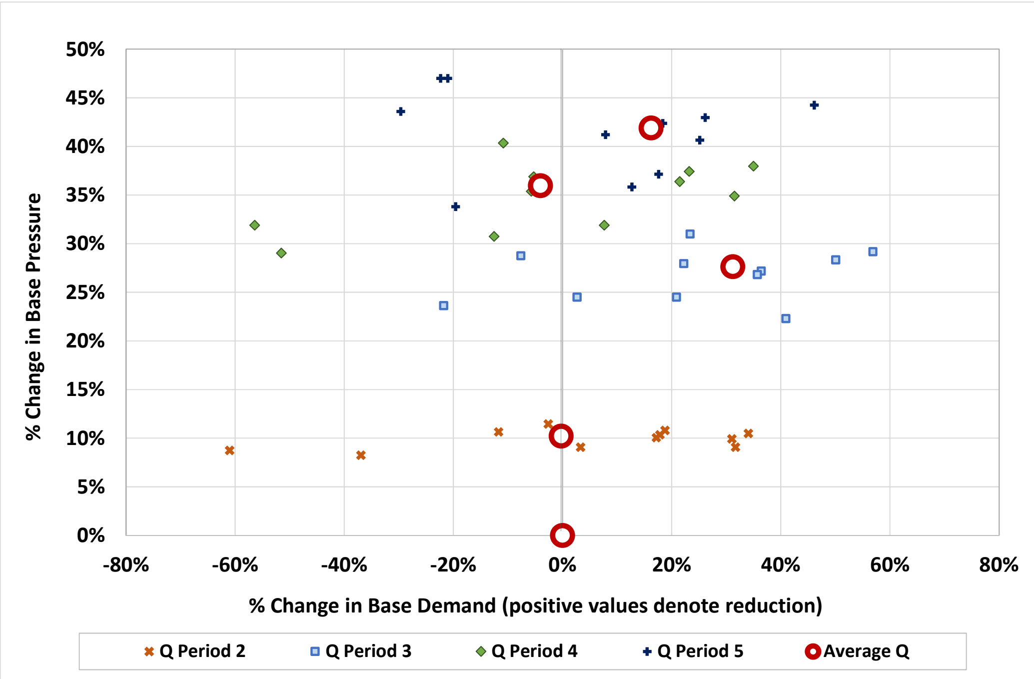

Figure 17: DMA1 Change in pressure versus change in consumer demand

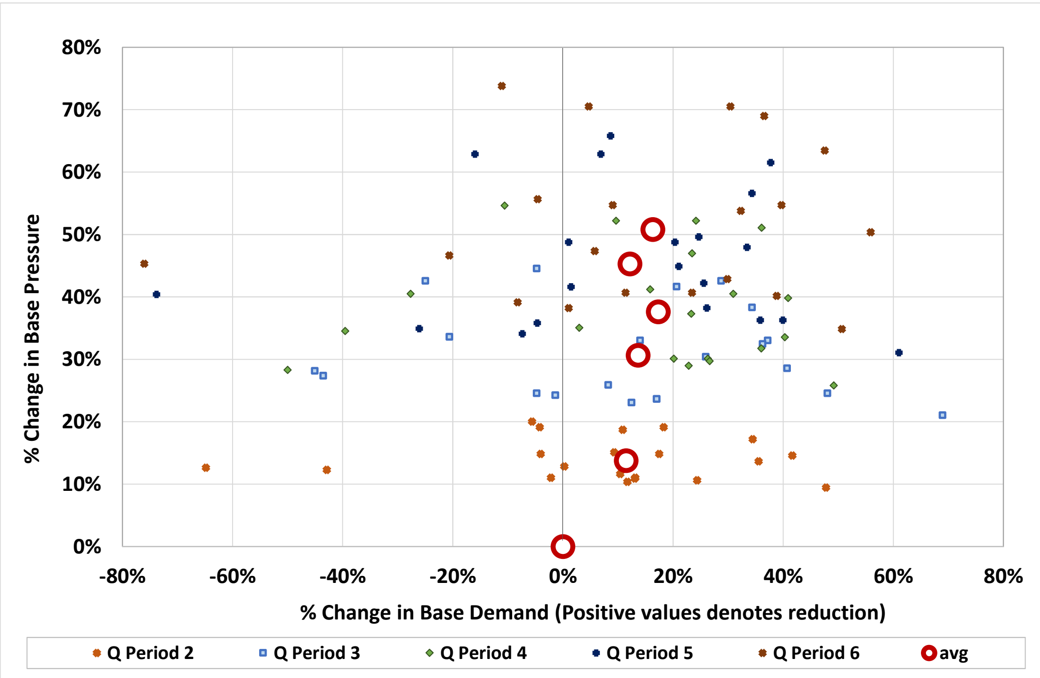

Figure 18: DMA2 Change in pressure versus change in consumer demand

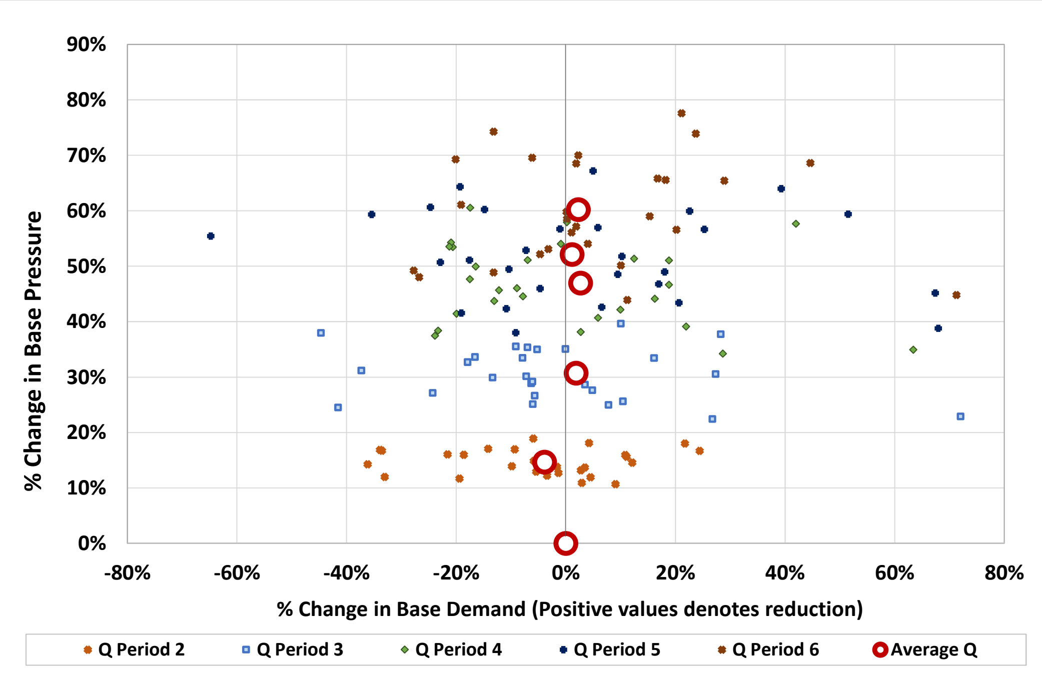

Figure 19: DMA3 Change in pressure versus change in consumer demand

When the consumers with medium or high MNF were filtered out the average ΔQ values for DMA1 and DMA3 did not show a noticeable reduction with reduced pressure (Figure 17 and Figure 19). In DMA2 the average ΔQ values did, however, show a reduction with reduced pressure after the properties with medium or high MNF were filtered out (Figure 18).

3.9.2.1 Re-Filtering of Individual Consumer Data

The individual consumer data for DMA1 and DMA2 was further re-filtered and analysed in order to identify if potential outlier events were contributing towards the wide ΔQ-range, visible in Figure 14 and Figure 15. The re-filtering procedure included:

- Option 1: Filtering out data for 24 h intervals with zero demand;
- Option 2: Filtering out data for 24 h intervals where the demand was higher than 5 times the average daily demand over the entire field exercise;
- Option 3: Filtering out data for the single highest and single lowest 24 h intervals in each recording period;
- Option 4: Filtering out data for the two highest and two lowest 24 h intervals in each recording period;
- Option 5: Filtering out the data for 24h intervals that fell outside the 95 percentile daily average demand over the entire field exercise.

The re-filtering of data in Option 1 to Option 5 was a time-consuming process that revealed after analysis that a wide ΔQ-range remained visible with each re-filtering option. The outcome of the data re-filtering suggests that the wide ΔQ-range was not caused by a few potential outlier events and the re-filtered data was not used in any further analysis.

3.9.3 Average Consumer Flow Graphs

In order to compare the flow data for individual consumers with the flow data for the DMA the average consumer water demand in each period was calculated and plotted against the corresponding pressure head, as shown in Figure 20 to Figure 22. The average consumer demand was calculated using three datasets for each DMA, as summarised below:

- $Q_{dem\text{-}c1}$ = Average demand for all individual consumers in used dataset.
- $Q_{dem\text{-}c2}$ = Average demand for individual consumers in used dataset, excluding consumers where high MNF was recorded as per Table 7.
- $Q_{dem\text{-}c3}$ = Average demand for all individual consumers in used dataset, excluding consumers where medium or high MNF was recorded as per Table 7.

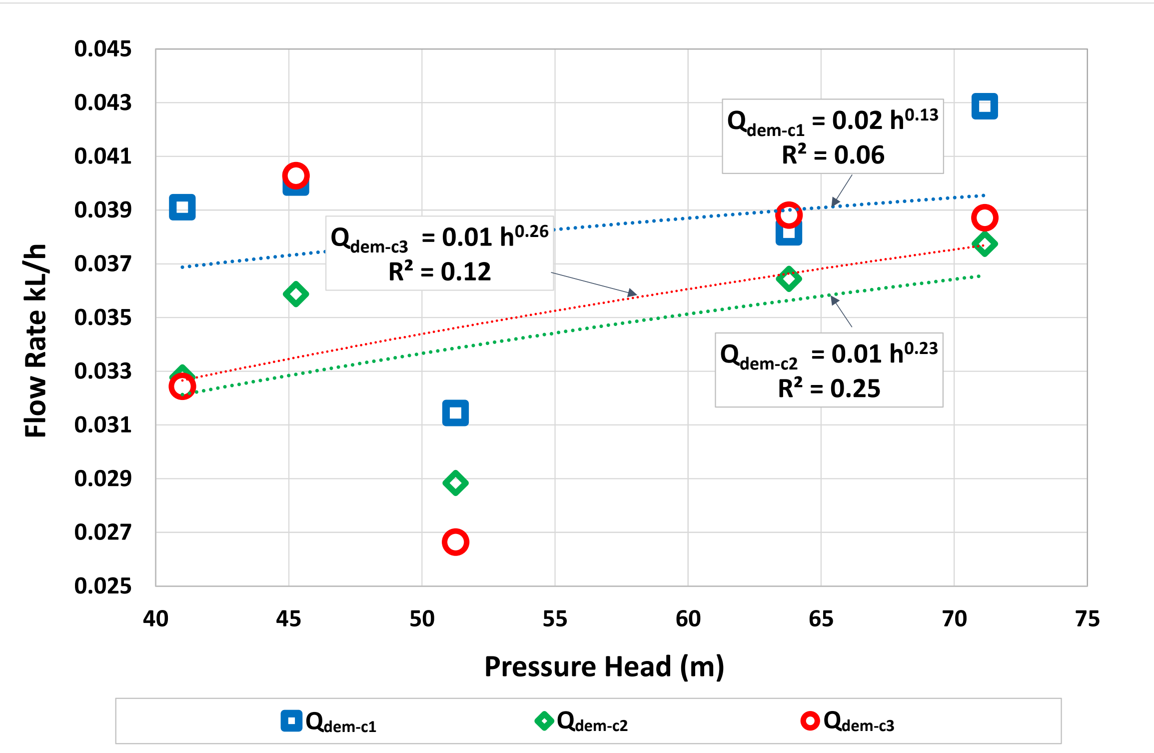

Figure 20: DMA1 $Q_{dem\ c1}$, $Q_{dem\ c2}$, $Q_{dem\ c3}$ versus pressure head

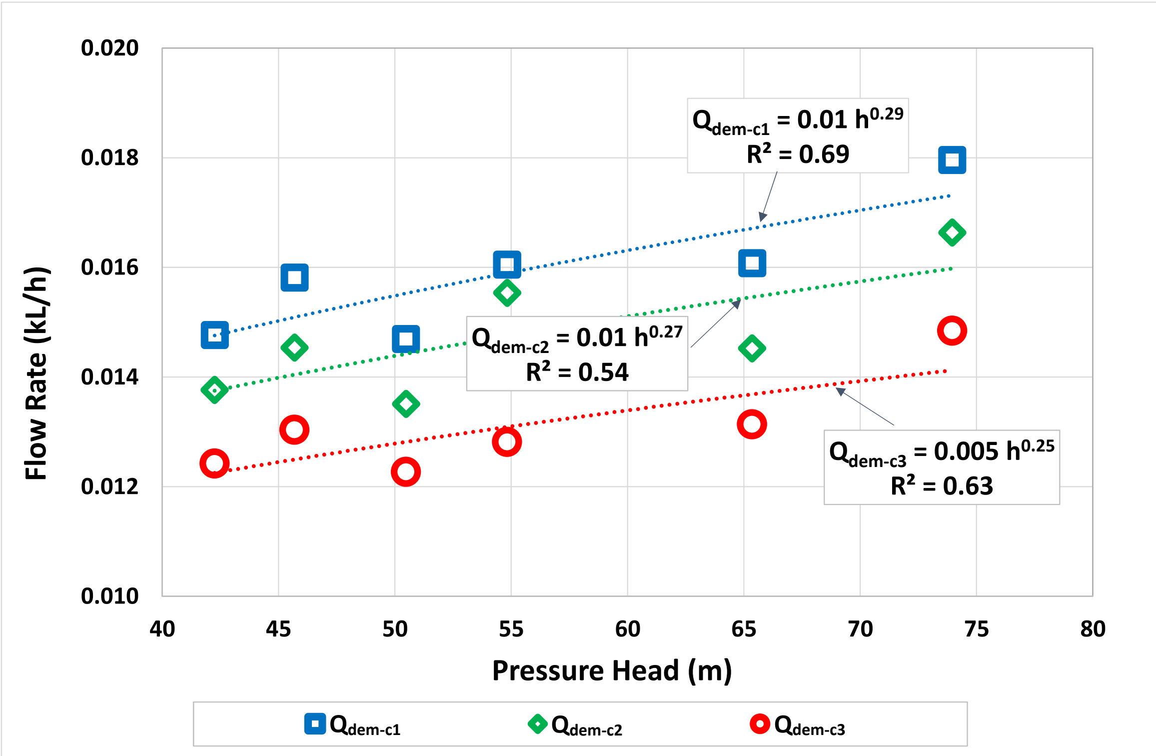

Figure 21: DMA2 $Q_{dem\ c1}$, $Q_{dem\ c2}$, $Q_{dem\ c3}$ versus pressure head

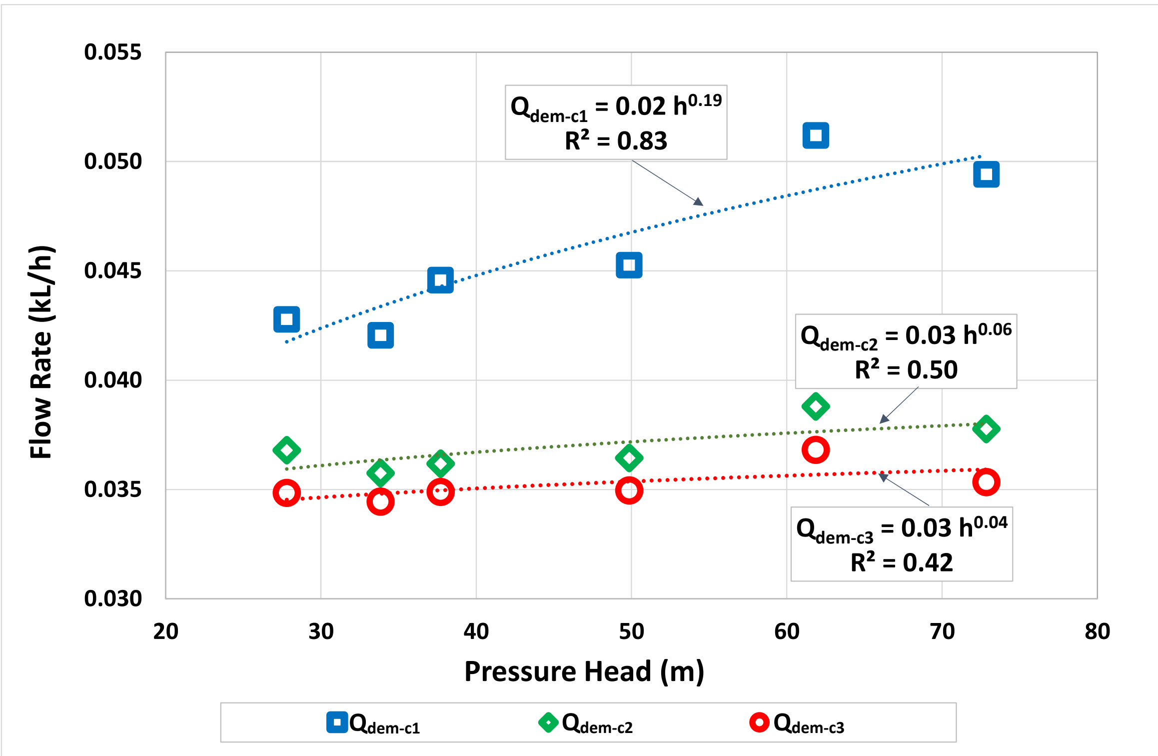

Figure 22: DMA3 $Q_{dem\ c1}$, $Q_{dem\ c2}$, $Q_{dem\ c3}$ versus pressure head

Trend lines based on power regression equations were fitted on Figure 20 to Figure 22**.** The trend lines indicate the approximate pressure-demand relationship for the particular cases in question and do not take into account the potential role of other external factors on consumer demand. The power regression relationships for Q_{dem} versus pressure head for DMA1, DMA2 and DMA3 are summarised in Table 8. The β values represent the total pressure-demand relationship for each scenario and no differentiation was made between indoor and outdoor usage.

Table 8: Summary of trend lines shown in Figure 20 to Figure 22

Sample name	Equation		R^2	β
DMA1: All Consumers	$Q_{dem-c1} = 0.02\ h^{0.13}$	(14)	0.06	0.13
DMA1: High MNF Excluded	$Q_{dem-c2} = 0.01\ h^{0.23}$	(15)	0.25	0.23
DMA1: Medium + High MNF Excluded	$Q_{dem-c3} = 0.01\ h^{0.26}$	(16)	0.12	0.26
DMA2 All Consumers	$Q_{dem-c1} = 0.01\ h^{0.29}$	(17)	0.69	0.29
DMA2: High MNF Excluded	$Q_{dem-c2} = 0.01\ h^{0.27}$	(18)	0.54	0.27
DMA2: Medium + High MNF Excluded	$Q_{dem-c3} = 0.01\ h^{0.25}$	(19)	0.63	0.25
DMA3: All Consumers	$Q_{dem-c1} = 0.02\ h^{0.19}$	(20)	0.83	0.19
DMA3: High MNF Excluded	$Q_{dem-c2} = 0.03\ h^{0.06}$	(21)	0.5	0.06
DMA3: Medium + High MNF Excluded	$Q_{dem-c3} = 0.03\ h^{0.04}$	(22)	0.42	0.04

4 ANALYSIS AND DISCUSSION

4.1 ELASTICITY OF DEMAND TO PRESSURE

4.1.1 Overview

The relationship between changes in demand and changes in pressure head was generally positive for all three DMAs, where reduced pressure led to reduced demand. A summary of the elasticity of demand to pressure values (β in equation 8), for the different equations presented in Section 3 is summarised in Table 9. Equation numbers are shown in brackets.

Table 9: Summary of elasticity of demand to pressure (β)

	Elasticity of demand to pressure (β)			
	DMA Data	Individual Consumer Data		
	Q_{dem}	Q_{dem-c1}	Q_{dem-c2}	Q_{dem-c3}
DMA1	0.07 (11)	0.13 (14)	0.23 (15)	0.26 (16)
DMA2	0.22 (12)	0.29 (17)	0.27 (18)	0.25 (19)
DMA3	0.05 (13)	0.19 (20)	0.06 (21)	0.04 (22)

Where:

Q_{dem} = Total consumer demand component for DMA.

Q_{dem-c1} = Average demand for all individual consumers in used dataset, where flow was recorded.

Q_{dem-c2} = Average demand for individual consumers in used dataset, excluding consumers where high MNF was recorded, as per Table 7.

Q_{dem-c3} = Average demand for all individual consumers in used dataset, excluding consumers where medium or high MNF was recorded, as per Table 7.

4.1.2 Comparison of β values

The Q_{dem} β values shown in Table 9 represent the pressure-demand relationship for the DMA as a whole when all leakage in the DMA is excluded (in the water network and on-site at consumers). It could be expected that Q_{dem} β would be similar to Q_{dem-c3} β where all consumers with potential leakage have been excluded from the calculation. The β values for each scenario investigated are discussed below.

4.1.2.1 DMA1 β Values

Contrary to what was expected, the Q_{dem} β value (0.07) was not similar to the Q_{dem-c3} β value (0.26). It should, however, be noted that the sample size for consumer flow recording was smaller in DMA1 than in DMA2 and DMA3. Furthermore, with the calculation of Q_{dem-c3} an even smaller data set (8 consumers) was used to exclude all the consumers with MNF.

Another aspect to take into account is that one consumer in the DMA1 sample experienced abnormal high demand in the last recording period (Figure 23), equal to three times the average demand in the preceding four time periods. This particular consumer also experienced a high MNF in the final recording period and was therefore excluded from the Q_{dem-c3} calculation. If this particular consumer is included in the Q_{dem-c3} calculation the β value changes to -0.05, which highlights the impact of this one consumer on the β calculation. Based on this observation, the sample size (for individual consumer flow recording in DMA1) was considered to be too small to draw accurate conclusions from the β values for individual consumer data in DMA1.

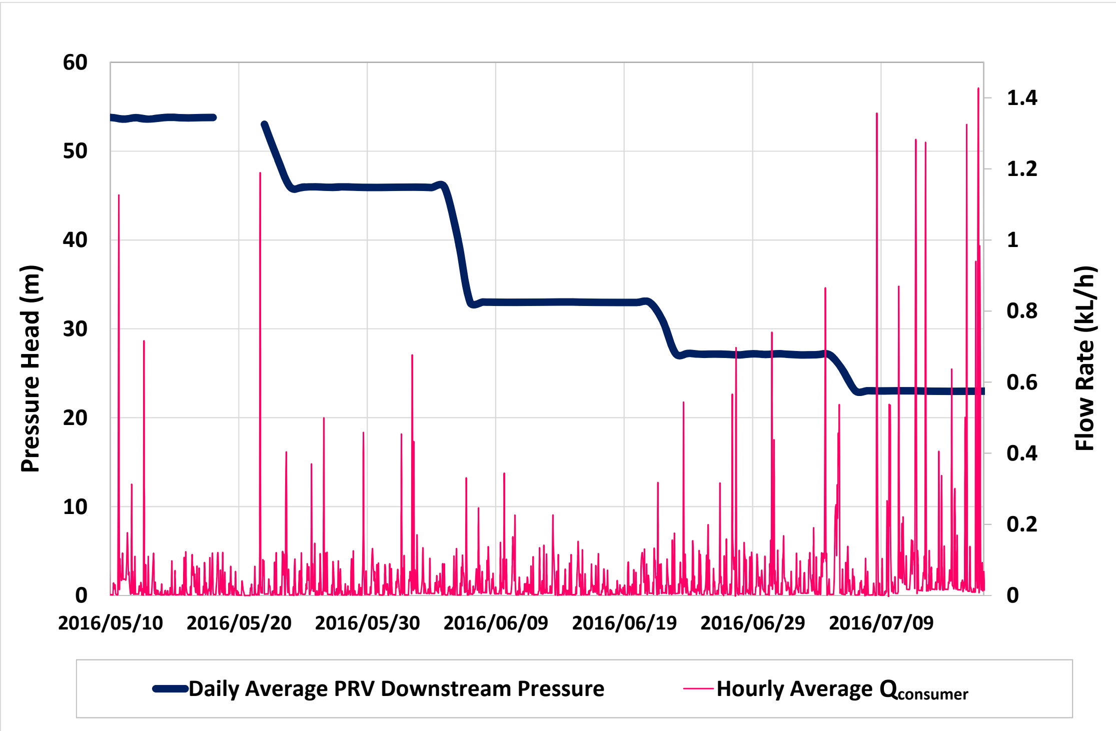

Figure 23: Consumer in DMA1 with high demand in Period 5

4.1.2.2 DMA2 β Values

The Q_{dem} β (0.22) was similar to Q_{dem-c3} β (0.25). This suggests that the demand at the sample of properties in DMA2 which excluded on-site leakage (Q_{dem-c3}) responded in a similar manner to the demand component calculated for the whole DMA (Q_{dem}). This provides support that Q_{dem} β offers a fair representation of the elasticity of demand to pressure at individual consumers.

Parameter Q_{dem-c1} β (0.29) was similar to Q_{dem-c2} β (0.27) as well as Q_{dem-c3} β (0.25). This suggests that the demand component which includes on-site leakage (Q_{dme-c1}) responded in a similar manner to the demand component which excluded on-site leakage (Q_{dem-c2} and Q_{dem-c3}). This highlighted that on-site leakage is not the only driving force behind the pressure-demand relationship in DMA2 and that the actual demand (excluding on-site leakage) reacted to pressure changes.

4.1.2.3 DMA3 β Values

The Q_{dem} β (0.05) was similar to Q_{dem-c3} β (0.04). This suggests that, similar to DMA2, the demand at the sample of properties in DMA3 which excluded on-site leakage (Q_{dem-c3}) responded in a similar manner to the demand component calculated for the whole DMA (Q_{dem}). Again, this provides support that Q_{dem} β offers a fair representation of the elasticity of demand to pressure at individual consumers (excluding on-site leakage).

There was a noticeable difference between Q_{dme-c1} β (0.19) and Q_{dem-c3} β (0.04). This suggests that leakage at consumers was one of the main drivers behind the pressure-demand relationship at individual consumers and that if leakage is excluded the impact of pressure on demand becomes much smaller.

Parameter Q_{dme-c2} β (0.06) was similar to Q_{dem-c3} (0.04). This suggests that the leakage at five properties in the sample with high MNF (≥ 15L/h) was the main factor influencing Q_{dme-c1} β. The impact of excluding the additional data for four consumers with medium MNF (5 < MNF < 15 L/h) did not change the elasticity significantly (β of 0.06 versus β of 0.04).

4.1.3 Comparison with Results from Previous Studies

Bartlett (2004) reported that the indoor β value at a student village was approximately 0.2. Bamezai & Lessick (2003) did not report on β values, although the results obtained by them were equivalent to a β of 0.11 for general domestic properties and 0.24 for properties where significant garden irrigation was expected. The β values obtained in this study compared reasonably well with the results from previous studies. The Q_{dem-c1} β values varied from 0.13 to 0.29 (based on data from individual properties including those with on-site leakage), and the Q_{dem} β values varied from 0.05 to 0.22 (based on DMA flow data when all leakage was excluded in the DMA network and on-site at consumers). None of previous studies investigated the pressure-demand relationship separately for properties with and without on-site leakage

4.2 CONTROL TESTS

In order to validate the impact of pressure on demand in the three test DMAs, the data for three corresponding control areas was obtained and evaluated. The pressure in the control areas was kept constant during the same time that the pressure was reduced in each of the three test DMAs. The control areas were located in different parts of the City of Tshwane than the test DMAs and selected to be supplied by PRVs and in the same income groups as the respective test DMAs. The daily average pressures and daily average flows for each of the three control areas are shown in Figure 24 to Figure 26.

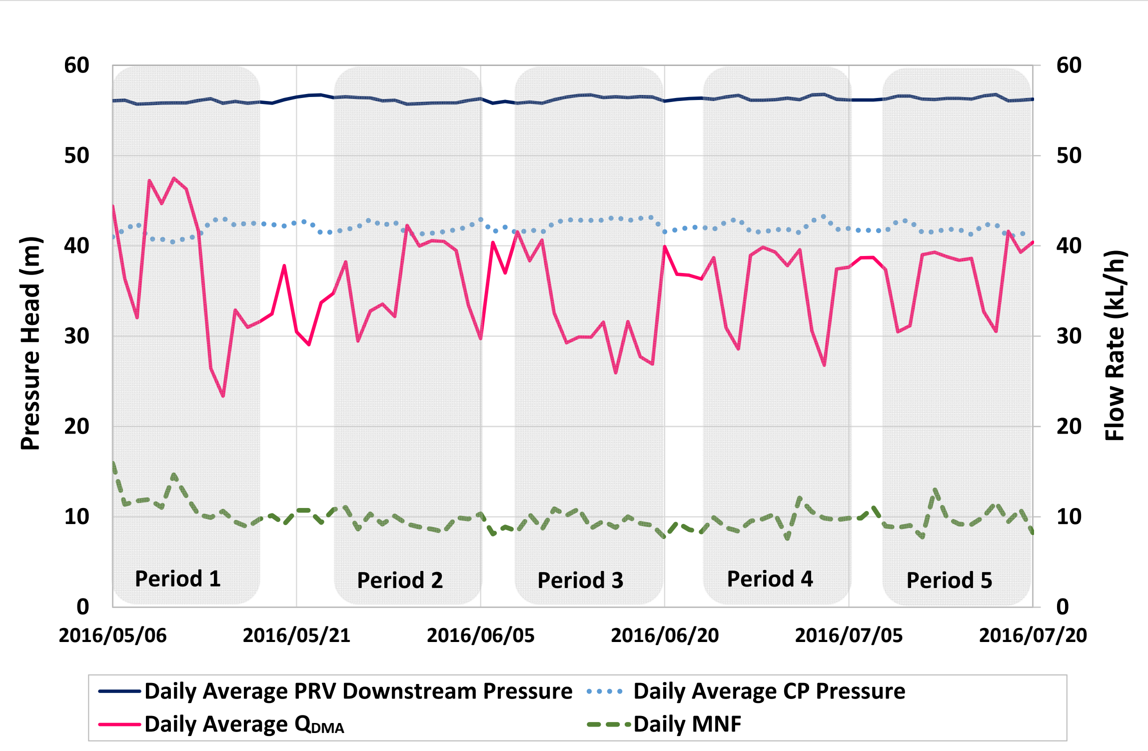

Figure 24: Control area for DMA1 time series pressure and flow profile

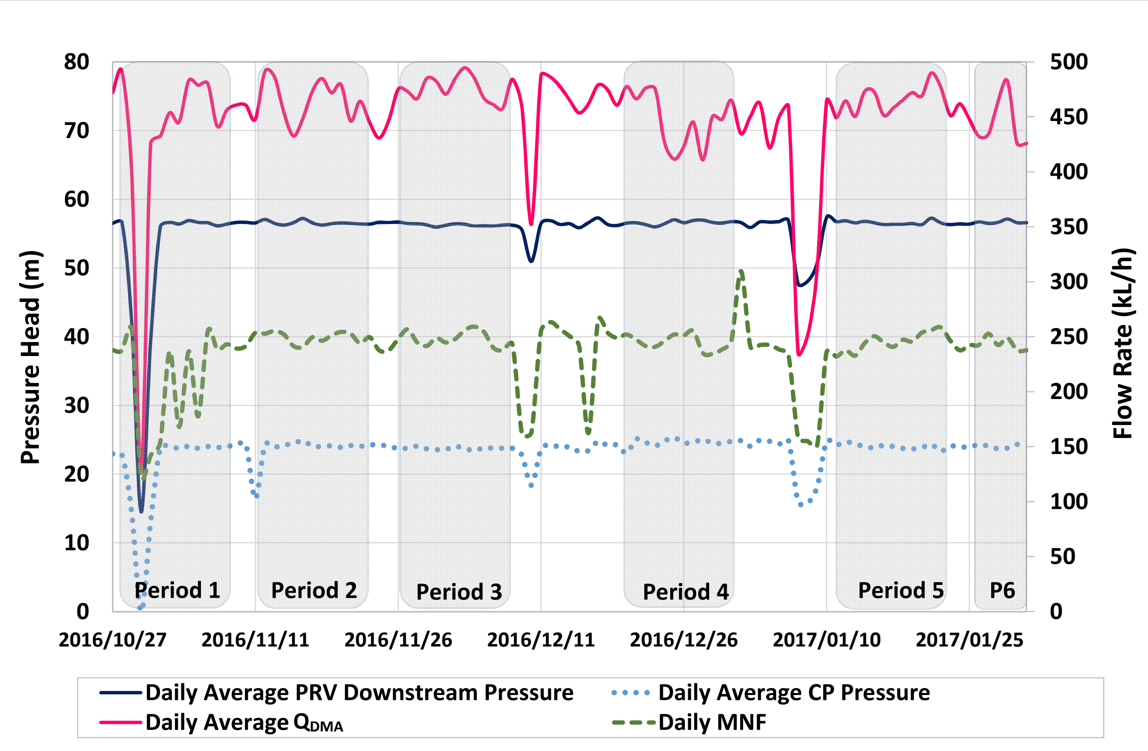

Figure 25: Control area for DMA2 time series pressure and flow profile

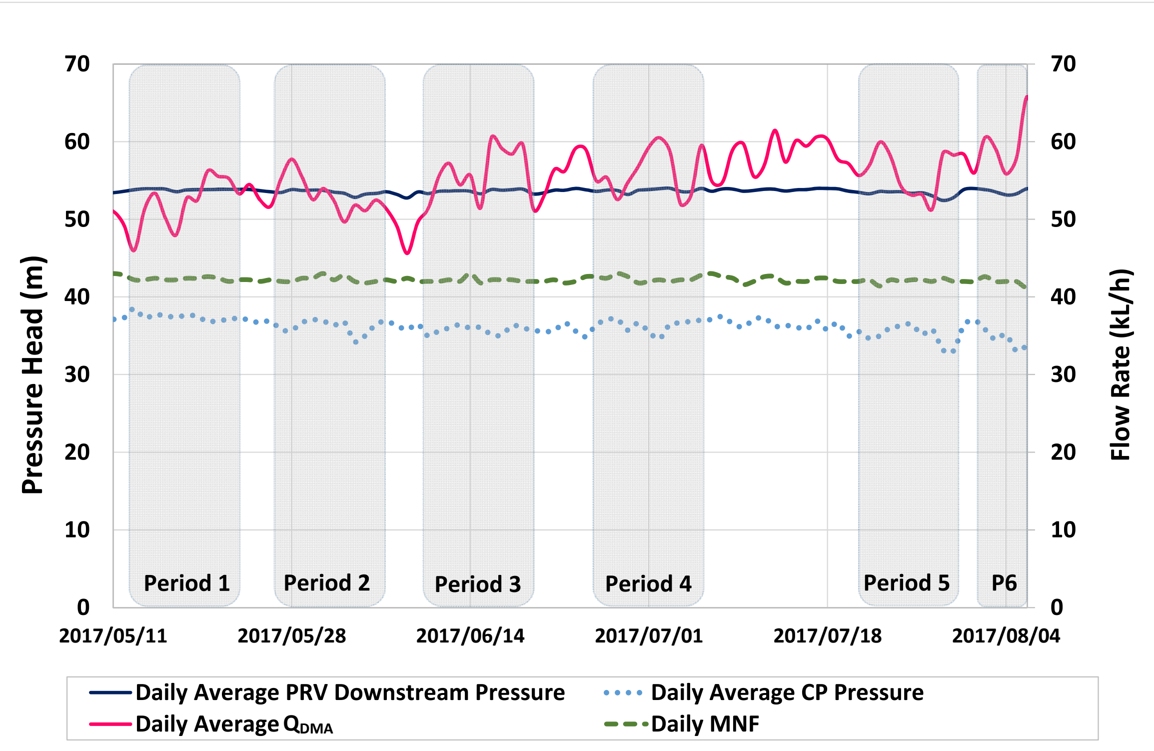

Figure 26: Control area for DMA3 time series pressure and flow profile

In control area 1 the flow remained relatively constant with constant pressure. The flow in control area 1 reduced notably for a few days in Period 1 and again in Period 3 over the same time that the flow reduced in DMA1 (Figure 5). This suggests that weather related parameters such as rainfall and temperature could have impacted on the recorded flow in DMA1 and control area 1.

In control area 2 the flow also remained relatively constant with constant pressure. A water supply interruption occurred in Period 1 in control area 2. In control area 3 the flow increased slightly during the field exercise while the pressure was kept constant, which may have been caused by increased garden irrigation. It should be noted that control area 3 is a slightly higher income area than DMA3 with slightly larger properties, and therefore it can be expected that garden irrigation in control area 3 would be more prominent than in DMA3.

The control tests confirmed that with the pressure kept constant the flow remained relatively constant. This supports the conclusion that the reduction in flow observed in DMA1, DMA2 and DMA3 was caused by a reduction in pressure.

4.3 FACTORS IMPACTING ON THE PRESSURE-DEMAND RELATIONSHIP

4.3.1 Garden Irrigation

DMA1 is a medium to high-income area, where garden irrigation is expected to be a notable contributor to the overall demand. DMA2 is a low-income area with minimum visible garden irrigation and DMA3 is a medium-income area with some visible garden irrigation. Garden irrigation is usually pressure dependent and therefore it was expected that a reduction in pressure should have led to decreased garden irrigation, and thus reduced consumer demand (Bamezai and Lessick 2003). Previous work suggested that the elasticity of demand to pressure would typically be higher for outdoor use than for indoor use (Bamezai and Lessick 2003, Cullen 2004, Van Zyl and Clayton 2007, Koeller and Lalonde 2010). As a result, the highest β was expected for DMA1 followed by DMA3, with the smallest expected β for DMA2. The results show, however, that the Q_{dem} β was higher in DMA2 than in DMA1 or DMA3. Potential factors (relating to garden irrigation) that may contribute towards the lower than expected Q_{dem} β in DMA1 include:

- In Figure 5 it is shown that the demand in DMA1 increased slightly in Periods 4 and 5. The increase in demand was possibly caused by increased garden irrigation in the latter part of the dry season. This suggests that for DMA1 it may not be appropriate to compare the demand in the first three periods to the demand in Periods 4 and 5, since the level of irrigation may not have been consistent during the respective test periods. In this regard the calculated β values for DMA1 should potentially be viewed with caution. Investigating the extent of garden irrigation was outside the scope of this study.

- DMA1 is a medium to high-income area, where some consumers may have on-site boreholes which can be used for irrigation. For consumers with on-site boreholes changes in the WDS pressure would not affect the irrigation water demand. Identification of on-site boreholes was outside the scope of this study.

4.3.2 Household Plumbing PRVs

A potential factor that may have influenced the calculated β values is the presence of household plumbing PRVs. If the pressure to a building is regulated by a household plumbing PRV (often installed on the supply to a hot water geyser) then changes in the WDS pressure are not expected to influence supply pressure at individual end-uses downstream of such a plumbing PRV, unless the WDS pressure is reduced below the setting of the plumbing PRV. In some older areas in South Africa only the hot water household plumbing systems are pressure controlled, and in accordance with SANS 10252-1 (2012) for many newer areas both the hot and cold-water plumbing systems would be pressure controlled.

According to Weber (2017), the most prevalent pressure rating for hot water geysers in South Africa is 400 kPa, for which pressure regulation is typically in the range of 280-320 kPa. That entails that if the supply pressure to a property with a 400 kPa geyser remains above 320 kPa it should not affect the pressure dependent demand component for any end-uses downstream of a pressure control valve.

DMA1 is a medium to high-income and DMA3 a medium-income area and it can be expected that most properties in these DMAs would be equipped with hot water geysers, and therefore pressure control valves. DMA2 is a low-income area and a few random checks revealed that a number of properties in this area are not equipped with hot water geysers. This observation suggests that a large component of the demand in DMA1 and DMA3 would not be affected by pressure changes in the WDS if the supply pressure to properties remains above the household pressure control range. Since there are fewer properties with hot water geysers in DMA2, a larger component of the demand is expected to be pressure dependent. This could partially explain why Q_{dem} β was lower in DMA1 and DMA3 than in DMA2.

4.3.3 Changes in Weather Parameters

The impact on consumer water demand as a result of changes in weather parameters was outside the scope of this study. A few random checks did however suggest that weather related parameters may have influenced the demand, especially in DMA1. The impact of changes in weather parameters could be researched in conjunction with the impact of pressure changes on demand in a future study.

4.4 FACTORS IMPACTING ON THE INDIVIDUAL CONSUMER FLOW DATA

4.4.1 Wide Range in ∆Q for Individual Consumers

A wide ∆Q-range was apparent for individual consumers in Figure 14 to Figure 16. Potential contributing factors are summarised below:

- The wide ∆Q-range for individual consumers can in part be attributed the unpredictable behaviour of people (Torriti 2014), which was not (and could not) be controlled in this relatively large full-scale study. A significant fluctuation in demand was observed at certain individual consumers even during periods when the pressure was kept constant. At other consumers the demand increased during certain periods when the pressure was reduced, possibly due to increased garden irrigation. Also, the field exercise confirmed that individual consumer demand would not necessarily reduce with reduced pressure. The impact of non-technical aspects could surpass pressure-induced changes for an individual consumer.
- Sudden changes in consumer MNF, which did not correspond to changes in pressure, highlighted the potential impact of leakages in altering the consumer demand over a short period, as shown in Figure 13.
- Three consumers in DMA2 had very low monthly water demand (lower than 5 kL per month). The percentage change in water demand from one period to the next can be significant for such low usage consumers, and in some cases this may dominate the percentage change in demand over other potential influences. For example, a consumer with 100 L/d normal usage could experience a significant percentage change in demand with a relatively small change in usage (e.g. five additional toilet flushes daily would result in a ~50% change in demand).

The above-mentioned factors highlight that the pressure-demand relationship is not expected to be uniform from one consumer to the next, and also not from one DMA to the next. In order to draw meaningful conclusions from the average pressure and flow measurements at individual consumers the sample size should preferably be of sufficient size to be representative of the DMA.

4.4.2 Consumer MNF

A significant MNF was recorded at a number of the consumers, as summarised below:

- The average consumer MNF for the properties selected for flow recording was 7 L/h, 6 L/h and 9L/h in DMA 1, DMA2 and DMA3 respectively.
- The average MNF represented approximately 19% of the total demand of the consumers selected for flow recording in DMA1, 32% in DMA2 and 20% in DMA3. This corresponds to findings of a study where on-site leakage for a sample of 182 properties in Johannesburg was 25% of the metered demand, with an average leakage rate of 12 kL/month per residential property (Lugoma et al 2012).

It was assumed that a consistent MNF at a consumer was as a result of on-site leakage. According to the IWA water balance (Figure 1) any leakage after the consumer supply point forms part of authorised consumption and is therefore not be included in the water loss component for the water utility. Notwithstanding this, in the light of water availability shortcomings in South Africa it is recommended that both water utilities and consumers alike should aim to reduce on-site leakage as far as possible.

5 CONCLUSION

5.1 SUMMARY OF FINDINGS

A series of pressure adjustments in three operational DMAs were successfully conducted to assess the impact of pressure change on the total water demand in each DMA, as well as on the water demand of 76 consumers. All three research sites reported a positive relationship between pressure change and consumer demand, where reduced pressure resulted in reduced demand. The power regression model suggested an elasticity of demand to pressure (β) 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. An elasticity of 0.25 would mean that the demand would decrease by 2.5% for every 10% reduction in pressure.

The impact of pressure changes on consumer demand may be perceived to be relative low, but could be partially explained by the presence of household plumbing PRVs. In DMA1 and DMA3, where household plumbing PRVs were likely to be present at most properties, the impact of pressure changes on demand (excluding on-site leakage) was found to be less than in the low-income DMA2 where fewer properties were likely to have household plumbing PRVs. The elasticity of demand to pressure (excluding on-site leakage) was in the range of ≈0.05 for DMA1 and DMA3 and in the range of ≈0.25 for DMA2. This finding has significant implications for pressure management programmes, suggesting that consumer demand (excluding on-site leakage) in some suburban areas may not reduce notably with relatively large changes in pressure, probably due to the presence of household plumbing PRVs, which would have controlled pressure to end-use points in the home in the first place.

It was shown that the demand in DMA1 increased slightly during Periods 4 and 5, while the pressure was reduced. The increase in demand was possibly caused by increased garden irrigation in the latter part of the dry season. This suggests that for DMA1 it may not be appropriate to compare the demand in the first three periods to the demand in Periods 4 & 5 since the level of irrigation may not have been consistent between the test periods. In this regard the calculated β values for DMA1 should potentially be viewed with caution.

The field exercise confirmed that individual consumer demand would not necessarily decrease with reduced pressure, and that the impact of non-technical aspects could surpass pressure-induced change for an individual consumer.

A basic but useful approach was proposed to estimate the demand component in the DMA from the flow recording data.

On-site leakage on consumer properties (downstream of the consumer meter) was estimated to be 19% of the consumer demand in DMA1, 32% in DMA2 and 20% in DMA3. The average consumer MNF for the selected properties was 7 L/h, 6 L/h and 9L/h respectively for the three DMAs investigated.

The study also highlighted the practical lower limit of pressure reduction in the DMAs investigated, which may be of use for water utilities when planning pressure reduction programmes:

- In DMA1 the minimum pressure achieved at the CP was 18m, during which time a number of low pressure complaints were reported.
- In the low-income DMA2 the minimum pressure achieved at the CP was 10m. The municipality received four complaints of no-water during the test in DMA2, but no complaints of low pressure were reported.
- In the medium-income DMA3 the minimum pressure achieved at the CP was 14m, after which a low-pressure complaint was reported. The complaint came from a multi-storey apartment building where no residual water pressure remained at the top floor of the building.

5.2 CONCLUSION

The results from this study confirmed that reduced pressure should result in reduced water demand. The impact of pressure on demand was however expected to be more significant than observed in this research. The elasticity of demand to pressure for the three DMAs investigated ranged from ≈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. The elasticity of demand to pressure compared reasonably well with the results from previous studies although none of previous studies investigated the pressure-demand relationship separately for properties with and without on-site leakage.

Based on the results presented in this study two significant factors were identified which could influence the elasticity of demand to pressure: 1) the presence of on-site leakage and 2) the presence of household plumbing pressure reducing devices. For the sites investigated, on-site leakage was one of the main drivers behind the pressure-demand relationship. Where on-site leakage was excluded the impact of pressure change on consumer demand was generally found to reduce. In some cases the presence of household plumbing PRVs could potentially negate the impact of pressure changes on household demand. The elasticity of demand to pressure (excluding on-site leakage) was significantly lower in areas with a high likelihood of household plumbing PRVs compared to an area with a lower likelihood of such PRVs.

5.3 FUTURE RESEARCH

The impact on consumer water demand as a result of changes in weather parameters was outside the scope of this study. A few random checks did however suggest that weather related parameters may have influenced the demand, especially in DMA1. The impact of changes in weather parameters could be researched in conjunction with the impact of pressure changes on demand in a future study.

Future research can be undertaken to assess the prevalence and pressure regulation ranges of household plumbing PRVs. In a future study a model could be developed to simulate the pressure-demand relationship and the following factors could be taken into account: pressure, presence of household plumbing PRVs and the pressure regulation range of those PRVs, presence and extent of on-site leakage, weather parameters, impact on end-uses and garden irrigation.

In this study the sample size was dictated by the availability of data recorders. An attempt could be made to increase the sample size in a future study in order to improve the data confidence levels. The study could also be expanded to include tests in other water utilities in different climatic regions.

In future work an attempt could be made to combine trace analysis (Willis et al. 2013) with the pressure-demand analysis to determine how different water end-uses (as well as indoor versus outdoor end-uses) are affected by pressure changes and what the actual minimum pressure is for specific household end-uses.

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